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Imperfect market, emissions trading scheme, and technology adoption: A case study of an energy-intensive sector

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ABSTRACT

It is widely accepted that the firms included in an emissions trading scheme (ETS) come mostly from oligopolistic industries. The "exclusionary manipulation" of these heterogeneous emitters can distort both output and permit markets and lead to differences in abatement technology adoption. We studied the impacts of asymmetric firms' market power on the diffusion of abatement technologies. A model for technology adoption among heterogeneous firms has been established, which takes into account diversity in production capacity and the integration of firms' strategic behaviour in both the carbon permit and the output markets. Our model reveals that, considering the direct and strategic effects in adoption benefits, firms' production capacity can directly determine their sequence order of adoption, and their market power can accelerate the diffusion of a new abatement technology. A case study of an energy-intensive sector in China is illustrated to support the conclusions derived from the model and help policymakers better understand the diffusion of abatement technologies under imperfect market structure.

1. Introduction

A wide debate is currently taking place over the effect of an emissions trading scheme (ETS) on the diffusion of environmentally friendly technologies. Kumar and Managi (2010) and Tietenburg (2010) believe that a permit market establishes a clear price signal that provides firms with more incentives to invest in environmental research and development (R&D) than command and control regulations. However, opponents of this idea, such as Laffont and Tirole (1996) and Fadaee and Lambertini (2015), use a theoretical analysis to illustrate that pollution permits diminish or eliminate firms' incentives to develop green R&D when the firms have acquired the right to pollute for free. Meanwhile, the permit market is empirically found to provide insufficient incentives for corporate innovation activities, especially if the regulators choose unreasonable allocation rules for the permit markets (e.g., an emissions trading scheme (ETS), Schleich and Betz, 2005; Hoffmann, 2007; Leiter et al., 2011; Rogge et al., 2011; Bergek et al., 2014).

It is common to observe that firms manipulate the market when they are included in the ETS (Kolstad and Wolak, 2008; Hintermann, 2011; Liao and Shi, 2018), which may become a serious problem, especially in some localized permit markets with imperfect trading mechanisms (Sartzetakis, 1997; Dickson and MacKenzie, 2018). In addition, it is often neglected that most firms usually behave as oligopolists in the output markets because they come from energy-intensive sectors such as iron and steel (Wang et al., 2018). With market power in the output market, firms can also distort the permit market price to increase their rivals' costs in the output market (Hahn, 1984; Hintermann, 2017). Such strategic behaviour has been called "exclusionary manipulation" in Misiolek and Elder (1989), and it aggravates the inefficiencies occurring in both output and permit markets (Malueg, 1990; Song et al., 2018).

It is worth asking whether the introduction of an ETS increases firms' economic incentives to accelerate the diffusion of abatement technologies because of the imperfectly competitive permit market. In contrast to a perfectly competitive setting in which tradable permits can perform better than command and control with respect to creating incentives for the adoption of abatement technologies to promote technology adoption (Montero, 2002a; Requate, 2005a), heterogeneous firms can distort both output and permit market prices under possible exclusionary

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manipulation. Then, such strategic behaviours can result in certain consequences on their expected technology adoption benefits and the process of technology diffusion. Therefore, it is necessary to re-evaluate firms' decisions on technology adoption in imperfectly competitive markets.

This paper studied firms' strategic behaviour in their decision to adopt abatement technology with the consideration of exclusionary manipulation. An analytical framework for technology adoption among asymmetric firms with diversity in production capacity has been established, and a two-stage non-cooperative cooperative game model is integrated to characterize the strategic behaviour of heterogeneous firms (Godal, 2005). With this model, we can determine the heterogeneous firms' benefits from technology adoption in the imperfect market and the optimal date of adoption. A case study of an energy-intensive sector in China is illustrated to support the conclusions derived from the model and present a more comprehensive discussion on the diffusion of abatement technologies in imperfectly competitive markets.

Similar to our paper, Coria (2009) explores how the choice between taxes and permits affects the pattern of adoption of an abatement technology. The dynamic approach she proposed provides a valuable starting point for further studies exploring firms' timing decisions regarding upgrading technology. We extend the analytical framework and contribute to the previous literature in the following ways.

1) We investigated the effect of market power in the permit market on the diffusion of technology. Firms' decisions regarding technology adoption have been examined in a duopolistic framework in Reinganum (1981), Fudenberg and Tirole (1985), and Huisman and Kort (2003). Coria (2009) adopts a framework for the adoption of an abatement technology but does not consider market power in the permit market. Under imperfect market conditions, R&D incentives to invest in abatement technologies depend on both the direct and strategic effects that are generated by market-based instruments (Montero, 2002a; Bruneau, 2004; Nelissen and Requate, 2007; Requate, 2005a). Given that emissions cannot be symmetric in terms of costs for the firms proposed in Ambec and Coria (2013) and the differences in the potential for abatement before technology adoption lead to sequential adoption among the firms (Thirtle and Ruttan, 1987; Karshenas and Stoneman, 1993), the market power in the permit market will obviously affect abatement technology adoption and should not be neglected.
2) An integrated two-stage game model is proposed for characterizing the strategic behaviour of firms. The market prices of both output and permits can be simultaneously distorted because of firms' exclusionary manipulation (Misiolek and Elder, 1989; Chesney et al., 2016). The effects of policy instruments are ambiguous with respect to technology adoption under Cournot competition in the output market (Montero, 2002b; Gersbach and Requate, 2004; Requate, 2005b; Sanin and Zanaj, 2007). The traditional Hahn-Westskog model featured only large agents with market power and a fringe in a Stackelberg-type game (Hahn, 1984; Westskog, 1996), and there is no market-clearing device in the absence of price takers (Montero, 2009). Then, referring to Flåm and Jourani (2003), Godal (2005), and Wang et al. (2018), we assume that each heterogeneous firm can become a strategist with more or less market power in the ETS. A two-stage noncooperative cooperative game is introduced to describe the coexistence of strategic and non-strategic behaviours in the permit market, and a Cournot model is combined to characterize firms' strategic behaviour in the output market.
3) The diversity in firms' production capacity has been identified to describe the heterogeneity. Production capacity has been identified as one of the factors that influence a firm's adoption of abatement technologies (Ge et al., 2017). The scale of enterprises and their adoption costs determine the effect of market-based instruments on low-carbon technology diffusion (Mohr, 2006; Fan and Dong, 2018). Production capacity can also directly lead to firms' strategic behaviour in both the output market and permit market. Therefore, different from Coria and Mohlin (2017) and Moner-Colonques and Rubio (2015), we incorporate production capacity to reflect asymmetric firms' heterogeneity. With this model, we present how the optimal date of technology adoption among heterogeneous firms can be determined in association with production capacity and corresponding adoption benefits.

The remainder of the paper is structured as follows. Section 2 presents the development of the models. Section 3 proposes an analytical framework for the impact in an imperfectly competitive market. In Section 4, we develop quantitative examples to illustrate the analytical results of the previous sections. We provide concluding remarks in Section 5.

2. Model formulation

2.1. Preliminaries

Let I be the fixed and finite set of heterogeneous firms producing a homogeneous good in an energy-intensive sector. Each firm $j \in I (j = 1, \dots, n)$ is included in an ETS. The linear inverse demand function for the good is given by:

$$P = P(Q) = a - b \cdot Q \tag{1}$$

where Q denotes the aggregate level of output in the sector, i.e., $Q = \sum_{j=1}^{n} q_j$, and q_j denotes the level of production of firm j; a and b are positive parameters.

Similar to Coria (2009), we assume that when they produce output, firms emit a homogeneous pollutant—that is, carbon dioxide (CO_2)—and each unit of output generates a unit of emissions, e ($\partial e_j / \partial q_j = 1$). To manage these emissions, firms install abatement technology. The level of production is not affected when, in the end, the firm generates emissions e_j.[1]

Suppose that a new technology becomes available at the beginning of period 1, and i firms choose to install this new technology. This technology allows each of these firms to reduce emissions at a lower total abatement cost $TC_j(r_j)$ $(j = 1, 2, \dots, i)$:

$$TC_j(r_j) = \frac{c}{2} \cdot r_j^2 = \frac{c}{2} \cdot \left(q_j - e_j\right)^2 \tag{2}$$

where c is a parameter and r_j is the level of emissions reduction. At this moment, $n - i$ firms still do not intend to adopt the new technology. For each of them k, the respective total abatement cost function is given by

$$TC_k(r_k) = \frac{c_k}{2} \cdot r_k^2 = \frac{c_k}{2} \cdot (q_k - e_k)^2 \tag{3}$$

where c_k is the parameter corresponding to each firm, and r_k is firms' level of emissions reduction. We assume that the new technology allows firms to reduce emissions at a lower total abatement cost, that is, $c_k > c$ for any firm k.

When all the firms are included in the ETS and i firms have adopted the new technology, firm j (adopters) and firm k (non-adopters) receive a number of freely allocated tradable permits, ε_j and ε_k, respectively,

[1] This assumption is reasonable when most firms adopt end-of-pipe technologies to curb emissions. Therefore, here, it is necessary for us to consider the interplay between firms' market power in output and permit markets.

under grandfathering or benchmarking. Then, $\overline{E}=\sum_{j=1}^{i}\varepsilon_j+\sum_{k=i+1}^{n}\varepsilon_k$ is the number of permits available to all firms. Unlike in Song et al. (2018), we assume that both adopters and non-adopters are not allowed to choose non-compliance in the permit market. They can only optimize their respective outputs and emissions to fulfil the emissions reduction target.

2.2. Model of technology upgrading

Referring to the dynamic setting in Coria (2009), we propose a new model of technology upgrading among heterogeneous firms by taking into account both abatement cost and production capacity. Firms' differences in abatement cost before and after technology adoption can directly affect their adoption benefits, and their production capacity can also determine the final costs for the new technology.

It is assumed that each firm needs to consider its production capacity $\overline{q_j}$, where $q_j\le\overline{q_j}$, when it decides to adopt the same technology. k is the investment cost for per unit production capacity, which is identical among the firms in the beginning. Firm j adopts the new technology at a cost $k\cdot\overline{q}_j$ at the beginning of period 1. τ_j denotes the date of adoption of firm j. Then, we order the adoption dates for all the firms, such that $0<\tau_1\le\tau_2\le\ \dots\ \tau_{j-1}\le\tau_j\le\tau_{j+1}\ \dots\ \le\tau_{n-1}\le\tau_n<\infty$.

It is also assumed that when the number of firms adopting the new technology increases, more firms will enter the market to supply the new technology. This lowers the adoption cost $k\cdot\overline{q}_j$ according to the function $K_j(\tau_j)=k\cdot\overline{q}_j\cdot e^{-(\delta+\theta_j)^{\tau_j}}$, where δ is the intertemporal discount rate, and θ_j is used to represent the order effect on the investment cost of technology. The investment cost K_j decreases with the number of firms that have already adopted the technology at the rate θ_j, where θ_j exhibits the usual properties: $\theta_j>0$, $\partial\theta_j/\partial j>0$, $\partial^2\theta_j/\partial^2 j\le 0$.[2]

Let $\pi(i)_j^A$ be the rate of Cournot-Nash profit flow to firm j, when i firms have adopted the new technology and firm j belongs to the fraction that has already adopted. Let $\pi(i)_j^{NA}$ be the rate of Cournot-Nash profit flow to firm j, when i firms have adopted the new technology and firm j belongs to the fraction that has not yet been adopted. Similar to Coria (2009), we assume that $\pi(i)_j^A$ and $\pi(i)_j^{NA}$ are known with certainty by firms. Then, it can be easily proven that the sequence of firms' adoption dates $0<\tau_1\le\tau_2\le\ \dots\ \tau_{j-1}\le\tau_j\le\tau_{j+1}\ \dots\ \le\tau_{n-1}\le\tau_n<\infty$ is a perfect equilibrium in sub-games, when the four assumptions, which are approximately the same as in Coria (2009, p. 252), are required.[3] However, in consideration of firms' production capacity, the original assumption (iv) provided in Coria (2009) should be modified as

$$\frac{\bar{q}_j}{\bar{q}_{j-1}}\cdot\Delta\pi_{j-1}\cdot e^{[\theta_{j-1}-\theta_j]\cdot\tau_{j-1}}-[\theta_{j-1}-\theta_j]\cdot k\cdot\bar{q}_j\cdot e^{[-\theta_j]\cdot\tau_{j-1}}>\Delta\pi_j>\frac{\bar{q}_j}{\bar{q}_{j+1}}\cdot\Delta\pi_{j+1}\cdot e^{[\theta_{j+1}-\theta_j]\cdot\tau^*_{j+1}}-[\theta_{j+1}-\theta_j]\cdot k\cdot\bar{q}_j\cdot e^{-[\theta_j]\cdot\tau^*_{j+1}} \tag{4}$$

where $\Delta\pi_{j-1}=\pi(i)_{j-1}^A-\pi(i)_{j-1}^{NA}$. As indicated in Coria (2009), this assumption states that the adoption cost decreases with the number of firms that have already adopted at a (sufficiently and slowly) increasing rate to ensure that firm j's objective function defined in Eq. (5) is strictly concave in j's choice variable τ_j.

[2] We consider the parameter θ_i as defined by Coria (2009). Moreover, we assume that its value does not depend on firms' capacity and the initial investment cost of technology.

[3] The proof of this statement is similar to that in Appendix A in Coria (2009: 263–285). We will not repeat it here.

Then, we provide the present value of firm j's profits, or the net adoption costs when it adopts the new technology on date τ_j, characterized as follows:

$$V^j(\tau_1,\dots,\tau_j,\dots,\tau_n)=\sum_{i=0}^{j-1}\int_{\tau_i}^{\tau_{i+1}}\pi(i)_j^{NA}\cdot e^{-\delta t}dt+\sum_{i=j}^{n}\int_{\tau_i}^{\tau_{i+1}}\pi(i)_j^A\cdot e^{-\delta t}dt-k\cdot\bar{q}_j\cdot e^{-(\delta+\theta_j)^{\tau_j}} \tag{5}$$

where $\tau_0=0$, $\tau_{n+1}=\infty$. Then, the optimal date of adoption for each firm is found by maximizing V^j via the choice of τ_j from the interval $[\tau_{j-1},\tau_{j+1}]$. The corresponding first-order condition is given by

$$\frac{\partial V^j}{\partial\tau_j}=\left[\pi_j^{NA}-\pi_j^A\right]\cdot e^{-\delta\tau_i^*}+(\delta+\theta_j)\cdot k\cdot\bar{q}_j\cdot e^{-(\delta+\theta_j)\tau_j^*}=0 \tag{6}$$

Then, firm j will adopt the new technology at τ_j^*:

$$\tau_j^*=\frac{1}{\theta_j}\left(\frac{(\delta+\theta_j)\cdot k\cdot\bar{q}_j}{\pi_j^A-\pi_j^{NA}}\right) \tag{7}$$

With Eq. (7), firms' heterogeneity in both production capacity and abatement cost directly affects their dates of adoption in the imperfect market: 1) firms' production capacity can affect their initial cost of adopting technology. If a firm has a smaller scale of production, $\overline{q_j}$, it will bear less initial investment cost than other firms, and the adoption will also be earlier than in other firms. Then, the sequence order of adoption can be determined. 2) Firms' abatement cost affects their benefits from exclusionary manipulation in the permit market. If a firm can acquire more benefits from exclusionary manipulation, $\pi(i)_j^A-\pi(i-1)_j^{NA}$, it will adopt the technology earlier than others with lower abatement cost. In sum, the firm will upgrade the technology earlier if adoptions yield more net benefits for per unit production capacity, $[\pi(i)_j^A-\pi(i-1)_j^{NA}]/\bar{q}_j$.

2.3. Model of an imperfectly competitive permit market

A dynamic game model is proposed to characterize firms' exclusionary manipulation in the permit market. To calculate and compare the firms' benefits from technology adoption, we assume that $\pi(i)_j^{A,\ C}$ is the rate of Cournot-Nash profit flow to firm j in the perfectly competitive permit market, when i firms have adopted the new technology and firm j belongs to the fraction that has already adopted; $\pi(i)_j^{NA,\ C}$ is the rate of Cournot-Nash profit flow to firm j in the perfectly competitive permit market when i firms have adopted the new technology and firm j belongs to the fraction that has not yet adopted. Furthermore, $p(i)$ denotes the equilibrium permit price in the perfectly competitive permit market. Coria (2009) provides the corresponding first-order conditions for firms' output and emissions when the permit market is perfectly competitive.

The strategic interaction among firms is construed as a two-stage noncooperative cooperative game, as in Flåm and Jourani (2003) and Godal (2005):

> **Stage 1**: Both adopters and non-adopters partition the cap $\overline{E}$ noncooperatively, with total permits remaining constant.

Endowed with the initial permits, all firms want to manipulate the market to their own advantage, regardless of whether they are adopters or non-adopters. If the firm comes forward as a permit buyer, it wants to push the permit price down. Such a firm does so by bringing more than ε_j or ε_k to the ETS, thereby "flooding" that market. In contrast, if such a firm acts as a permit seller, it wants to drive the price up and then brings less than ε_j or ε_k to the ETS.

Therefore, both adopters and non-adopters want to partition the cap E to noncooperatively determine a new emissions target in consideration of the abatement cost. The new emissions targets for adopters and non-adapters are denoted by $z_j (j = 1,2, \ldots ,i)$ and z_k $(k = i+1, i+2, \ldots ,n)$, respectively. The total of their emissions targets, $z_N := \sum_{j=1}^{i} z_j + \sum_{k=i+1}^{n} z_k$, must not exceed the emissions cap $\overline{E}$. Therefore, all firms are considered fully fledged Cournot oligopolists, foreseeing how their own decision will affect the market permit price.

Stage 2: All the firms join a coalition I to share the compliance costs in a reasonable manner.

Being engaged in the ETS, the concerned firms are encouraged to pool their initial allowances and then achieve better outcomes for everyone (Evstigneev and Flåm, 2001). Therefore, they can join a coalition to coordinate the abatement targets with each other to reduce their compliance costs. This coalition can incur a stand-alone cost with the aim of distributing prospective savings among its members (Evstigneev and Flåm, 2001). The corresponding core solution to this game can be derived, which relates to cost sharing among firms when their personal valuations of the permit rights coincide (Flåm, 2016).

Therefore, the trade in permits among firms is construed as a coalition game. However, at this stage, both adopters and non-adopters consider z_j and z_k as their new emissions target, respectively. Furthermore, we assume that adopters and non-adopters decide to emit y_j and y_k, respectively, when they choose z_j and z_k as their emissions targets. The respective abatement costs for adopters and non-adopters are denoted by $\frac{c_j}{2} \cdot (q_j - y_j)^2$ and $\frac{c_k}{2} \cdot (q_k - y_k)^2$. Then, each firm decides its output q_j or q_k and emissions y_j or y_k such that the total compliance costs of the (grand) coalition $\left(\sum_{j=1}^{i} \frac{c_j}{2} \cdot (q_j - y_j)^2 + \sum_{k=i+1}^{n} \frac{c_k}{2} \cdot (q_k - y_k)^2 \right)$ are minimized, with the constraint that total emissions $\left(\sum_{j=1}^{i} y_j + \sum_{k=i+1}^{n} y_k \right)$ do not exceed the specific cap z_N. Adopters' optimization model with respect to emissions y_j is

$$\min_{q_j, y_j} \sum_{j=1}^{i} \frac{c_j}{2} \cdot \left(q_j - y_j\right)^2 + \sum_{k=i+1}^{n} \frac{c_k}{2} \cdot (q_k - y_k)^2, \ j = 1, 2, \ldots, i \tag{8}$$

Similarly, non-adopters' optimization model with respect to emissions y_k is

$$\min_{q_k, y_k} \sum_{j=1}^{i} \frac{c_j}{2} \cdot \left(q_j - y_j\right)^2 + \sum_{k=i+1}^{n} \frac{c_k}{2} \cdot (q_k - y_k)^2, \ k = (i+1), (i+2), \ldots, n \tag{9}$$

Appendix A presents the solution to the game model and the conditions for the stability of the coalition to find the optimal solution to the game.

It is assumed that this is a dynamic game model under complete information—that is, cost sharing in the coalition game at the second stage is commonly understood at the first stage in the model. Furthermore, each firm accounts for how its first stage choice in z_j or z_k affects the outcome of the second stage to minimize its total compliance costs. Let $\pi(i)_j^{A,\ NC}$ be the rate of Cournot-Nash profit flow to firm j in the imperfectly competitive permit market when i firms have adopted the new technology and firm j belongs to the fraction that has already adopted. Let $\pi(i)_k^{NA,\ NC}$ be the rate of Cournot-Nash profit flow to firm j in the perfectly competitive permit market when i firms have adopted the new technology and firm k belongs to the fraction that has not yet been adopted. Then, firm j acts as if solving

$$\max_{q_j, z_j, y_j} \pi(i)_j^{A,NC} = P(Q) \cdot q_j - \frac{c_j}{2} \cdot \left(q_j - y_j + z_j - \varepsilon_j\right)^2 - \lambda(i) \cdot \left(y_j - z_j\right), \ j = 1, 2, \ldots, i \tag{10}$$

and the corresponding first-order conditions with respect to (q_j, z_j, y_j) are given by

$$a - b \cdot Q - b \cdot q_j - c_j \cdot \left(q_j - y_j + z_j - \varepsilon_j\right) = 0 \tag{11}$$

$$\left(\lambda(i) - c_j \cdot \left(q_j - y_j + z_j - \varepsilon_j\right)\right) \cdot \left(1 - \lambda(i)' \cdot y_j'\right) - \lambda(i)' \cdot \left(y_j - z_j\right) = 0 \tag{12}$$

$$\lambda(i) - c_j \cdot \left(q_j - y_j\right) = 0 \tag{13}$$

where

$$y_j' = \frac{dy_j}{d\lambda(i)} = -\frac{1}{c_j}$$
$$\lambda(i)' = \frac{\partial\lambda}{\partial z_j} = \frac{\partial\lambda}{\partial z_k} = -\frac{1}{\sum_{j=1}^{i} \frac{1}{c_j} + \sum_{k=i+1}^{n} \frac{1}{c_k}} \tag{14}$$

Similarly, firm k acts as if solving

$$\max_{q_k, z_k, y_k} \pi(i)_k^{NA,NC} = P(Q) \cdot q_k - \frac{c_k}{2} \cdot (q_k - y_k + z_k - \varepsilon_k)^2 - \lambda(i) \cdot (y_k - z_k), \ k = i+1, 2, \ldots, n \tag{15}$$

and the corresponding first-order conditions with respect to (q_k, z_k, y_k) are given by

$$a - b \cdot Q - b \cdot q_k - c_k \cdot (q_k - y_k + z_k - \varepsilon_k) = 0 \tag{16}$$

$$(\lambda(i) - c_k \cdot (q_k - y_k + z_k - \varepsilon_k)) \cdot \left(1 - \lambda(i)' \cdot y_k'\right) - \lambda(i)' \cdot (y_k - z_k) = 0 \tag{17}$$

$$\lambda(i) - c_j \cdot \left(q_j - y_j\right) = 0 \tag{18}$$

where

$$y_k' = \frac{dy_k}{d\lambda(i)} = -\frac{1}{c_k}$$
$$\lambda(i)' = \frac{\partial\lambda}{\partial z_j} = \frac{\partial\lambda}{\partial z_k} = -\frac{1}{\sum_{j=1}^{i} \frac{1}{c_j} + \sum_{k=i+1}^{n} \frac{1}{c_k}} \tag{19}$$

Eqs. (13) and (18) indicate that at the optimum, each firm faces a marginal abatement cost equal to the permit price $\lambda(i)$ at the second stage of the game. However, the firms have strategically chosen z_j or z_k rather than ε_j or ε_k as their emissions caps, respectively. A firm's strategic choice in z_j or z_k can make its final marginal abatement cost deviate from the permit price, as indicated in Eqs. (12) and (17).

Firm j's adoption benefits in the imperfectly competitive market, $\pi(i)_j^A - \pi(i-1)_j^{NA}$, are calculated based on Eqs. (11) and (15), and its corresponding optimal date to adopt the new technology is determined based on Eq. (7).

3. The impact from an imperfectly competitive market

3.1. Proposition on the market structure and firm's decision on technology adoption

According to Eq. (7), we can compare firms' net benefits from technology adoption between perfectly and imperfectly competitive permit markets. Two assumptions are proposed here:

Assumptions

1) *All firms in the sector face a downward-sloping inverse demand function for a homogeneous good;*
2) *A new technology becomes available in the market that allows firms to reduce emissions at a lower total abatement cost than before.*

Then, Proposition 1 and a corollary are presented:

Proposition 1. *The strategic behaviour of asymmetric firms in both the output and permit markets accelerates the diffusion of new abatement technology.*

Corollary. *All firms will adopt the new technology much earlier in an imperfectly competitive permit market if*

(a) *Parameter a in the linear-inverse product demand function becomes much smaller,*
(b) *Parameter b in the linear-inverse product demand function becomes much larger, or*
(c) *Parameter c in the abatement cost function of the new abatement technology becomes much smaller.*

Appendix B provides proof of the proposition and the corollary.

3.2. Decomposition of the incentives for technology adoption among firms

We divide firms' adoption benefits into a direct effect and a strategic effect within the analytical framework in Tirole (1988) and Coria (2009). With such effects, the intrinsic reasons can be explained as to why firms' market power in both output and permit markets leads to the earlier adoption of an abatement technology. Firms' benefits from the direct and strategic effects are compared in the imperfectly competitive permit market.

Adoption benefits from the direct effect account for the change in costs when the adopters re-optimize the mix of abatement plus emissions permits but does not account for the effect of adoption on the price of permits and other firms' choice of output. We assume that the permit price still equals $\lambda(j-1)$ after j's adoption. Then, profits from the direct effect in an imperfectly competitive market are identified as $\Delta\pi_j^{DE,\,NC}$:

$$\Delta\pi_j^{DE,NC} = \frac{1}{2}\cdot\left[\frac{1}{c_j\cdot\left(\frac{i-1}{c}+\sum_{k=i+1}^{n}\frac{1}{c_k}\right)^2}-\frac{1}{c\cdot\left(\frac{i}{c}+\sum_{k=i+1}^{n}\frac{1}{c_k}\right)^2}\right]\cdot\left[q_j(\lambda(j-1))-\varepsilon_j+\left(\frac{i-1}{c}+\sum_{k=i+1}^{n}\frac{1}{c_k}\right)\cdot\lambda(j-1)\right]^2+\lambda(j-1)\cdot\left[\frac{1}{c\cdot\left(\frac{i}{c}+\sum_{k=i+1}^{n}\frac{1}{c_k}\right)}-\frac{1}{c_j\cdot\left(\frac{i-1}{c}+\sum_{k=i}^{n}\frac{1}{c_k}\right)}\right]\cdot\left(q_j(\lambda(j-1))-\varepsilon_j+\left(\frac{i-1}{c}+\sum_{k=i+1}^{n}\frac{1}{c_k}\right)\cdot\lambda(j-1)\right) \quad (20)$$

Adoption benefits from the strategic effect come from the permit and output markets. On the one hand, the strategic effect from the permit market results from the influence of the change in permit prices on the adopter's output and emissions, while other firms' choice of output is still assumed to equal $\overline{Q_{-j}}(\lambda(j-1))$. On the other hand, the strategic effect from the output market results from the impact of the change in permit prices on the marginal abatement cost and their output of the adopter's rivals.

We emphasize that it becomes more complicated to identify the adoption benefits from the strategic effect in an imperfectly competitive market: we infer that changes in the number of adopters will lead to changes in market concentration by comparing the difference from the potential for abatement among firms before and after the adoption of the new technology. The permit price does not always decrease when some firms upgrade the technology if the adopters manipulate the permit price in the ETS. Therefore, the strategic effect from the output market also does not always become negative. Then, the profits from the strategic effect in an imperfectly competitive market are identified as follows:

$$\Delta\pi_j^{SE,NC} = \Delta\pi_j^{SEP,NC}+\Delta\pi_j^{SEO,NC} = P[Q(\lambda(j))]\cdot q_j(\lambda(j))-P[Q(\lambda(j-1))]\cdot q_j(\lambda(j-1))+\frac{c}{2}\cdot\frac{1}{c^2\cdot\left(\frac{i}{c}+\sum_{k=i+1}^{n}\frac{1}{c_k}\right)^2}\cdot\left[q_j(\lambda(j-1))-\varepsilon_j+\left(\frac{i-1}{c}+\sum_{k=i+1}^{n}\frac{1}{c_k}\right)\cdot\lambda(j-1)\right]^2-\frac{c}{2}\cdot\frac{1}{c^2\cdot\left(\frac{i}{c}+\sum_{k=i+1}^{n}\frac{1}{c_k}\right)^2}\cdot\left[q_j(\lambda(j))-\varepsilon_j+\left(\frac{i-1}{c}+\sum_{k=i+1}^{n}\frac{1}{c_k}\right)\cdot\lambda(j)\right]^2+\lambda(j-1)\cdot\left(1-\frac{1}{\left(i+c\cdot\sum_{k=i+1}^{n}\frac{1}{c_k}\right)}\right)\cdot\left(q_j(\lambda(j-1))-\varepsilon_j-\frac{\lambda(j-1)}{c}\right)-\lambda(j)\cdot\left(1-\frac{1}{c_j\cdot\left(\frac{i-1}{c}+\sum_{k=i}^{n}\frac{1}{c_k}\right)}\right)\cdot\left(q_j(\lambda(j))-\varepsilon_j-\frac{\lambda(j)}{c_j}\right)$$

Appendices C and D show the detailed derivation process of the adoption benefits from both the direct effect and the strategic effect, respectively.

Proposition 2 proposed a comparison of firms' adoption benefits under both perfect and imperfect markets:

Proposition 2. *The firms adopt a new abatement technology earlier in an imperfectly competitive market for the following reasons:*

(a) *Each firm's adoption benefits from the direct effect in an imperfectly competitive market are less than those in a perfectly competitive market;*
(b) *Each firm's adoption benefits from the strategic effect in an imperfectly competitive market are larger than those in a perfectly competitive market;*

Furthermore,

(c) *The increase in each firm's adoption benefits from the strategic effect is larger than needed to compensate for the decline in the adoption benefits from the direct effect in an imperfectly competitive market.*

Therefore, each firm's net benefits from technology adoption in an imperfectly competitive market are larger than those in a perfectly competitive market.

Appendix E provides proof of Proposition 2.

The above two propositions have been proven in Appendices A and E, respectively, in the scenario with two asymmetric firms. We use one permit buyer and one permit seller to illustrate firms' behaviour in the permit market. As it is difficult to directly compare firms' benefits from technology adoption as presented in Eqs. (20) and (21), we provide evidence in the quantitative case study with more than two heterogeneous firms in Section 4. The effect from the production capacity diversity is taken into account in the discussions below.

3.3. Calculation of total social welfare

Social welfare is calculated to further analyse firms' strategic behaviour in the diffusion of abatement technologies. Given that each firm's adoption dates vary under the two market structures, social welfare is calculated as the discounted sum of consumer surplus (*CS*) plus firms' profits (exclusive of profits from permit trades)[4] minus investment cost (*IC*). Unlike Coria (2009), we do not consider the damage from emissions here because the total emissions cap is constant regardless of whether the firms act strategically in the permit market. Therefore, given the demand curve and other key parameters, social welfare is given by $W(i)$:

$$W(i) = [CS(i) + PP(i) - IC(i)] \cdot e^{-\delta\tau_i} = \left[\frac{b}{2} \cdot Q^2(i) + \sum_{l=1}^{n} \pi_l - k\overline{q}_i e^{-\theta_i \tau_i}\right] \cdot e^{-\delta\tau_i} \tag{22}$$

4. Case study

4.1. Data and scenarios

We undertake a quantitative case study of an energy-intensive sector to analyse the impact of heterogeneous firms' strategic behaviour on the diffusion of abatement technologies. Appendix Table F1 shows the sources or accounting approach for the data on firm-specific emissions intensities and the parameters for the inverse product demand functions; Appendix Table F2 lists the values of the other key parameters used in our case study.

Our sample consists of six firms in the iron and steel sector in the pilots, except Beijing and Shenzhen: Baoshan Iron & Steel (BG), Chongqing Iron & Steel (CG), Shaoguan Iron & Steel Group (SG), Tianjin Iron & Steel Group (TG), Tianjin Tiantie Metallurgical Group (TY), and Wuhan Iron & Steel (WG). All of these firms are included in the ETS pilots and are in the list of enterprises participating in the "*Top-10,000 Energy-Consuming Enterprises Program*"[5] (hereinafter referred to as the "*Program*") in the twelfth five-year plan (FYP) period (2011–2015).

To estimate the parameters for firms' abatement cost functions, we first define the so-called old and new abatement technologies in our case study. Because the electric arc furnace (EAF) has been implemented in only a small number of firms (Li and Zhu, 2014), we regard the entire technological process without and with EAF as an old and new abatement technology, respectively. We can estimate the parameters for logarithmic marginal abatement cost (MAC) corresponding to the old and new technology using the data from Li and Zhu (2014).

Furthermore, we estimate the parameters in each sample firm's abatement cost functions to reflect the difference in the potential for abatement among them before technology adoption. Specifically, we first estimate each firm's emissions based on their share of total sectoral energy saving targets in the *Program* and the emissions in the iron and steel sector. The added value of the firms comes from the Chinese industrial enterprise database 2011. Then, we estimate firms' logarithmic MAC curves using the aggregated approach proposed in Wang et al. (2018). Furthermore, we choose the linear form to fit the new set of "observations" of firms' MAC curves again. The corresponding parameters are also estimated based on the least squares method.

For other key parameters, we should note that, first, the parameters in the inverse demand function in Eq. (1) are estimated based on the data on domestic iron and steel price adjusted for inflation to the level in 2012, and the demand for crude steel products from 2005 to 2010; second, each sample firm's production capacity is estimated based on its production in 2010, assuming that capacity utilization reached 75%, the average rate in the iron and steel sector in China; and finally, the data on the discount rate and the rate of technology diffusion come from Worrell et al. (2000) and Coria (2009), respectively.

We assume that all firms receive their initial permits under grandfathering: they all cut emissions to 10% below the 2010 level. Furthermore, we do not adjust their initial permits in our case study, as Coria (2009) does, because, on the one hand, it is not necessary for us to guarantee that older firms in the sequence receive more permits before the arrival of new technology, and on the other hand, the initial permit distribution should be done properly among firms because it can influence firms' market power in an imperfectly competitive permit market (Hahn, 1984).

In addition, we set up a total of 9 representative scenarios based on the sample firms in our case study. These scenarios with different numbers of firms are adopted to reveal the possible differences in the permit markets with varying degrees of monopoly. The results can better demonstrate the effect from the imperfect market on the diffusion of the abatement technologies.[6] More specifically, the results from the scenarios with more than two incumbent firms can help to confirm the propositions in Section 3. Here, the scenario with the largest number of firms is regarded as the *Base Scenario*.

The Herfindahl-Hirschman Index (HHI) is adopted to reflect the respective degree of monopoly from the perspective of permit buyers and sellers in each scenario. This index is calculated based on each firm's market share in a perfectly competitive permit market. Table 1 presents the corresponding information about all scenarios. We believe that we have considered the most situations with regard to the degree of monopoly in the permit market: for example, a firm with the greatest potential for abatement dominates the market in the *Base Scenario*, *Scenario* 5-1, *Scenario* 4-3 and *Scenario* 3-2; the potentially largest permit buyer monopolizes the market in *Scenario* 4-2, *Scenario* 4-7 and *Scenario* 3-8; and the permit buyers have comparable market power with permit sellers in *Scenario* 5-2 and *Scenario* 4-4.

4.2. Results: Base Scenario

4.2.1. Production capacity and the sequence of adoption

Table 2 compares firms' adoption dates with that in consideration of capacity constraints in the *Base Scenario*. Without regard to the capacity constraints, all the firms' investment is assumed to be equal to RMB 22, 9000, the average level of their current expenses related to technology adoption. The corresponding results without regard to the capacity constraints can verify the statement in Coria (2009) that each firm takes its adoption benefits into account to decide its optimal adoption date.

A firm's production capacity constraints have a significant effect on the final time path of adoption. The adoption benefits for per unit of production capacity directly affect each firm's date of adoption. For example, the firm WG, subject to the relatively large production capacity, obtains less benefits per capacity from technology adoption. Thus, it adopts the new abatement technology later than the firms SG, TG and TY. Furthermore, firms CG, SG, TG and TY adopt the technology earlier than that in the *Base Scenario* without regard to the capacity constraints because they have a relatively lower productivity.

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[4] Incomes from permit transactions are not included because they only represent transfers between the firms and the government (Coria, 2009).

[5] The *Top-10,000 Energy-Consuming Enterprises Program,* put forward in 2011, aims to cover two-thirds of China's total energy consumption or 15,000 industrial enterprises that use more than 10,000 tce per year and approximately 160 large transportation enterprises and public buildings that use more than 5000 tce per year. The total number of enterprises covered by this program reaches approximately 17,000. The target of the Top 10,000 Program is an absolute energy-saving target of 250 Mtce by 2015.

[6] Limited by the length of the article, we only present the simulation results from some representative scenarios. The readers can obtain the overall results from all cases based on the sample firms from the supplementary data in the Appendix G.

Table 1
Scenarios in our simulations.

Scenarios	Number of the sample firms	Sample firms	HHI index of permit sellers	HHI index of permit buyers
Base Scenario	6	CG; SG; TG; TY; WG; BG	0.996	0.289
Scenario 5-1	5	CG; SG; TG; WG; BG	1.000	0.288
Scenario 5-2	5	CG; SG; TG; TY; WG	0.607	0.642
Scenario 4-1	4	CG; SG; TG; BG	1.000	0.369
Scenario 4-2	4	CG; SG; TY; WG	0.789	0.671
Scenario 4-3	4	CG; SG; TG; WG	0.518	0.865
Scenario 4-4	4	CG; TG; TY; WG	0.736	1.000
Scenario 3-1	3	CG; SG; TY	1.000	0.702
Scenario 3-2	3	CG; TY; WG	0.890	1.000

Note: BG-Baoshan Iron & Steel, CG-Chongqing Iron & Steel, SG-Shaoguan Iron & Steel Group, TG-Tianjin Iron & Steel Group, TY-Tianjin Tiantie Metallurgical Group, WG-Wuhan Iron & Steel.

Table 2
Effect of the production capacity on the firms' technology adoption in the *Base Scenario*.

(a) Without regard to the production capacity

Firms	CG	WG	SG	TG	TY	BG
Perfectly competitive market						
Date of adoption	60.71	61.04	61.91	62.45	63.09	66.42
Adoption benefits for per unit production capacity	0.0237	0.0234	0.0226	0.0222	0.0217	0.0191
Imperfectly competitive market						
Date of adoption	60.56	60.87	61.74	62.27	62.88	66.14
Adoption benefits for per unit production capacity	0.0238	0.0235	0.0228	0.0223	0.0218	0.0193

(b) With regard to the production capacity

Firms	CG	SG	TG	TY	WG	BG
Perfectly competitive market						
Date of adoption	26.28	29.75	30.16	33.04	79.62	89.58
Adoption benefits for per unit production capacity	0.0877	0.0761	0.0743	0.0661	0.0107	0.0072
Imperfectly competitive market						
Date of adoption	26.13	29.58	29.98	32.85	79.43	89.31
Adoption benefits for per unit production capacity	0.0882	0.0766	0.0748	0.0666	0.0108	0.0073

Note: BG-Baoshan Iron & Steel, CG-Chongqing Iron & Steel, SG-Shaoguan Iron & Steel Group, TG-Tianjin Iron & Steel Group, TY-Tianjin Tiantie Metallurgical Group, WG-Wuhan Iron & Steel.

4.2.2. Market structure and the adoption timing

Table 2 also indicates that firms' heterogeneity in abatement cost rather than in their production capacity has no effect on their respective sequence order of technology adoption. Nevertheless, the findings have also proven the validity of Proposition 1 that all firms adopt the new technology earlier in an imperfectly competitive permit market, which is always true regardless of whether the emitters bear the same initial investment cost.

Furthermore, we decompose the incentives for updating technology among the firms in both perfectly and imperfectly competitive permit markets in Table 3. The corresponding results confirm the statement in Proposition 2 that, in the imperfect market, the changes in firms' adoption benefits lead to the earlier diffusion of the new technology.

In terms of the direct effect, all firms intend to manipulate the market to obtain more benefits after the adoption of the technology and then reduce the supply of the permits to raise the permit price. Then, the adoption benefits from the direct effect decrease more than those in a perfectly competitive market.

However, with respect to the strategic effect, the permit price will decline less because of firms' strategic power, even if more firms adopt the new technology. Then, the non-adopters will not increase their output because their marginal abatement cost will also rise. In the end, the adopters' benefits from the strategic effect exceed those in a perfectly competitive market. Furthermore, the adoption benefits from the strategic effect become positive, to the point that they can more than compensate for the decline in those from the direct effect.

As a result, greater adoption benefits induce all firms to upgrade technology earlier in an imperfectly competitive permit market.

4.2.3. Total welfare and the adoption timing

The associated social welfare in perfectly and imperfectly competitive permit markets is identified based on Eq. (22). The corresponding results in the *Base Scenario* are presented in Table 4.

There is no significant variation in both consumers' and producers' benefits. Adopters intend to reduce the supply of permits to drive up the permit price to fulfil their obligations by only reducing more emissions. However, the non-adopters can only decrease their output to reduce their demand for permits to meet the targets. Therefore, the increase in adopters' output can more than compensate for the decrease in the non-adopters' output, which leads to a slight decrease in the output price and therefore a minor increase in the consumer surplus, as well as an eventual small loss in total firms' profits. At the same time, when more firms adopt the new technology, the gap in both consumers' and producers' benefits narrows between the two market structures. This narrowing is because, after technology adoption, firms will have

Table 3
Firms' incentives for updating technology in the *Base Scenario*.

Firms	CG	SG	TG	TY	WG	BG
Perfectly competitive market						
Total effects for per unit production capacity	0.0877	0.0761	0.0743	0.0661	0.0107	0.0072
Including direct effect	0.0879	0.0764	0.0748	0.0666	0.0108	0.0074
Strategic effect	−0.0002	−0.0004	−0.0005	−0.0006	−0.0001	−0.0002
Imperfectly competitive market						
Total effects for per unit production capacity	0.0882	0.0766	0.0748	0.0666	0.0108	0.0073
Including direct effect	0.0420	0.0631	0.0682	0.0631	0.0104	0.0074
Strategic effect	0.0461	0.0135	0.0066	0.0034	0.0004	0.0001

Note: BG-Baoshan Iron & Steel, CG-Chongqing Iron & Steel, SG-Shaoguan Iron & Steel Group, TG-Tianjin Iron & Steel Group, TY-Tianjin Tiantie Metallurgical Group, WG-Wuhan Iron & Steel.

Table 4
Social welfare when the firms upgrade technology in the *Base Scenario*.

Firms	CG	SG	TG	TY	WG	BG
Perfectly competitive market						
Consumer surplus	2355.09	2612.31	2877.66	3149.75	3453.11	3718.0877
Firm's profits	188,992.03	193,995.17	198,893.62	203,676.95	208,760.98	213,012.92
Total investment costs	22,803.39	21,813.22	21,341.71	20,818.92	22,235.59	18,360.65
Discount factor	0.0052	0.0026	0.0024	0.0013	1.21×10^{-7}	1.66×10^{-8}
Discounted welfare	879.18	455.77	433.03	250.80	0.0231	0.0033
Imperfectly competitive market						
Consumer surplus	2355.29	2612.85	2878.46	3150.65	3454.65	3718.0877
Firm's profits	188,991.80	193,994.66	198,892.88	203,676.13	208,759.60	213,012.60
Total investment costs	22,934.40	21,952.06	21,489.20	20,976.23	22,400.33	18,555.26
Discount factor	0.0054	0.0027	0.0025	0.0014	1.26×10^{-7}	1.75×10^{-8}
Discounted welfare	905.38	470.70	448.35	260.48	0.0239	0.0035

Note: BG-Baoshan Iron & Steel, CG-Chongqing Iron & Steel, SG-Shaoguan Iron & Steel Group, TG-Tianjin Iron & Steel Group, TY-Tianjin Tiantie Metallurgical Group, WG-Wuhan Iron & Steel.

equivalent potential for abatement, which results in less capacity in manipulating the market.

In addition, the discount factor plays an important role in calculating total social welfare. In an imperfect market, the present value of the investment cost of technology adoption will increase when all firms adopt the technology earlier. Nevertheless, the corresponding discount factor will also increase at the same time, which leads to an increase in the net present value of total social welfare. Moreover, the increment in total welfare resulting from firms' strategic behaviour can be offset when more firms adopt the new technology.

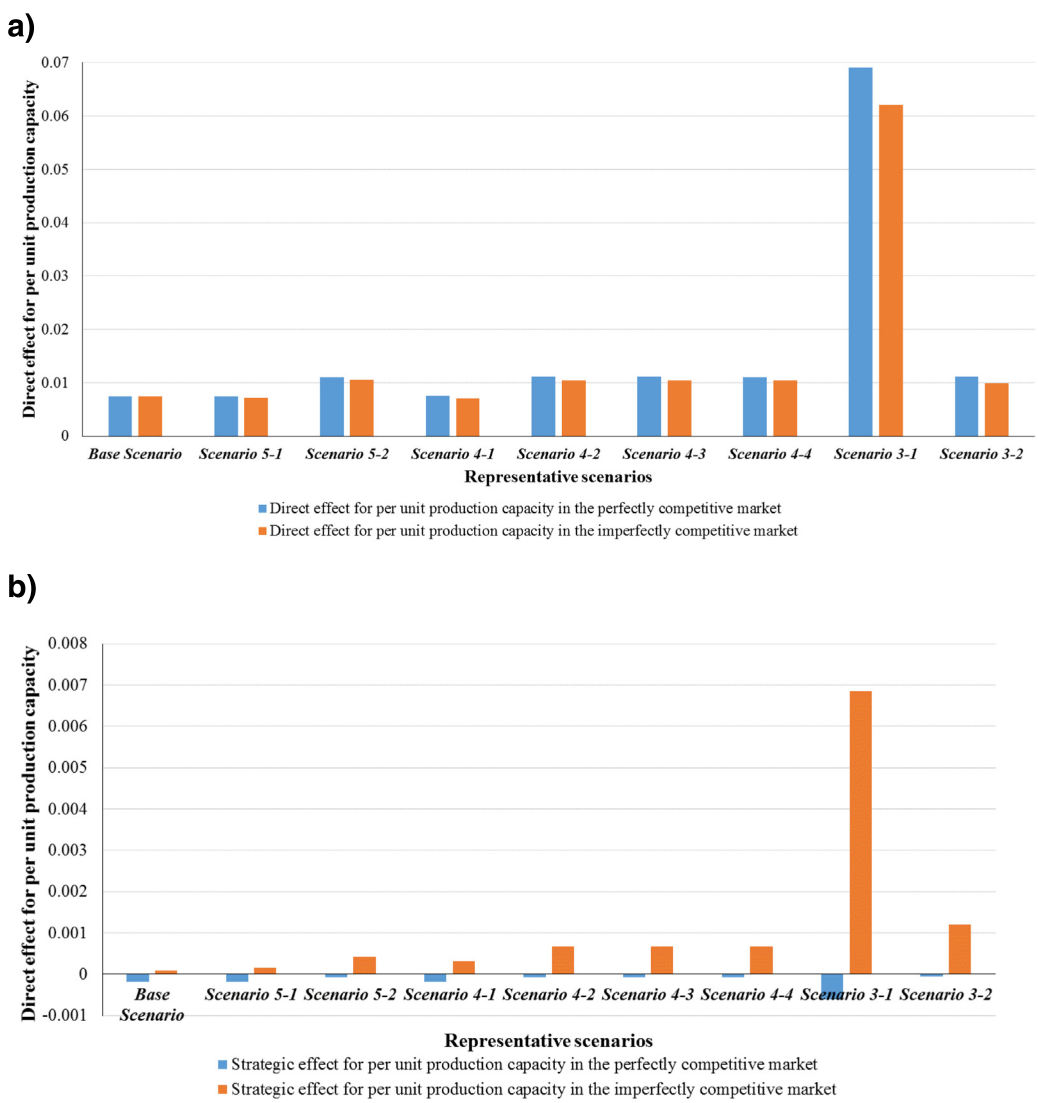

Fig. 1. The comparison in adoption benefits for per unit production capacity from both the direct effect (a) and strategic effect (b) for the last firms in the sequence of adoption between the perfectly and imperfectly competitive permit markets.

4.3. Results: multiple scenarios

The simulation results in the nine representative scenarios (see Table 1) indicate that firms' strategic power in both permit and output markets can always accelerate the diffusion of technology. However, in Fig. 1, the last firm's adoption benefits differ considerably from one another in these scenarios. Nevertheless, the corresponding benefits from the strategic effect are always larger than needed to compensate for the decline in those from the direct effect in an imperfect market, which provides more incentives for technology adoption.

Furthermore, in Fig. 2, the firms adopt the new technology much earlier in *Scenario 4-1*, *Scenario 5-1*, and the *Base Scenario*, where the HHI value is higher among the allowance sellers (see Table 1). It can be inferred that the firms will adopt the new technology earlier if the allowance sellers have much stronger market power than buyers; thus, they can obtain more benefits from exclusionary manipulation.

4.4. Results: effects from the key parameters in the model

In relation to firms' market power, production capacity and abatement cost can play an important role in technology diffusion. These parameters include a and b in the linear inverse demand function, c in the abatement cost function of the new technology, and production capacity $\overline{q_j}$. Fig. 3 illustrates the impact of parameters a, b and c on the differences in adoption dates for the last firms in the sequence of adoption between perfect and imperfect markets.

The changes in parameters a and b represent the change in output demand and then influence firms' decision on both production and emissions reduction. The results show that our propositions and the corollary can be confirmed regardless of the number of firms. In general, the firms will adopt the new technology later when parameter a becomes larger (shown in Fig. 3a), as it becomes more difficult for firms to gain more adoption benefits through manipulation in both the output and permit markets. The firms will adopt the new technology much earlier if output demand is less elastic (b becomes larger, as shown in Fig. 3b), as it becomes much easier for the firms to distort both the output and permit prices to obtain additional benefits from technology adoption. Furthermore, the effects from these parameters can be more significant when the allowance sellers have stronger market power, as shown in *Scenario 4-1*, *Scenario 5-1*, and the *Base Scenario*.

Parameter c directly reflects the abatement potential of new technology. Firms will adopt the new technology much earlier when c declines (shown in Fig. 3c), as they can achieve greater abatement potential and then exert market power to obtain greater adoption benefits. Similarly, a more notable effect from this parameter is identified in *Scenario 4-1*, *Scenario 5-1*, and the *Base Scenario*.

Firms' production capacity constraints have a significant effect on the time path of adoption. We calculate the adoption dates of each sample firm in the *Base Scenario*, subject to different levels of the production capacity, as indicated in Table F2. Their corresponding ranking in terms of technology adoption and the effect from the market structure on adoption dates are presented in Table 5. The results confirm our statement again that the firms will adopt new technology earlier if their production capacities are lower than those of other firms. From the comparison between firms with different abatement costs before technology adoption, it can be seen that firms will update their technology much earlier in an imperfect market if they already have stronger market power as allowance sellers. For example, the sample firm BG can obtain more benefits from exclusionary manipulation in a permit market when it upgrades its technology.

5. Conclusion and policy recommendations

In this paper, we have explored the impact of the strategic behaviour of heterogeneous firms on the diffusion of abatement technology under an imperfect market structure. More specifically, we improved the analytical framework in Coria (2009) from two aspects: firms' diversity in production capacity is introduced to reflect firms' heterogeneity; an integrated two-stage model is proposed to describe firms' exclusionary manipulation in a permit market. Furthermore, firms' adoption benefits are decomposed into direct and strategic effects to

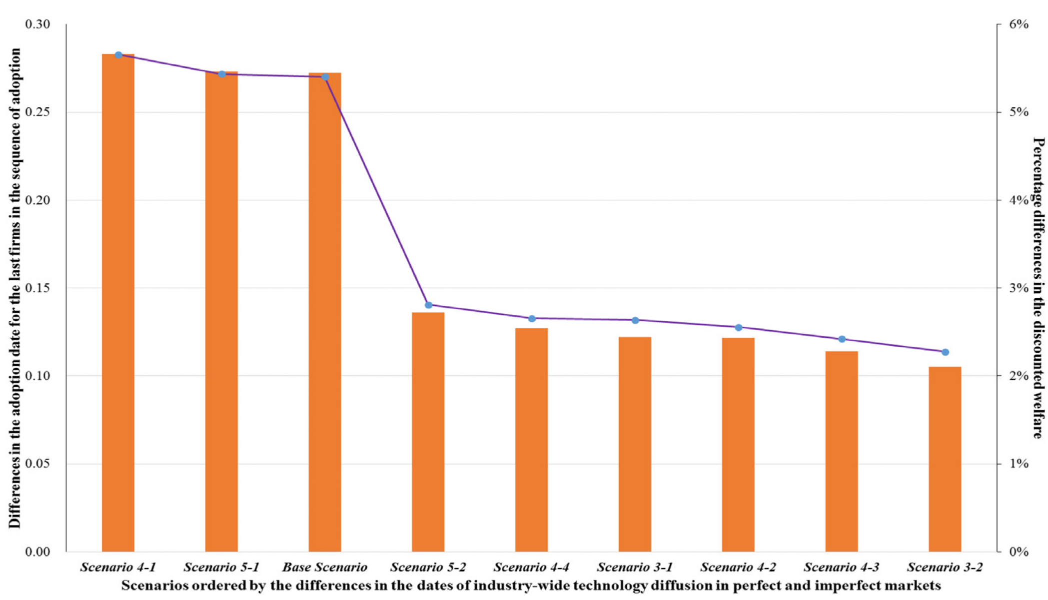

Fig. 2. The differences in both adoption date for the last firms in the sequence of adoption and the discounted welfare between the perfectly and imperfectly competitive permit markets in 9 representative scenarios.

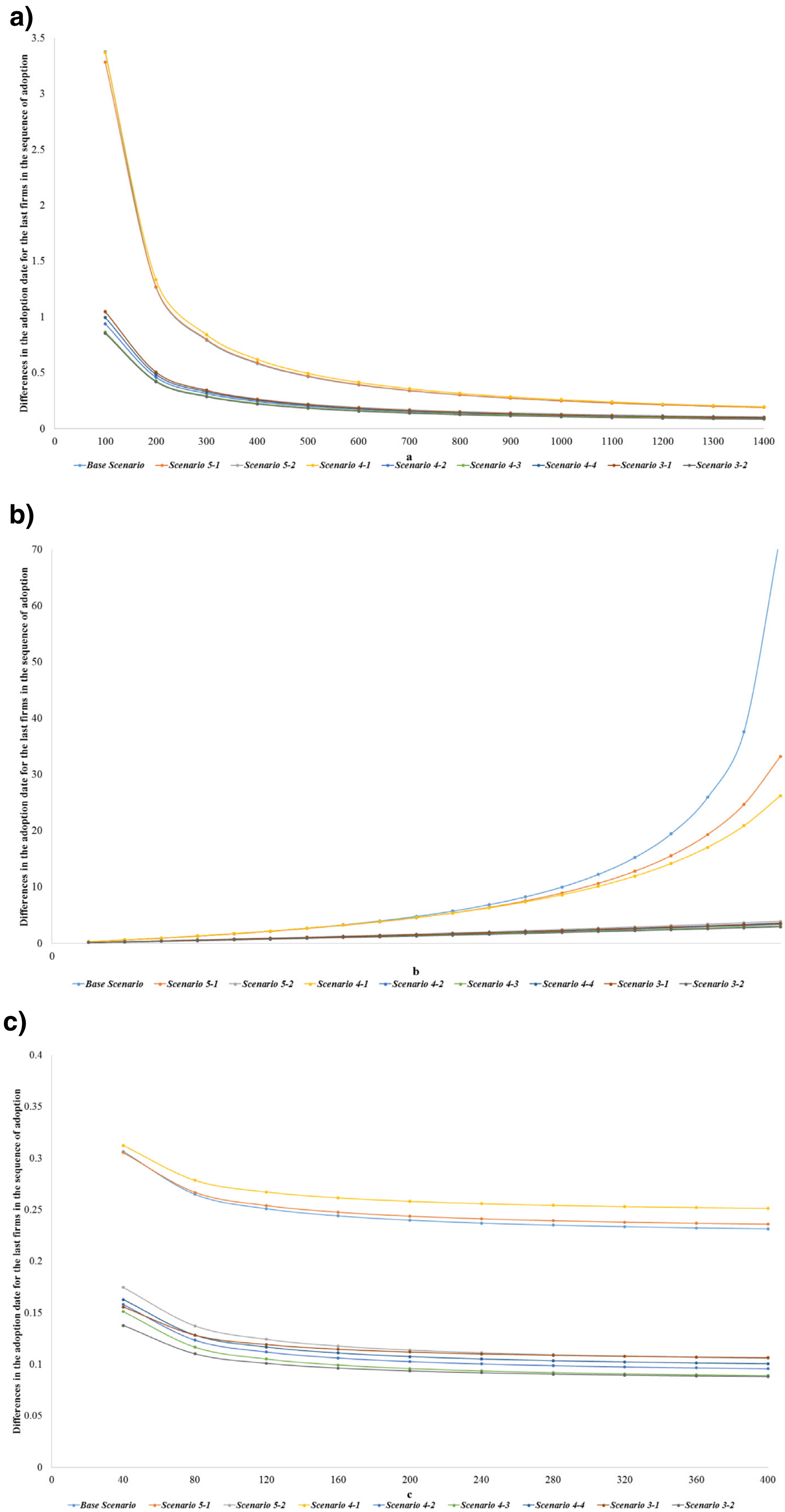

Fig. 3. Effects of changes in parameters a (a) and b (b) in the linear inverse demand function and parameter c (c) in the abatement cost function of new technology on the difference in the date for the last firms in the sequence of adoption between perfectly and imperfectly competitive permit markets in 9 representative scenarios.

Table 5
Effect from the different level of production capacity on the firms' technology adoption in the *Base Scenario*.

Sample firms	Production capacity (Mt)	6.08	6.71	6.73	7.39	48.73	59.33
CG	Ranking in terms of technology adoption	1	1	2	3	5	5
	The difference of adoption dates between the perfect and imperfect permit markets	0.15	0.15	0.16	0.16	0.18	0.18
WG	Ranking in terms of technology adoption	1	2	2	4	5	6
	The difference of adoption dates between the perfect and imperfect permit markets	0.16	0.17	0.17	0.18	0.19	0.20
SG	Ranking in terms of technology adoption	1	2	2	4	3	5
	The difference of adoption dates between the perfect and imperfect permit markets	0.16	0.17	0.17	0.26	0.17	0.18
TG	Ranking in terms of technology adoption	1	2	3	4	5	6
	The difference of adoption dates between the perfect and imperfect permit markets	0.17	0.17	0.18	0.18	0.19	0.20
TY	Ranking in terms of technology adoption	1	3	3	4	5	4
	The difference of adoption dates between the perfect and imperfect permit markets	0.18	0.19	0.19	0.19	0.20	0.21
BG	Ranking in terms of technology adoption	3	4	4	4	6	6
	The difference of adoption dates between the perfect and imperfect permit markets	0.25	0.26	0.26	0.26	0.27	0.27

Note: BG-Baoshan Iron & Steel, CG-Chongqing Iron & Steel, SG-Shaoguan Iron & Steel Group, TG-Tianjin Iron & Steel Group, TY-Tianjin Tiantie Metallurgical Group, WG-Wuhan Iron & Steel.

further reveal the relationship between the market structure and technology diffusion.

With a case study of the iron and steel sector in China, our model reveals that, to obtain more adoption benefits from the strategic effect, all firms will upgrade their abatement technology earlier in an imperfectly competitive permit market, and the time will be even earlier when firms have greater abatement potential than other firms before adoption and when firms can distort both output and permit prices easier if output demand is less elastic. Firms' production capacity constraints have a significant effect on the final time path of adoption among firms.

Our study demonstrates a comprehensive approach to discuss the relationship between market structure and the diffusion of abatement technology. It supports the findings of Schumpeter et al. (1950) with respect to market-based instruments to curb greenhouse gas emissions. The so-called Schumpeterian hypothesis also identifies the positive linkages between market concentration and innovative activity. Furthermore, our results show that social welfare is also improved when heterogeneous firms adopt the new technology earlier in an imperfectly competitive market.

The messages delivered from the model and the results can help policymakers better understand the diffusion of abatement technologies under an imperfect market structure. The behaviour of firms with a larger scale of production in the ETS should be considered because these firms with the potential to obtain market power can be encouraged to conduct R&D on abatement technologies to raise the technological level of the entire industry.

Our study is not without limitations, and the subject would benefit from further research. First, the game model can be improved to characterize firms' market power in the permit market. Second, factors other than production capacity can be taken into account to model heterogeneous firms to further investigate the interaction between firms' heterogeneity and strategic behaviour in technology adoption. Third, a better data source for the key parameters would help to derive more precise results in the case study. Finally, other issues related to the permit market can be integrated to further describe firms' strategic behaviour in the permit market, for example, the allocation approaches, such as auctions, and firms' other behaviour, such as choosing non-compliance.

Acknowledgments

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Appendix A. Details of the coalition game model in Section 2.3

In light of the coalition N of all the n firms in the ETS, we first define its characteristic function as a set-valued function $v(N): P(N) \to R$. The value of the function is the minimum for total compliance costs among the firms when their total initial permits are no more than the cap, $\overline{E}$. Considering that both adopters and non-adopters want to guarantee the stability of the coalition, we do not distinguish between them and denote all the firms' variables by subscript l here. The characteristic function of the coalition is given by

$$v(N) = \inf\left\{\sum_{l\in N}\frac{c_l}{2}(q_l - y_l)^2 \middle| \sum_{l\in N} y_l \in \sum_{l\in N} z_l : z_N\right\} \tag{A1}$$

Then we give the solution to assign the compliance costs among the firms, with at least one vector $co = (co_l)_{l\in N} \in R^n$, where co_l denotes the compliance cost imposed on the firm l, to guarantee the stability of the coalition. For the coalitional game featuring characteristic function $v(N)$, we let notions of efficiency and fairness be formalized by core solutions axiomatized by Peleg (1992). A cost allocation $co = (co_l)_{l\in N} \in R^n$ belongs to the core if it entails

$$\textbf{\textit{Pareto efficiency}}: \sum_{l\in I} co_l = v(I) \tag{A2}$$

$$\textbf{\textit{Stability}}: \sum_{l\in S} co_l \le v(S) \text{ for all coalition } S \subset I \tag{A3}$$

where *Pareto efficiency* means that all the firms jointly obtain the compliance cost savings in the coalition; otherwise, some firms can split away and play on their own. All allocation vectors satisfying Eq. (A2) constitute a non-empty set of costs pre-allocation:

$$I^*(v) = \left\{co \in R^n \middle| \sum_{l\in N} co_l = V(N)\right\} \tag{A4}$$

In order to guarantee the stability of the coalition, the cost allocation vector co in Eq. (A4) must also satisfy the *Stability* condition in Eq. (A3): no single firm or coalition $S \subset N$ can lower its cost by splitting away and playing on its own. This property is easily achieved, as indicated in Evstigneev and Flåm (2001).

According to Evstigneev and Flåm (2001), we construct a standard Lagrangian associated with the characteristic function to solve the adopters' and non-adopters' optimization problem respectively:

$$F_j(q_1,\dots,q_i;y_1,\dots,y_i;\lambda(i))=\sum_{j=1}^{i}\frac{c_j}{2}\left(q_j-y_j\right)^2+\lambda(i)\cdot\left(\sum_{j=1}^{i}y_j+\sum_{k=i+1}^{n}y_k-\sum_{j=1}^{i}z_j-\sum_{k=i+1}^{n}z_k\right) \tag{A5}$$

$$F_k(q_{i+1},\dots,q_n;y_{i+1},\dots,y_n;\lambda(i))=\sum_{k=i+1}^{n}\frac{c_k}{2}(q_k-y_k)^2+\lambda(i)\cdot\left(\sum_{j=1}^{i}y_j+\sum_{k=i+1}^{n}y_k-\sum_{j=1}^{i}z_j-\sum_{k=i+1}^{n}z_k\right) \tag{A6}$$

where $\lambda(i)$ is a Lagrange multiplier when i firms have adopted the new technology. As indicated in Theorem 1 in Evstigneev and Flåm (2001), $\lambda(i)$ can be understood as the equilibrium market price for permits in an imperfectly competitive market. Then the cost allocation for an adopter and non-adopter—i.e., co_j or co_k—for the grand coalition I respectively satisfies

$$co_j^*=\min_{q_j,y_j}\left\{\lambda(i)\cdot\left(y_j-z_j\right)+\frac{c_j}{2}\cdot\left(q_j-y_j\right)^2\right\} \tag{A7}$$

$$co_k^*=\min_{q_k,y_k}\left\{\lambda(i)\cdot(y_k-z_k)+\frac{c_k}{2}\cdot(q_k-y_k)^2\right\} \tag{A8}$$

which satisfies the Pareto efficiency condition indicated in Eq. (A2); meanwhile the total amount of emissions equals that of the new initial permits, i.e., $\sum_{j=1}^{i}y_j+\sum_{k=i+1}^{n}yk=\sum_{j=1}^{i}z_j+\sum_{k=i+1}^{n}z_k$.

Appendix B. Proof of the Proposition 1 and corresponding corollary in Section 3.1

τ_j^{C*} and τ_j^{NC*} are the dates of adoption of firm j in a perfectly and imperfectly competitive market, respectively. $\Delta\pi_j^C$ and $\Delta\pi_j^{NC}$ are the firm's adoption benefits in a perfectly and imperfectly competitive market, respectively. $\Delta\tau_j=\tau_j^{C*}-\tau_j^{NC*}$ is the difference between the above two dates. Therefore, in order to prove our proposition, we only need to show the difference in firm's adoption benefits between the two market structures $delta_j$:

$$delta_j=\Delta\pi_j^{NC}-\Delta\pi_j^C>0 \tag{B1}$$

We suppose that the ETS includes only two firms—i.e., Firm 1 and Firm 2. Each behaves as a permit buyer and a permit seller respectively in the market. Also, we assume that Firm 2 can reduce emissions at a lower total abatement cost than Firm 1. Furthermore, a new technology arrives that has much more potential for abatement. Then their corresponding parameters in the abatement cost function satisfy $c<c_2<c_1$. Then the linear inverse demand function is simply given by $P=a-b\cdot(q_1+q_2)$. Let $\pi_j^{C,\,A}(j=1,2)$ be the rate of Cournot-Nash profit to firm j when it adopt the new technology in the perfectly competitive permit market. Let $\pi_j^{C,\,NA}(j=1,2)$ be the rate of Cournot-Nash profit to firm j when it does not adopt the new technology in the perfectly competitive permit market. Then the adoption benefits of Firms 1 and 2 are defined respectively as

$$\Delta_1^C=\left(\pi_1^{C,A}-\pi_1^{C,NA}\right) \tag{B2}$$

$$\Delta_2^C=\left(\pi_2^{C,A}-\pi_2^{C,NA}\right) \tag{B3}$$

Let $\pi_j^{NC,\,A}(j=1,2)$ be the rate of Cournot-Nash profit to firm j when it adopt the new technology in the imperfectly competitive permit market. Let $\pi_j^{NC,\,NA}(j=1,2)$ be the rate of Cournot-Nash profit to firm j when it does not adopt the new technology in the imperfectly competitive permit market. Then the adoption benefits of Firms 1 and 2 are defined respectively as

$$\Delta_1^{NC}=\left(\pi_1^{NC,A}-\pi_1^{NC,NA}\right) \tag{B4}$$

$$\Delta_2^{NC}=\left(\pi_2^{NC,A}-\pi_2^{NC,NA}\right) \tag{B5}$$

Therefore, we define the difference in Firm 1's and Firm 2's adoption benefits between perfectly and imperfectly competitive permit markets respectively as

$$delta1=\frac{(c_1-c)\cdot b\cdot\left[\sum_{i=1}^{11}\begin{array}{c}b^i\cdot\sum_{j=2}^{i+2}c^j\cdot c_1^{j+2}\cdot\varepsilon_1\cdot\varepsilon_2+\\ \sum_{i=1}^{11}b^i\cdot\sum_{j=2}^{i+3}c^j\cdot c_1^{j+2}\cdot\varepsilon_1^2+a\cdot\sum_{i=1}^{11}b^i\cdot\sum_{j=2}^{i+4}c^j\cdot c_1^{j+2}\cdot\varepsilon_2^2\end{array}\right]}{2\cdot A^2\cdot B^2\cdot C^2\cdot D^2\cdot\varepsilon_1^2} \tag{B6}$$

$$delta2=\frac{(c_2-c)\cdot b\cdot\left[a\cdot\sum_{i=1}^{8}\begin{array}{c}b^i\cdot\sum_{j=2}^{i+2}c^j\cdot c_2^{j-2}\cdot\varepsilon_1\cdot\varepsilon_2+\\ \sum_{i=1}^{8}b^i\cdot\sum_{j=1}^{i+2}c^j\cdot c_2^{j-2}\cdot\varepsilon_1^2+a\cdot\sum_{i=1}^{8}b^i\cdot\sum_{j=4}^{i+1}c^j\cdot c_2^{j-2}\cdot\varepsilon_2^2\end{array}\right]}{8\cdot(2b+c)^2\cdot(3b+c)\cdot A^2\cdot C^2\cdot\varepsilon_2^2} \tag{B7}$$

where $A=3\cdot b\cdot c+3\cdot b\cdot c_2+2\cdot c\cdot c_2$, $B=3\cdot b\cdot c_1+3\cdot b\cdot c_2+2\cdot c_1\cdot c_2$, $C=2\cdot b\cdot c^2+6\cdot b^2\cdot c+2\cdot b\cdot c_2^2+6\cdot b^2\cdot c_2+c\cdot c_2^2+c^2\cdot c_2+6\cdot b\cdot c\cdot c_2$, $D=2\cdot b\cdot c_1^2+6\cdot b^2\cdot c_1+2\cdot b\cdot c_2^2+6\cdot b^2\cdot c_2+c_1\cdot c_2^2+c^2\cdot c_2+6\cdot b\cdot c_1\cdot c_2$.

It is not difficult to find that $delta1>0$ because all parameters are positive and $c_1>c$ in Eq. (B6). Similarly, $c_2>c$ and then $delta2>0$. Therefore adoptions yield more net benefits for both Firms 1 and 2 when they exert market power in the permit market. Both of them adopt the new technology earlier in an imperfectly competitive permits market.

Furthermore, according to Eqs. (B6) and (B7), it is also easy to show that

$$\begin{aligned}&\frac{\partial delta\,j}{\partial a}<0,\ \forall a>0,\ \ j=1,2\\ &\frac{\partial delta\,j}{\partial b}>0,\ \forall b>0,\ \ j=1,2\\ &\frac{\partial delta\,j}{\partial c}<0,\ \forall c<c_j,\ \ j=1,2\end{aligned} \tag{B8}$$

Meanwhile, as to the parameters on the boundary of their space, they satisfy that

$$\begin{aligned}&\frac{\partial delta\,j}{\partial a}\Big|_{a=0}>0,\ \ j=1,2\\ &\frac{\partial delta\,j}{\partial b}\Big|_{b=0}>0,\ \ j=1,2\\ &\frac{\partial delta\,j}{\partial c}\Big|_{c=c_n}<0,\ \ j=1,2;n=\max\{j\}\end{aligned} \tag{B9}$$

Thus we have proved not only the proposition but also the corresponding corollary in Section 3.1.

Appendix C. Calculation of the adapter's adoption benefits from the direct effect in an imperfectly competitive market

Using the first-order conditions for (q_j, z_j, y_j) or (q_k, z_k, y_k)—i.e., Eqs. (11)–(13) and (16)–(18)—we first obtain

$$\left(\frac{1}{\sum_{j=1}^{i}\frac{1}{c}+\sum_{k=i+1}^{n}\frac{1}{c_k}}-c\right)\cdot\left(z_j-y_j\right)+\left(\frac{1}{\sum_{j=1}^{i}\frac{1}{c}+\sum_{k=i+1}^{n}\frac{1}{c_k}}-c\right)\cdot\left(q_j-\varepsilon_j\right)-\left(\frac{1}{c\cdot\left(\sum_{j=1}^{i}\frac{1}{c}+\sum_{k=i+1}^{n}\frac{1}{c_k}\right)}-1\right)\cdot\lambda(j)+\frac{1}{\sum_{j=1}^{i}\frac{1}{c}+\sum_{k=i+1}^{n}\frac{1}{c_k}}\cdot\left(y_j-z_j\right)=0 \tag{C1}$$

which can be rewritten as

$$\left(y_j-z_j\right)=\left(1-\frac{1}{c\cdot\left(\sum_{j=1}^{i}\frac{1}{c}+\sum_{k=i+1}^{n}\frac{1}{c_k}\right)}\right)\cdot\left(y_j-\varepsilon_j-\frac{\lambda(j)}{c}\right) \tag{C2}$$

For adopters and non-adopters, we use $Y_j^A(\lambda(j-1))$ and $Y_j^{NA}(\lambda(j-1))$ to replace the term on the left side of Eq. (C2) respectively:

$$\begin{aligned}Y_j^A(\lambda(j-1))&=y_j^A(\lambda(j-1))-z_j^A(\lambda(j-1)\\&=\left(1-\frac{1}{\left(i+c\cdot\sum_{k=i+1}^{n}\frac{1}{c_k}\right)}\right)\cdot\left(q_j(\lambda(j-1))-\varepsilon_j-\frac{\lambda(j-1)}{c}\right)\end{aligned} \tag{C3}$$

$$\begin{aligned}Y_j^{NA}(\lambda(j-1))=y_j^{NA}(\lambda(j-1))-z_j^{NA}(\lambda(j-1)=&\left(1-\frac{1}{c_j\cdot\left(\frac{i-1}{c}+\sum_{k=i}^{n}\frac{1}{c_k}\right)}\right)\\&\cdot\left(q_j(\lambda(j-1))-\varepsilon_j-\frac{\lambda(j-1)}{c_j}\right)\end{aligned} \tag{C4}$$

Then the adopter's adoption benefits from the direct effect in an imperfectly competitive permit market become

$$\begin{aligned}\Delta\pi_j^{DE,NC}=&\frac{c_j}{2}\left[q_j(\lambda(j-1))-Y_j^{NA}(\lambda(j-1))-\varepsilon_j\right]^2\\&-\frac{c}{2}\left[q_j(\lambda(j-1))-Y_j^{A}(\lambda(j-1))-\varepsilon_j\right]^2\\&+\lambda(j-1)\cdot\left[Y_j^{NA}(\lambda(j-1))-Y_j^{A}(\lambda(j-1))\right]\end{aligned} \tag{C5}$$

where

$$\begin{aligned}&q_j(\lambda(j-1))-Y_j^{NA}(\lambda(j-1))-\varepsilon_j=\frac{1}{c_j\cdot\left(\frac{i-1}{c}+\sum_{k=i+1}^{n}\frac{1}{c_k}\right)}\cdot\left[q_j(\lambda(j-1))-\varepsilon_j+\left(\frac{i-1}{c}+\sum_{k=i+1}^{n}\frac{1}{c_k}\right)\cdot\lambda(j-1)\right]\\&q_j(\lambda(j-1))-Y_j^{A}(\lambda(j-1))-\varepsilon_j=\frac{1}{c\cdot\left(\frac{i}{c}+\sum_{k=i+1}^{n}\frac{1}{c_k}\right)}\cdot\left[q_j(\lambda(j-1))-\varepsilon_j+\left(\frac{i-1}{c}+\sum_{k=i+1}^{n}\frac{1}{c_k}\right)\cdot\lambda(j-1)\right]\\&Y_j^{NA}(\lambda(j-1))-Y_j^{A}(\lambda(j-1))=\left[\frac{1}{c\cdot\left(\frac{i}{c}+\sum_{k=i+1}^{n}\frac{1}{c_k}\right)}-\frac{1}{c_j\cdot\left(\frac{i-1}{c}+\sum_{k=i}^{n}\frac{1}{c_k}\right)}\right]\cdot\left(\begin{matrix}q_j(\lambda(j-1))-\varepsilon_j+\\\left(\frac{i-1}{c}+\sum_{k=i+1}^{n}\frac{1}{c_k}\right)\cdot\lambda(j-1)\end{matrix}\right)\end{aligned} \tag{C6}$$

They can also be rewritten as

$$\begin{aligned}\Delta\pi_j^{DE,NC}=&\frac{1}{2}\cdot\left[\frac{1}{c_j\cdot\left(\frac{i-1}{c}+\sum_{k=i+1}^{n}\frac{1}{c_k}\right)^2}-\frac{1}{c\cdot\left(\frac{i}{c}+\sum_{k=i+1}^{n}\frac{1}{c_k}\right)^2}\right]\cdot\left[q_j(\lambda(j-1))-\varepsilon_j+\left(\frac{i-1}{c}+\sum_{k=i+1}^{n}\frac{1}{c_k}\right)\cdot\lambda(j-1)\right]^2\\&+\lambda(j-1)\cdot\left[\frac{1}{c\cdot\left(\frac{i}{c}+\sum_{k=i+1}^{n}\frac{1}{c_k}\right)}-\frac{1}{c_j\cdot\left(\frac{i-1}{c}+\sum_{k=i}^{n}\frac{1}{c_k}\right)}\right]\cdot\left(q_j(\lambda(j-1))-\varepsilon_j+\left(\frac{i-1}{c}+\sum_{k=i+1}^{n}\frac{1}{c_k}\right)\cdot\lambda(j-1)\right)\end{aligned} \tag{C7}$$

Appendix D. Calculation of the adopter's adoption benefits from the strategic effect in an imperfectly competitive market

According to the definitions of the strategic effect from the output and permit markets respectively, we first obtain

$$\begin{aligned}
\Delta\pi_j^{SEP,NC}+\Delta\pi_j^{SEO,NC} &= \left\{\begin{array}{l} P\left[\overline{Q_{-j}}(\lambda(j-1))+q_j(\lambda(j))\right]q_j(\lambda(j))- \\ \frac{c}{2}\cdot\left[q_j(\lambda(j))-Y_j^A(\lambda(j))-\varepsilon_j\right]^2-\lambda(j)\cdot Y_j^A(\lambda(j)) \end{array}\right\} \\
&\quad -\left\{\begin{array}{l} P[Q(\lambda(j-1))]q_j(\lambda(j-1))- \\ \frac{c}{2}\cdot\left[q_j(\lambda(j-1))-Y_j^A(\lambda(j-1))-\varepsilon_j\right]^2-\lambda(j-1)\cdot Y_j^A(\lambda(j-1)) \end{array}\right\} \\
&\quad +\left\{P[Q(\lambda(j))]-P\left[\overline{Q_{-j}}(\lambda(j-1))+q_j(\lambda(j))\right]\right\}q_j(\lambda(j)) \\
&= P\left[\begin{array}{l} Q(\lambda(j))]q_j(\lambda(j))-P[Q(\lambda(j-1))]q_j(\lambda(j-1))+ \\ \frac{c}{2}[q_j(\lambda(j-1))-Y_j^A(\lambda(j-1))-\varepsilon_j \end{array}\right]^2 \\
&\quad -\frac{c}{2}\left[q_j(\lambda(j))-Y_j^A(\lambda(j))-\varepsilon_j\right]^2 \\
&\quad +\lambda(j-1)\cdot Y_j^A(\lambda(j-1))-\lambda(j)\cdot Y_j^A(\lambda(j))
\end{aligned} \tag{D1}$$

Using Eqs. (C3) and (C4), we therefore obtain

$$\begin{aligned}
\Delta\pi_j^{SEP,NC}+\Delta\pi_j^{SEO,NC} &= P[Q(\lambda(j))]q_j(\lambda(j))-P[Q(\lambda(j-1))]q_j(\lambda(j-1)) \\
&\quad +\frac{c}{2}\cdot\frac{1}{c^2\cdot\left(\frac{i}{c}+\sum_{k=i+1}^{n}\frac{1}{c_k}\right)^2}\cdot\left[q_j(\lambda(j-1))-\varepsilon_j+\left(\frac{i-1}{c}+\sum_{k=i+1}^{n}\frac{1}{c_k}\right)\cdot\lambda(j-1)\right]^2 \\
&\quad -\frac{c}{2}\cdot\frac{1}{c^2\cdot\left(\frac{i}{c}+\sum_{k=i+1}^{n}\frac{1}{c_k}\right)^2}\cdot\left[q_j(\lambda(j))-\varepsilon_j+\left(\frac{i-1}{c}+\sum_{k=i+1}^{n}\frac{1}{c_k}\right)\cdot\lambda(j)\right]^2 \\
&\quad +\lambda(j-1)\cdot\left(1-\frac{1}{\left(i+c\cdot\sum_{k=i+1}^{n}\frac{1}{c_k}\right)}\right)\cdot\left(q_j(\lambda(j-1))-\varepsilon_j-\frac{\lambda(j-1)}{c}\right) \\
&\quad -\lambda(j)\cdot\left(1-\frac{1}{c_j\cdot\left(\frac{i-1}{c}+\sum_{k=i}^{n}\frac{1}{c_k}\right)}\right)\cdot\left(q_j(\lambda(j))-\varepsilon_j-\frac{\lambda(j)}{c_j}\right)
\end{aligned} \tag{D2}$$

Appendix E. Proof of the Proposition 2 in Section 3.2

Still assume that there are two firms—i.e., Firm 1 and Firm 2 included in a permit market. As a permit seller, Firm 2 can reduce emissions at a lower total abatement cost than Firm 1. Moreover, at the beginning of period 1, a new technology arrives that has much more potential for abatement.

Let $\Delta\pi_j^{DE,\,C}(j=1,2)$ be the adoption benefits from the direct effect for firm $j(j=1,2)$ in a perfectly competitive market, and let $\Delta\pi_j^{DE,\,NC}(j=1,2)$ be the adoption benefits from the direct effect for firm $j(j=1,2)$ in an imperfectly competitive market. Similarly, let $\Delta\pi_j^{SE,\,C}(j=1,2)$ be the adoption benefits from the strategic effect for firm $j(j=1,2)$ in a perfectly competitive market, and let $\Delta\pi_j^{SE,\,NC}(j=1,2)$ be the adoption benefits from the strategic effect for firm $j(j=1,2)$ in an imperfectly competitive market.

Therefore, we identify the adoption benefits from the direct effect and strategic effect for firm $j(j=1,2)$ in a perfectly competitive market from Eqs. (26) and (30) in Coria (2009, p. 256), respectively:

$$\Delta\pi_1^{DE,C}=\frac{[p(0)]^2}{2}\cdot\left(\frac{1}{c}-\frac{1}{c_1}\right) \tag{E1}$$

$$\Delta\pi_1^{SE,C}=\frac{[a-p(1)]^2-[a-p(0)]^2}{9\cdot b}+\frac{[p(1)]^2-[p(0)]^2}{2\cdot c}+[p(1)-p(0)]\cdot\varepsilon_1 \tag{E2}$$

$$\Delta\pi_2^{DE,C}=\frac{[p(1)]^2}{2}\cdot\left(\frac{1}{c}-\frac{1}{c_2}\right) \tag{E3}$$

$$\Delta\pi_2^{SE,C}=\frac{[a-p(2)]^2-[a-p(1)]^2}{9\cdot b}+\frac{[p(2)]^2-[p(1)]^2}{2\cdot c}+[p(2)-p(1)]\cdot\varepsilon_2 \tag{E4}$$

Furthermore, we write the adoption benefits from the direct effect and strategic effect for firm $j(j = 1,2)$ in an imperfectly competitive market from Eqs. (20) and (21) in Section 3.2, respectively:

$$\begin{aligned}\Delta\pi_1^{DE,NC} = &\frac{c_1 \cdot [q_1(\lambda(0)) - y_1(\lambda(0)) + z_1(\lambda(0)) - \varepsilon_1]^2}{2} \\ &-\frac{c}{2}\cdot\left[(q_1(\lambda(0)) - \left(1-\frac{1}{1+\frac{c}{c_2}}\right)\cdot\left(q_1(\lambda(0)) - \varepsilon_1 - \frac{\lambda(0)}{c}\right) - \varepsilon_1\right]^2 \\ &+\lambda(0)\cdot\left[y_1(\lambda(0)) - z_1(\lambda(0)) - \left(1-\frac{1}{1+\frac{c}{c_2}}\right)\cdot\left(q_1(\lambda(0)) - \varepsilon_1 - \frac{\lambda(0)}{c}\right)\right]\end{aligned} \tag{E5}$$

$$\begin{aligned}\Delta\pi_1^{SE,NC} = &[a - b\cdot(q_1(\lambda(1)) + q_2(\lambda(1)))]\cdot q_1(\lambda(1)) - [a - b\cdot(q_1(\lambda(0)) + q_2(\lambda(0)))]\cdot q_1(\lambda(0)) \\ &+\frac{c}{2}\cdot\left[(q_1(\lambda(0)) - \left(1-\frac{1}{1+\frac{c}{c_2}}\right)\cdot\left(q_1(\lambda(0)) - \varepsilon_1 - \frac{\lambda(0)}{c}\right) - \varepsilon_1\right]^2 \\ &-\frac{c}{2}\cdot[(q_1(\lambda(1)) - y_1(\lambda(1)) + z_1(\lambda(1)) - \varepsilon_1]^2 \\ &+\lambda(0)\cdot\left(1-\frac{1}{1+\frac{c}{c_2}}\right)\cdot\left(q_1(\lambda(0)) - \varepsilon_1 - \frac{\lambda(0)}{c}\right) - \lambda(1)\cdot[y_1(\lambda(1)) - z_1(\lambda(1))]\end{aligned} \tag{E6}$$

$$\begin{aligned}\Delta\pi_2^{DE,NC} = &\frac{c_2 \cdot [q_2(\lambda(1)) - y_2(\lambda(1)) + z_2(\lambda(1)) - \varepsilon_2]^2}{2} \\ &-\frac{c}{2}\cdot\left[(q_2(\lambda(1)) - \frac{1}{2}\cdot\left(q_2(\lambda(1)) - \varepsilon_2 - \frac{\lambda(1)}{c}\right) - \varepsilon_2\right]^2 \\ &+\lambda(1)\cdot\left[y_2(\lambda(1)) - z_2(\lambda(1)) - \frac{1}{2}\cdot\left(q_2(\lambda(1)) - \varepsilon_2 - \frac{\lambda(1)}{c}\right)\right]\end{aligned} \tag{E7}$$

$$\begin{aligned}\Delta\pi_2^{SE,NC} = &[a - b\cdot(q_1(\lambda(2)) + q_2(\lambda(2)))]\cdot q_2(\lambda(2)) - [a - b\cdot(q_1(\lambda(1)) + q_2(\lambda(1)))]\cdot q_2(\lambda(1)) \\ &+\frac{c}{2}\cdot\left[(q_2(\lambda(1)) - \frac{1}{2}\cdot\left(q_2(\lambda(1)) - \varepsilon_2 - \frac{\lambda(1)}{c}\right) - \varepsilon_2\right]^2 \\ &-\frac{c}{2}\cdot[(q_2(\lambda(2)) - y_2(\lambda(2)) + z_2(\lambda(2)) - \varepsilon_2]^2 \\ &+\frac{\lambda(1)}{2}\cdot\left(q_2(\lambda(1)) - \varepsilon_2 - \frac{\lambda(1)}{c}\right) - \lambda(2)\cdot[y_2(\lambda(2)) - z_2(\lambda(2))]\end{aligned} \tag{E8}$$

According to the calculated results in Appendix B, we compute the difference in the adoption benefits from the direct effect in a perfectly and imperfectly competitive market for firm $j(j = 1,2)$:

$$\Delta\pi_1^{DE,C} - \Delta\pi_1^{DE,NC} = \frac{(c_1 - c)\cdot\left[\begin{array}{l}\sum_{i=1}^{6} b^{7-i}\cdot\sum_{j=1}^{6-i} c^j\cdot c_2^{j-1}\cdot\varepsilon_1^2 + a\cdot\sum_{i=1}^{6} b^i\cdot\sum_{j=4}^{5-i} c^j\cdot c_2^{j-1}\cdot\varepsilon_2^2 \\ +\sum_{i=1}^{6} b^{5-i}\cdot\sum_{j=2}^{i} c^j\cdot c_2^{j-1}\cdot\varepsilon_1\cdot\varepsilon_2\end{array}\right]}{2\cdot c\cdot(c+c_2)^2\cdot B^2\cdot D^2\cdot\varepsilon_1^2} \tag{E9}$$

$$\Delta\pi_2^{DE,C} - \Delta\pi_2^{DE,NC} = \frac{(c_2 - c)\cdot b^2\cdot\left[\sum_{i=1}^{8}\begin{array}{l} b^{11-i}\cdot\sum_{j=4}^{7-i} c^j\cdot c_2^{j-1}\cdot\varepsilon_2^2 + \\ a\cdot\sum_{i=1}^{8} b^{10-i}\cdot\sum_{j=1}^{6-i} c^j\cdot c_2^{j-1}\cdot\varepsilon_1^2 + \end{array}\sum_{i=1}^{9} b^{9-i}\cdot\sum_{j=1}^{5-i} c^j\cdot c_2^{j-1}\cdot\varepsilon_1\cdot\varepsilon_2\right]}{8\cdot c\cdot(3bc + 3bc_2 + 2cc_2)^2\cdot\left(2bc^2 + 6b^2c + 2bc_2^2 + 6b^2c_2 + cc_2^2 + c^2c_2 + 6bcc_2\right)^2\cdot\varepsilon_2^2} \tag{E10}$$

and the difference in the adoption benefits from the strategic effect in a perfectly and imperfectly competitive market for firm $j(j = 1,2)$:

$$\Delta\pi_1^{SE,NC} - \Delta\pi_1^{SE,C} = \frac{(c_1 - c)\cdot\left[\sum_{i=1}^{12}\begin{array}{l} b^{13-i}\cdot\sum_{j=1}^{6-i} c^j\cdot c_1^{j-1}\cdot\varepsilon_1^2 + \\ a\cdot\sum_{i=1}^{12} b^{12-i}\cdot\sum_{j=4}^{5-i} c^j\cdot c_2^{j-1}\cdot\varepsilon_2^2\end{array} + \sum_{i=1}^{12} b^{11-i}\cdot\sum_{j=2}^{5-i} c^j\cdot c_2^{j-1}\cdot\varepsilon_1\cdot\varepsilon_2\right]}{2\cdot c\cdot(c+c_2)^2\cdot A^2\cdot B^2\cdot C^2\cdot D^2\cdot\varepsilon_1^2} \tag{E11}$$

$$\Delta\pi_2^{SE,NC}-\Delta\pi_2^{SE,C}=\frac{(c_2-c)\cdot\left[\sum_{i=1}^{8}\begin{array}{l} b^{10-i}\cdot\sum_{j=1}^{6-i}c^j\cdot c_2^{j-1}\cdot\varepsilon_2^2+\\ a\cdot\sum_{i=1}^{8}b^{9-i}\cdot\sum_{j=1}^{5-i}c^j\cdot c_2^{j-1}\cdot\varepsilon_1^2+\end{array}\sum_{i=1}^{8}b^{8-i}\cdot\sum_{j=1}^{i}c^j\cdot c_2^{j-1}\cdot\varepsilon_1\cdot\varepsilon_2\right]}{8\cdot c\cdot(2b+c)^2\cdot(3b+c)\cdot(3bc+3bc_2+2cc_2)^2\cdot\left(\begin{array}{l}2bc^2+6b^2c+2bc_2^2+6b^2c_2\\+cc_2^2+c^2c_2+6bcc_2\end{array}\right)^2\cdot\varepsilon_2^2}\tag{E12}$$

where the meaning of parameters A, B, C and D is the same as indicated in Appendix B.

Since $c<c_2<c_1$, we first find that $\Delta\pi_j^{DE,\,C}>\Delta\pi_j^{DE,\,NC}$ and $\Delta\pi_j^{SE,\,NC}>\Delta\pi_j^{SE,\,C}$ where $j=1,2$. Thereby, both the Proposition 2(a) and (b) have been proved. Furthermore, we define the difference in $(\Delta\pi_j^{SE,\,NC}-\Delta\pi_j^{SE,\,C})$ and $(\Delta\pi_j^{DE,\,C}-\Delta\pi_j^{DE,\,NC})$ where $j=1,\,2$, respectively, as:

$$\begin{aligned}\Delta^1&=\left(\Delta\pi_1^{SE,NC}-\Delta\pi_1^{SE,C}\right)-\left(\Delta\pi_1^{DE,C}-\Delta\pi_1^{DE,NC}\right)\\&=\frac{(c_1-c)\cdot\left[\sum_{i=1}^{11}b^{12-i}\cdot\sum_{j=1}^{6-i}c^j\cdot c_1^{j-1}\cdot\varepsilon_1^2+a\cdot\sum_{i=1}^{11}b^{11-i}\cdot\sum_{j=4}^{5-i}c^j\cdot c_2^{j-1}\cdot\varepsilon_2^2+\sum_{i=1}^{10}b^{11-i}\cdot\sum_{j=2}^{5-i}c^j\cdot c_2^{j-1}\cdot\varepsilon_1\cdot\varepsilon_2\right]}{2\cdot A^2\cdot B^2\cdot C^2\cdot D^2\cdot\varepsilon_1^2}\end{aligned}\tag{E13}$$

$$\begin{aligned}\Delta^2&=\left(\Delta\pi_2^{SE,NC}-\Delta\pi_2^{SE,C}\right)-\left(\Delta\pi_2^{DE,C}-\Delta\pi_2^{DE,NC}\right)\\&=\frac{(c_2-c)\cdot b\cdot\left[\sum_{i=1}^{8}b^{9-i}\cdot\sum_{j=1}^{5-i}c^j\cdot c_2^{j-1}\cdot\varepsilon_2^2+a\cdot\sum_{i=1}^{7}b^{8-i}\cdot\sum_{j=1}^{4-i}c^j\cdot c_2^{j-1}\cdot\varepsilon_1^2+\sum_{i=1}^{7}b^{7-i}\cdot\sum_{j=1}^{4-i}c^j\cdot c_2^{j-1}\cdot\varepsilon_1\cdot\varepsilon_2\right]}{8\cdot c\cdot(2b+c)^2\cdot(3b+c)\cdot(3bc+3bc_2+2cc_2)^2\cdot\left(2bc^2+6b^2c+2bc_2^2+6b^2c_2+cc_2^2+c^2c_2+6bcc_2\right)^2\cdot\varepsilon_2^2}\end{aligned}\tag{E14}$$

Then we can easily find that both Δ^1 and Δ^2 are positive. Therefore, the Proposition 2(c) has been proved.

Appendix F. Tables containing the contents of data and parameters used in case study

Table F1
The sources and accounting approaches for the data used in the simulations.

Variable	Source/approach
Data used to estimate the parameters in the firm-specific abatement cost functions	
Industrial value added	*China Statistical Yearbook 2011*
Energy consumption in industry	*China Energy Statistical Yearbook 2011*
Industrial emissions	Sum of the product of value in energy consumption at the industrial level and respective emissions factors corresponding to each fuel type in IPCC (2006)
Value added at the firm level	Chinese industrial enterprises database (NBSPRC, 2011a,b)
Emissions at the firm level	Estimated based on emissions at the industrial level and energy-saving targets for firms
Data used to estimate the parameters in the inverse product demand functions	
Domestic iron and steel prices inflation adjusted to the level in 2012	*China Statistical Yearbook*, 2006–2011 *China Steel Yearbook*, 2006–2011
Demand for crude steel products (domestic production plus net imports)	

Table F2
The values of the key parameters used in the simulations.

Parameters	Values
Parameters in firms' linear marginal abatement cost functions before technology adoption	
Tianjin Iron & Steel Group	576.7
Baoshan Iron & Steel	205.185
Shaoguan Iron & Steel Group	764.6
Chongqing Iron & Steel	3577.55
Wuhan Iron & Steel	2227.45
Tianjin Tiantie Metallurgical Group	449.57
Parameters in firm's linear marginal abatement cost function after technology adoption	35.481
Parameters in linear inverse demand function	
a	906.62
b	0.0956
Rate of technology diffusion θ_i	0.038; 0.0384; 0.0387; 0.0389; 0.039; 0.03905
Discount rate	0.2
Crude steel output of the sample firms in 2010 (Mt)[a]	
Tianjin Iron & Steel Group	5.0512
Baoshan Iron & Steel	44.4951
Shaoguan Iron & Steel Group	5.0355
Chongqing Iron & Steel	4.5597
Wuhan Iron & Steel	36.546
Tianjin Tiantie Metallurgical Group	5.5456
Investment cost in electric arc furnace (EAF) (million RMB)[b]	
Lifting appliance	0.45
Materials-loading equipment	0.5
EAF steel-making process	0.6
Electrical transmission equipment and wiring	0.35
Process pipeline	0.05
Dust removal system	0.65
Heating, ventilation, and air-conditioning system	0.05
Water treatment infrastructure	0.2
Scrapyard and warehouse	0.2
Electrical substation	0.35
Inspection equipment	0.5
Machine repair room	0.05
Air compression station	0.15
Oxygen station	0.9
Main building and auxiliary room	13
Equipment foundation	0.2

[a] Data on the crude steel output of the sample firms in 2010 comes from statistics on crude steel output of large and medium-size steel enterprises in December 2010 (http://info.glinfo.com/11/0124/11/2C1F2C63563A7B37.html).

[b] Data on the investment costs for electric arc furnaces (EAF) come from the construction plan of a short process EAF steelmaking plant with annual output of 0.22 million tons (http://max.book118.com/html/2013/1113/4960252.shtm).

Appendix G. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.eneco.2019.03.014.

References

Ambec, S., Coria, J., 2013. Prices vs quantities with multiple pollutants. J. Environ. Econ. Manag. 66 (1), 123–140. https://doi.org/10.1016/j.jeem.2012.11.002.

Bergek, A., Berggren, C., KITE Research Group, 2014. The impact of environmental policy instruments on innovation: a review of energy and automotive industry studies. Ecol. Econ. 106, 112–123. https://doi.org/10.1016/j.ecolecon.2014.07.016.

Bruneau, J.F., 2004. A note on permits, standards, and technological innovation. J. Environ. Econ. Manag. 48 (3), 1192–1199. https://doi.org/10.1016/j.jeem.2004.01.002.

Chesney, M., Gheyssens, J., Pana, A.C., Taschini, L., 2016. The economics of mitigation. In: Chesney, M., Gheyssens, J., Pana, A.C., Taschini, L. (Eds.), Environmental Finance and Investments, second ed. Springer-Verlag, Berlin Heidelberg, New York, pp. 49–72.

Coria, J., 2009. Taxes, permits, and the diffusion of a new technology. Resour. Energy Econ. 31 (4), 249–271. https://doi.org/10.1016/j.reseneeco.2009.04.004.

Coria, J., Mohlin, K., 2017. On refunding of emission taxes and technology diffusion. Strategic Behavior and the Environment 6 (3), 205–248. https://doi.org/10.1561/102.00000068.

Dickson, A., MacKenzie, I.A., 2018. Strategic trade in pollution permits. J. Environ. Econ. Manag. 2018 (87), 94–113. https://doi.org/10.1016/j.jeem.2017.04.009.

Evstigneev, I.V., Flåm, S.D., 2001. Sharing nonconvex costs. J. Glob. Optim. 20 (3–4), 257–271. https://doi.org/10.1023/A:1017599310112.

Fadaee, M., Lambertini, L., 2015. Non-tradeable pollution permits as green R&D incentives. Environ. Econ. Policy Stud. 17 (1), 27–42. https://doi.org/10.1007/s10018-014-0082-1.

Fan, R., Dong, L., 2018. The dynamic analysis and simulation of government subsidy strategies in low-carbon diffusion considering the behavior of heterogeneous agents. Energy Policy 117, 252–262. https://doi.org/10.1016/j.enpol.2017.12.003.

Flåm, S.D., 2016. Noncooperative games, coupling constraints, and partial efficiency. Economic Theory Bulletin 4 (2), 213–229. https://doi.org/10.1007/s40505-015-0079-3.

Flåm, S.D., Jourani, A., 2003. Strategic behavior and partial cost sharing. Games and Economic Behavior 43 (1), 44–56. https://doi.org/10.1016/S0899-8256(02)00547-X.

Fudenberg, D., Tirole, J., 1985. Preemption and rent equalization in the adoption of new technology. Rev. Econ. Stud. 52 (3), 383–401. https://doi.org/10.2307/2297399.

Ge, J., Sutherland, L.A., Polhill, J.G., Matthews, K., Miller, D., Wardell-Johnson, D., 2017. Exploring factors affecting on-farm renewable energy adoption in Scotland using large-scale microdata. Energy Policy 107, 548–560. https://doi.org/10.1016/j.enpol.2017.05.025.

Gersbach, H., Requate, T., 2004. Emission taxes and optimal refunding schemes. J. Public Econ. 88 (3), 713–725. https://doi.org/10.1016/S0047-2727(02)00215-3.

Godal, O., 2005. Strategic markets in property rights without price-takers. Working Paper in Department of Economics, University of Bergen, p. 05.

Hahn, R.W., 1984. Market power and transferable property rights. Q. J. Econ. 99 (4), 753–765. https://doi.org/10.2307/1883124.

Hintermann, B., 2011. Market power, permit allocation and efficiency in emission permit markets. Environ. Resour. Econ. 49 (3), 327–349. https://doi.org/10.1007/s10640-010-9435-9.

Hintermann, B., 2017. Market power in emission permit markets: theory and evidence from the EU ETS. Environ. Resour. Econ. 66 (1), 89–112. https://doi.org/10.1007/s10640-015-9939-4.

Hoffmann, V.H., 2007. EU ETS and investment decisions: the case of the German electricity industry. Eur. Manag. J. 25 (6), 464–474. https://doi.org/10.1016/j.emj.2007.07.008.

Huisman, K.J., Kort, P.M., 2003. Strategic investment in technological innovations. Eur. J. Oper. Res. 144 (1), 209–223. https://doi.org/10.1016/S0377-2217(01)00377-0.

Intergovernmental Panel on Climate Change (IPCC), 2006. IPCC Guidelines for National Greenhouse Gas Inventories. IPCC/IGES, Kanagawa, Japan.

Karshenas, M., Stoneman, P.L., 1993. Rank, stock, order, and epidemic effects in the diffusion of new process technologies: an empirical model. RAND J. Econ. 24 (4), 503–528. https://www.jstor.org/stable/2555742.

Kolstad, J., Wolak, F., 2008. Using emission permits prices to rise electricity prices: evidence from the California electricity market. Working Paper in Harvard University.

Kumar, S., Managi, S., 2010. Sulfur dioxide allowances: trading and technological progress. Ecol. Econ. 69 (3), 623–631. https://doi.org/10.1016/j.ecolecon.2009.09.013.

Laffont, J.J., Tirole, J., 1996. Pollution permits and environmental innovation. J. Public Econ. 62 (1), 127–140. https://doi.org/10.1016/0047-2727(96)01576-9.

Leiter, A.M., Parolini, A., Winner, H., 2011. Environmental regulation and investment: evidence from European industry data. Ecol. Econ. 70 (4), 759–770. https://doi.org/10.1016/j.ecolecon.2010.11.013.

Li, Y., Zhu, L., 2014. Cost of energy saving and CO_2 emissions reduction in China's iron and steel sector. Appl. Energy 130, 603–616. https://doi.org/10.1016/j.apenergy.2014.04.014.

Liao, X., Shi, X., 2018. Public appeal, environmental regulation and green investment: evidence from China. Energy Policy 119, 554–562. https://doi.org/10.1016/j.enpol.2018.05.020.

Malueg, D.A., 1990. Welfare consequences of emission credit trading programs. J. Environ. Econ. Manag. 18 (1), 66–77. https://doi.org/10.1016/0095-0696(90)90052-Z.

Misiolek, W.S., Elder, H.W., 1989. Exclusionary manipulation of markets for pollution rights. J. Environ. Econ. Manag. 16 (2), 156–166. https://doi.org/10.1016/0095-0696(89)90006-5.

Mohr, R.D., 2006. Environmental performance standards and the adoption of technology. Ecol. Econ. 58 (2), 238–248. https://doi.org/10.1016/j.ecolecon.2005.07.008.

Moner-Colonques, R., Rubio, S., 2015. The timing of environmental policy in a duopolistic market. Economía Agraria y Recursos Naturales/Agricultural and Resource Economics 15 (1), 11–40. https://doi.org/10.7201/earn.2015.01.02.

Montero, J.P., 2002a. Permits, standards, and technology innovation. J. Environ. Econ. Manag. 44 (1), 23–44. https://doi.org/10.1006/jeem.2001.1194.

Montero, J.P., 2002b. Market structure and environmental innovation. J. Appl. Econ. 5 (2), 293–325.

Montero, J.P., 2009. Market power in pollution permit markets. Energy J. 30 (SI2), 115–142. https://doi.org/10.5547/ISSN0195-6574-EJ-Vol30-NoSI2-6.

National Bureau of Statistics of the People's Republic of China, 2011. Chinese industrial enterprises database 2010. http://www.allmyinfo.com/data.

Nelissen, D., Requate, T., 2007. Pollution-reducing and resource-saving technological progress. Int. J. Agric. Resour. Gov. Ecol. 6 (1), 5–44. https://doi.org/10.1504/IJARGE.2007.012141.

Peleg, B., 1992. Axiomatizations of the core. In: Aumann, Robert J., Hart, Sergiu (Eds.), Handbook of Game Theory With Economic Applications, first ed. Elsevier, London, pp. 397–412.

Reinganum, J.F., 1981. Market structure and the diffusion of new technology. Bell J. Econ. 12 (2), 618–624. https://doi.org/10.2307/3003576.

Requate, T., 2005a. Dynamic incentives by environmental policy instruments: a survey. Ecol. Econ. 54 (2), 175–195. https://doi.org/10.1016/j.ecolecon.2004.12.028.

Requate, T., 2005b. Timing and commitment of environmental policy, adoption of new technology, and repercussions on R&D. Environ. Resour. Econ. 31 (2), 175–199. https://doi.org/10.1007/s10640-005-1770-x.

Rogge, K.S., Schneider, M., Hoffmann, V.H., 2011. The innovation impact of the EU emission trading system: findings of company case studies in the German power sector. Ecol. Econ. 70 (3), 513–523. https://doi.org/10.1016/j.ecolecon.2010.09.032.

Sanin, M.E., Zanaj, S., 2007. Environmental innovation under Cournot competition. Working Paper in Center for Operations Research and Econometrics (CORE), Université catholique de Louvain, p. 50.

Sartzetakis, E.S., 1997. Raising rivals' costs strategies via emission permits markets. Rev. Ind. Organ. 12 (5–6), 751–765. https://doi.org/10.1023/A:1007763019487.

Schleich, J., Betz, R., 2005. Incentives for energy efficiency and innovation in the European emission trading system. Proceedings of the 2005 ECEEE Summer Study—What Works & Who Delivers 7, pp. 1495–1506.

Schumpeter, J.A., Salin, E., Preiswerk, S., 1950. Kapitalismus, sozialismus und demokratie. first ed. Francke, Bern.

Song, X., Lu, Y., Shen, L., Shi, X., 2018. Will China's building sector participate in emission trading system? Insights from modelling an owner's optimal carbon reduction strategies. Energy Policy 118, 232–244. https://doi.org/10.1016/j.enpol.2018.03.075.

Thirtle, C.G., Ruttan, V.W., 1987. The Role of Demand and Supply in the Generation and Diffusion of Technical Change. First ed. Routledge, London.

Tietenburg, T.H., 2010. Emissions Trading: Principles and Practice. First ed. Routledge, London.

Tirole, J., 1988. The Theory of Industrial Organization. First ed. MIT Press, Cambridge.

Wang, X., Zhu, L., Fan, Y., 2018. Transaction costs, market structure and efficient coverage of emissions trading scheme: a microlevel study from the pilots in China. Appl. Energy 220, 657–671. https://doi.org/10.1016/j.apenergy.2018.03.080.

Westskog, H., 1996. Market power in a system of tradeable CO2 quotas. Energy J. (3), 85–103.

Worrell, E., Martin, N., Price, L., 2000. Potentials for energy efficiency improvement in the US cement industry. Energy 25 (12), 1189–1214. https://doi.org/10.1016/S0360-5442(00)00042-6.