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Does emission discrimination improve environmental effectiveness of emission trading schemes? A duopoly approach

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ABSTRACT

In this paper, we theoretically analyze that how emission discrimination policies affect the environmental effectiveness of carbon emission trading scheme under different emission permit allocation rules. By the setting of duopoly, we characterize the environmental effectiveness of carbon emission trading scheme, design various emission discrimination policies and then explore connections between the environmental effectiveness and emission discrimination policies. Our main results suggest that not all environmental effectiveness of carbon emission trading schemes are very sensitive to emission discrimination policies. Under grandfathering rule, the emission discrimination policy is not valid to facilitate the environmental effectiveness of carbon emission trading scheme. However under benchmarking rule, the environmental effectiveness of carbon emission trading scheme can be remarkably improved by an appropriate emission discrimination policy. Furthermore, we also compare the actual emissions in carbon emission trading schemes and conclude that the carbon emission trading scheme with benchmarking rule is a better choice for an 'active' regulatory authority from the viewpoint of policy efficiency.

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1. Introduction

In the 21st century, climate change has been considered as one of the most important challenges with the rapidly growing emissions of greenhouse gases (GHGs) in atmosphere. Governments and regulatory authorities are urged to employ stronger policies to achieve decarbonization. Carbon pricing mechanism is regarded as the most economically efficient way to reduce GHG emissions (Aldy 2015). So far there are three main categories in carbon pricing mechanism: emissions trading scheme (i.e. cap-and-trade), carbon taxation or hybrid mechanisms that combine elements of both (Narassimhan et al. 2018).

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'Cap and trade' is the main principle of ETS (short for emission trading scheme), companies under the cap are required to cover their emissions with emission allowances, which are handed out free of charge or auctioned (Germà and Stephan 2015). Emission allowances, however, with its specific commodity property, would just be regarded as one of the tradeable rights, and can be traded among facilities or countries enabling those that run short of allowances. Ordinarily, firms in ETS may trade allowances during a specified compliance period. Furthermore, firms with lower abatement costs are expected to sell their allowances to firms with higher abatement costs in the secondary market (Narassimhan et al. 2018).

The European Union has taken the lead in establishing a emissions trading scheme (The EU ETS) to promote sustainable development with the purpose of reaching GHG reduction goals cost-effectively since 2005. The EU climate target goal is at least an 80 percent reduction in GHG emissions (relative to 1990 levels) by 2050 (European Commission 2011). And thereafter that, many countries/regions have gradually launched their emission trading schemes such as USA, New Zealand, Australia, Korea, Canada, Ukraine, Brazil and Russia (Narassimhan et al. 2018). China also embarked on one of the largest endeavours in climate economics ever, and established a national emission trading schemes in 2015 (Yang et al. 2016).

On the other hand as we know, environmental effectiveness is one of the most important criteria on evaluating emission trading schemes (Narassimhan et al. 2018). The environmental effectiveness of each ETS are assessed via the following emitting sectors: (1) coverage of key emitting sectors; (2) emissions cap and (3) emission reductions achieved. In one carbon emission trading scheme, regulatory authorities focus on regulating the emissions of CO_2. And emission caps are set by an absolute cap in tons of GHG or a cap on GHG emission intensity, which are usually determined by regulatory authorities. Emissions reductions achieved by an ETS can be measured by the change in actual emissions covered by the ETS (Haites et al. 2018). Obviously, the last two sectors are largely dependent on one key energy policy of regulatory authority, that is how to allocate emission permits in one ETS.

Zetterberg et al. (2012) summarized that there are several commonly used CO_2 emission permit allocation rules in ETSs, which are grandfathering, benchmarking and auctioning rules. Free allocation reduces resistance from industry to stringent targets and serves as compensation to incumbent installations that are affected by the regulation (Åhman et al. 2007). Compared to grandfathering, the benchmarking allocation method avoids rewarding carbon intensive firms and punishing rapidly growing firms, and creates stronger emission reduction incentives to firms, which makes it be acceptable by carbon efficient firms.

As we know the establishment of marketization mechanism is very important for the environmental effectiveness of emission trading schemes. Many literature has been published to investigate the connection between marketization mechanism and the environmental effectiveness of emission trading schemes. It is a pity that the nonmarketization factors in emission trading schemes are seldom explored. In fact governments or regulatory authorities also play a very important role in emissions trading schemes for maintaining the environmental effectiveness. Hence we can not ignore the issue that how the environmental effectiveness of emission trading schemes is affected by emission policies of regulatory authorities.

It is interesting that Wang and Zhou (2017) defined the CO_2 emission allocation coefficient and the initially allocated CO_2 emission permits as exogenous parameters, which are determined by regulatory authorities. Then these emission parameters are regarded as a kind of emission policy. Hence following the settings in Wang and Zhou (2017), it is reasonable for us to make a perturbation analysis on these emission parameters and to investigate that how the environmental effectiveness of emission trading schemes is affected by the emission policies of regulatory authorities. We are particularly interested in the question that do emission discrimination policies improve environmental effectiveness of carbon emission trading schemes?

The contributions of our papers are twofold. First, a duopoly model is set up to characterize environmental effectiveness of carbon emission trading schemes under different emission permit allocation rules. The research gap between environmental effectiveness and emission discrimination policy in emission trading schemes is filled. Hence our results update the environmental effectiveness theory of carbon emission trading scheme by developing a framework where we allow for policy discrimination and different emission permit allocations.

Second, our findings indicate that the emission discrimination policy is not valid to facilitate the environmental effectiveness of carbon emission trading scheme with grandfathering rule. However under benchmarking rule, the environmental effectiveness of carbon emission trading scheme can be remarkably improved by an appropriate emission discrimination policy. Hence our findings also provide policy makers with additional information that can be used to design efficient and effective carbon emission reduction policies for the purpose of carbon abatement.

The rest of this paper is organized as follows. In section 2, we clarify and review the exist studies on emission trading schemes. In section 3, we present basic definitions and models to characterize environmental effectiveness of carbon emission trading scheme under different emission permit allocation rules. In section 4, we make a detailed analysis on the issue that how emission discrimination policy affects environmental effectiveness of carbon emission trading schemes. In section 5, we present the policy implications of our main results and draw conclusion remarks.

2. Literature review

By now a sizeable literature has been published to investigate emissions trading schemes by theoretical and/or empirical methods. Sijm et al. (2006) analysed the implications of the EU ETS for the power sector and presented empirical estimates of CO_2 cost pass-through for Germany and The Netherlands, indicated that the pass-through rates vary between 60% and 100% of CO_2 costs. Hahn and Stavins (2011) examined the independence property, which has been particularly important in obtaining political support for the use of emission trading schemes to address environmental issues. Hintermann (2011) addressed the effect of free allocation on price manipulation in the presence of explicit market power in both permit market as well as the linked output market. Sijm et al. (2012) analyzed the impact of power market structure on the pass-through rate of CO_2 emissions trading costs on electricity prices. Jouvet and Solier (2013) analyzed both the EU ETS phases and numerous countries, and proved that CO_2 cost pass-through sharply varies over time. Hintermann (2017) considered the interaction between input and output markets and proved that the well-known result 'market power in emission permit markets is that efficiency can be achieved by full free allocation to the dominant firm' breaks down under some general conditions.

Wen et al. (2018) investigated energy firms' carbon emissions abatement and pricing strategies in a competitive market when facing the pressure from both emissions trading price and consumer carbon awareness and found that carbon price and consumer awareness level have an additive effect on a firm's emissions abatement effort. Daskalakis (2018) studied temporal restrictions in emissions trading schemes and found that the temporal restrictions will result in higher polluters' hedging costs, which are mainly borne by consumers. Xie et al. (2019) performed an evaluation of the use of carbon emission rights in all provinces and suggested that the utilization rate of carbon emissions in eastern China is termed as the lowest. Makridou et al. (2019) investigated the profitability of firms participating in the EU ETS during the period from 2006 to 2014, their results indicated that both economic and energy-related variables significantly influence firms' profitability. Extensive surveys of the literature on emission trading scheme are presented by Ellerman et al. (2016), Fuss et al. (2018) and Hintermann et al. (2016).

And several literature showed that how to evaluate the effectiveness of the ETS in reducing GHG emissions by empirical methods. But it is difficult to directly and accurately attribute the results to measure the emissions reductions achieved with an ETS, while other complementary emissions-reduction policies are also adopted in realistic circumstance, for instance most of the jurisdictions with an ETS also have a carbon tax. Hence some problems arise, such as endogenous and simultaneous nature of interaction between complementary policies and the ETS, causing it hard to estimate the net impact of an ETS on overall emissions reduction (Hood 2013). An emissions trading system can interact strongly with other energy policies that also reduce emissions in the same sector and over the same timeframe, and the precise details of this interaction will depend on the design of the ETS chosen: in particular whether there is an absolute cap on emissions, or whether the ETS has output-based obligations (Hood 2013).

Zhou and Wang (2016) provided a literature review of CO_2 emissions allocations, and presented a comparison of the empirical results via ten popular indicator methods to show how indicator choice affects the allocation results. Wang and Zhou (2017) employed a linear Nash-cournot oligopolistic market equilibrium model to study how CO_2 cost pass-through rates are affected by different emission permit allocations. Their findings suggested that when grandfathering and auctioning rules are used to allocate emission permits, the CO_2 cost pass-through rates are higher than the rates under benchmarking rule.

3. Set-up of the models

3.1. Basic models

In this paper, we employ a duopoly model to characterize the environmental effectiveness of carbon emission trading scheme under different emission permit allocation rules.[1] In this model, it is assumed that there are two firms producing and selling a kind of homogeneous energy product in markets, denote the firms by $i \in \{1, 2\}$. The competitions for the two firms are twofold: one is from a product market and the other is from a carbon market. In the product market, the output of firm i is given by q_i. We assume that the two firms face a linear inverse demand function

$$P(Q) = a - b(q_1 + q_2),$$

where $Q = q_1 + q_2$ is a total output of the product. Let c_i be the marginal cost of firm i, which is assumed to be constant in a short-run analysis. Then the profit function of firm i in the product market can be expressed as:

$$\pi_i = P(Q)q_i - c_i q_i = (a - b(q_1 + q_2))q_i - c_i q_i. \tag{3.1}$$

Firm i maximizes its profit by choosing an optimal production output q_i^* in the production market.

In the carbon market, let ρ_i be the carbon intensity (CO_2 emissions per unit of product) of firm i, and TE_i be the CO_2 emissions of firm i, which is linearly correlated with the product output, where

$$TE_i = \rho_i q_i.$$

When the two firms enter the carbon market, it is supposed that firm i reduces its emissions by e_{ri}, moreover the initially allocated CO_2 emission permit is given by $\bar{e}_i$. Hence the amount of CO_2 emission permit purchased (or sold) by firm i is expressed as

$$\Delta e_i = \rho_i q_i - e_{ri} - \bar{e}_i.$$

Note that $\bar{e}_i$ is dependent on CO_2 emission permit allocation rules. Let r_i be the marginal abatement coefficient of firm i. By the assumption of the linear marginal abatement cost (see, Jones & Mendelson, 2011), we define the total abatement cost of firm i as:

$$TAC_i = \frac{1}{2} r_i e_{ri}^2.$$

In this paper, it is assumed that one regulatory authority employ the following two rules to allocate emission permits: *grandfathering* and *benchmarking*. When the grandfathering rule is used to allocate emission permits, it delivers free allocation of emission permits in proportion to the historical emissions of a firm as a fixed emissions cap. This reduces the emissions reductions that the ETS market must achieve, and so lowers the demand for ETS allowances and thus cut down their prices. Then $\bar{e}_i$ can be expressed as

$$\bar{e}_i = fe_0,$$

where f is a reduction rate and e_0 is the amount of historical emissions for the base year. By Wang and Zhou (2017), we know that both f and e_0 are determined by the regulatory authority, hence the two parameters are exogenous. On the other hand, emissions trading systems can also be designed as benchmarking rule, where emissions obligations are set per unit of production rather than as a fixed cap, then $\bar{e}_i$ is given by

$$\bar{e}_i = e_b q_i,$$

where e_b is the reference emission level per unit of product, which is also determined by the regulatory authority .

Combining the carbon market with the product market, the profit function of firm i can be expressed as:

$$\begin{aligned}\pi_i &= P(Q)q_i - c_i q_i - TAC_i - P_c \Delta e_i \\ &= \left(a - b(q_1 + q_2) - c_i\right)q_i - \frac{1}{2} r_i e_{ri}^2 - P_c(\rho_i q_i - e_{ri} - \bar{e}_i),\end{aligned} \tag{3.2}$$

where P_c refers to be a CO_2 emission permit price in the carbon market. Each firm maximizes its profit by choosing optimal production output and optimal emission reduction in the markets.

3.2. Environmental effectiveness

In this paper, we define the environmental effectiveness of a carbon ETS by the emissions reduction achieved, which is measured by the change in actual emissions covered by the carbon ETS. The actual emissions in our model is given by

$$TE = \sum_{i=1}^{2} TE_i = \sum_{i=1}^{2} \rho_i q_i.$$

Next we will characterize the actual emissions of firms under different market settings.

3.2.1. The actual emissions without the carbon market

Without the carbon market, we obtain the following equilibrium outputs of two firms:

$$\begin{cases} q_1 = \dfrac{a - 2c_1 + c_2}{3b}, \\ q_2 = \dfrac{a - 2c_2 + c_1}{3b}, \end{cases} \tag{3.3}$$

by computing a linear Cournot equilibrium. Hence the actual emissions of two firms are given by:

$$\begin{aligned} TE &= \rho_1 q_1 + \rho_2 q_2 \\ &= \frac{a(\rho_1+\rho_2) - 2c_1\rho_1 - 2c_2\rho_2 + c_1\rho_2 + c_2\rho_1}{3b}. \end{aligned} \tag{3.4}$$

3.2.2. The actual emissions with the carbon market

With the carbon market, we first consider that the regulatory authority allocates emission permits to the firms by grandfathering rule. Then the profit function of firm i is given by:

$$\pi_i^g = \left(a - b(q_1 + q_2) - c_i\right)q_i - \frac{1}{2}r_i e_{ri}^2 - P_c(\rho_i q_i - e_{ri} - fe_0). \tag{3.5}$$

By computing the first-order condition of the profit function π_i^g with respect to q_i, then the equilibrium outputs of two firms are expressed as:

$$\begin{cases} q_1^g = \dfrac{a - 2c_1 + c_2 - P_c(2\rho_1 - \rho_2)}{3b}, \\ q_2^g = \dfrac{a - 2c_2 + c_1 - P_c(2\rho_2 - \rho_1)}{3b}. \end{cases} \tag{3.6}$$

Correspondingly, the actual emissions of two firms in the carbon ETS with grandfathering rule (ETS_g) are given by:

$$\begin{aligned} TE^g &= \rho_1 q_1^g + \rho_2 q_2^g \\ &= TE - \frac{P_c(\rho_1^2 + \rho_2^2 + (\rho_1 - \rho_2)^2)}{3b}. \end{aligned} \tag{3.7}$$

If the regulatory authority allocates emission permits to the firms by benchmarking rule. Then the profit function of firm i is given by:

$$\pi_i^b = \left(a - b(q_1 + q_2) - c_i\right)q_i - \frac{1}{2}r_i e_{ri}^2 - P_c(\rho_i q_i - e_{ri} - e_b q_i). \tag{3.8}$$

Similarly, the equilibrium outputs of two firms can be expressed as:

$$\begin{cases} q_1^b = \dfrac{a - 2c_1 + c_2 - P_c(2\rho_1 - \rho_2 - e_b)}{3b}, \\ q_2^b = \dfrac{a - 2c_2 + c_1 - P_c(2\rho_2 - \rho_1 - e_b)}{3b}. \end{cases} \tag{3.9}$$

Hence the actual CO_2 emissions of two firms in the carbon ETS with benchmarking rule (ETS_b) are given by:

$$\begin{aligned} TE^b &= \rho_1 q_1^b + \rho_2 q_2^b \\ &= TE - \frac{P_c(\rho_1^2 + \rho_2^2 + (\rho_1 - \rho_2)^2 - e_b(\rho_1 + \rho_2))}{3b} \end{aligned} \tag{3.10}$$

$$= TE^g + \frac{P_c e_b(\rho_1 + \rho_2)}{3b}. \tag{3.11}$$

Obviously if the regulatory authority sets up a positive reference emission level e_b, then the actual emissions in the ETS_b are greater than that in the ETS_g.

4. Main results

In this section, it is assumed that the regulatory authority enforces different emission discrimination policies to the firms according to their carbon intensity. We focus on exploring the connections between the actual emissions; emission discrimination policies and emission permit allocation rules.

4.1. Grandfathering

Since in the ETS_g, the reduction rate f and the amount of historical emissions e_0 are determined by the regulatory authority, then it is assumed that the regulatory authority sets up the following emission parameters f_i and e_{0_i} to the firms, where

$$f_1 < f_2 \text{ and } e_{0_1} < e_{0_2}, \tag{4.1}$$

if $\rho_1 > \rho_2$.

Hence with the emission discrimination policy (4.1), the profit function of firm i in the ETS_g is changed to be:

$$\pi_i^{g*} = \left(a - b(q_1 + q_2) - c_i\right)q_i - \frac{1}{2} r_i e_{ri}^2 - P_c(\rho_i q_i - e_{ri} - f_i e_{0_i}). \tag{4.2}$$

The firm i chooses an output q_i such that its marginal cost is equal to marginal revenue for maximizing its profit. By computing the first-order condition of the profit function $\pi_i^{g^*}$ with respect to q_i, one has the following equilibrium outputs of two firms:

$$\begin{cases} q_1^{g^*} = \dfrac{a - 2c_1 + c_2 - P_c(2\rho_1 - \rho_2)}{3b}, \\ q_2^{g^*} = \dfrac{a - 2c_2 + c_1 - P_c(2\rho_2 - \rho_1)}{3b}. \end{cases} \tag{4.3}$$

Combining (4.3) with (3.6), we find that the equilibrium outputs of two firms in the ETS_g are independent on the emission discrimination policy (4.1). Consequently, the actual emissions of two firms in the ETS_g are not changed by the emission discrimination policy (4.1). That is

$$\begin{aligned} TE^{g^*} &= \rho_1 q_1^{g^*} + \rho_2 q_2^{g^*} \\ &= TE - \frac{P_c(\rho_1^2 + \rho_2^2 + (\rho_1 - \rho_2)^2)}{3b}. \end{aligned} \tag{4.4}$$

Summarizing the above obtained results, we have the following proposition to explore the connection between the environmental effectiveness and the emission discrimination policy (4.1) in the ETS_g.

Proposition 1. *The emission discrimination policy (4.1) is inefficient to improve the environmental effectiveness of ETS with grandfathering rule.*

Slight more intuitively, the main results in Proposition 1 can be explained as follows. In the ETS with grandfathering rule, the environmental effectiveness is measured by the actual emissions of two firms, and the actual emissions consist of emission intensity and output. Obviously, the emission intensities of two firms are not changed in the ETS_g. By (4.3), the outputs of firms are independent on the reduction rate f and the amount of historical emissions e_0, and then the actual emissions of the firms are also irrelevant to these emission parameters f and e_0. Hence the environmental effectiveness can not be improved by the emission discrimination policy (4.1) in the ETS_g.

4.2. Benchmarking

Since the reference emission level e_b is also determined by the regulatory authority in the ETS_b, then it is possible for the regulatory authority to enforce the following emission discrimination policy to the firms according to their emission intensities. Hence if the emission intensities $\rho_1 > \rho_2$, then the discriminative reference emission levels e_{b_1} and e_{b_2} are given to the firms, where

$$e_{b_1} < e_b < e_{b_2}. \tag{4.5}$$

We first consider how the outputs of two firms are changed by the emission discrimination policy (4.5).

Proposition 4.1. *If the regulatory authority enforces the emission discrimination policy (4.5) to the firms in the carbon market, then the outputs of firm 1 are distorted, in contrast the outputs of firm 2 are increased.*

Proof. After being enforced the emission discrimination policy (4.5) in the carbon market, the profit function of firm i is changed to be:

$$\pi_i^{b*} = \big(a - b(q_1 + q_2) - c_i\big)q_i - \frac{1}{2}r_i e_{ri}^2 - P_c(\rho_i q_i - e_{ri} - e_{b_i} q_i).$$

The firm i chooses an output q_i such that its marginal cost is equal to marginal revenue for maximizing its profit. Then similarly with the ETS_g, one has the following equilibrium outputs of two firms:

$$\begin{cases} q_1^{b*} = \dfrac{a - 2c_1 + c_2 - 2P_c\rho_1 + P_c\rho_2 + 2P_c e_{b_1} - P_c e_{b_2}}{3b}, \\ q_2^{b*} = \dfrac{a - 2c_2 + c_1 - 2P_c\rho_2 + P_c\rho_1 + 2P_c e_{b_2} - P_c e_{b_1}}{3b}. \end{cases} \tag{4.6}$$

By (3.9), the differences of two firms' outputs are given by:

$$\begin{cases} \Delta q_1^b = q_1^{b*} - q_1^b = \dfrac{2P_c e_{b_1} - P_c e_{b_2} - P_c e_b}{3b} = P_c(2e_{b_1} - e_{b_2} - e_b)/3b, \\ \Delta q_2^b = q_2^{b*} - q_2^b = \dfrac{2P_c e_{b_2} - P_c e_{b_1} - P_c e_b}{3b} = P_c(2e_{b_2} - e_{b_1} - e_b)/3b. \end{cases} \tag{4.7}$$

From the emission discrimination policy (4.5), obviously the outputs of firm 1 (with higher emission intensity) are distorted and the outputs of firm 2 (with lower emission intensity) are increased.

Let $\alpha_i = |e_b - e_{b_i}|$ be a discrimination degree of firm i's reference emission level, then we present the following proposition to reveal the connection between the environmental effectiveness and the emission discrimination policy (4.5) in the ETS_b.

Proposition 2. *If the regulatory authority enforces the emission discrimination policy (4.5) to the firms, then one has*

1. when $\rho_2 \in \left(0, \frac{\rho_1}{2}\right)$, then the environmental effectiveness is constantly improved by the discrimination policy;
2. when $\rho_2 \in \left(\frac{\rho_1}{2}, \rho_1\right)$, if

$$\frac{\alpha_1}{\alpha_2} \leq \frac{2\rho_2 - \rho_1}{2\rho_1 - \rho_2}, \tag{4.8}$$

then the emission discrimination policy (4.5) is inefficient to improve the environmental effectiveness.

Proof. From the equilibrium outputs (4.6), we know the actual emissions of two firms after being implemented the emission discrimination policy (4.5) are expressed as:

$$\begin{aligned} TE^{b*} &= \rho_1 q_1^{g*} + \rho_2 q_2^{g*} \\ &= TE - \frac{2P_c(\rho_1^2 + \rho_2^2) - 2P_c\rho_1\rho_2 - 2P_c\rho_1 e_{b_1} - 2P_c\rho_2 e_{b_2} + P_c\rho_2 e_{b_1} + P_c\rho_1 e_{b_2}}{3b} \end{aligned} \tag{4.9}$$

$$= TE^g + \frac{2P_c\rho_1 e_{b_1} + 2P_c\rho_2 e_{b_2} - P_c\rho_2 e_{b_1} - P_c\rho_1 e_{b_2}}{3b}. \tag{4.10}$$

By the formulae (3.10) and (4.9), we know that the difference of actual emissions of two firms is expressed as:

$$\begin{aligned} TE^{b*} - TE^b &= \frac{2P_c\rho_1 e_{b_1} + 2P_c\rho_2 e_{b_2} - P_c\rho_2 e_{b_1} - P_c\rho_1 e_{b_2} - P_c e_b(\rho_1 + \rho_2)}{3b} \\ &= \frac{P_c[\rho_1(2e_{b_1} - e_{b_2} - e_b) + \rho_2(2e_{b_2} - e_{b_1} - e_b)]}{3b}. \end{aligned} \tag{4.11}$$

Denote $e_b - e_{b_i}$ by α_i, the above equation can be simplified as:

$$\begin{aligned} TE^{b*} - TE^{b} &= \frac{P_c[(-2\alpha_1 - \alpha_2)\rho_1 + (2\alpha_2 + \alpha_1)\rho_2]}{3b} \\ &= \frac{P_c[\alpha_2(2\rho_2 - \rho_1) - \alpha_1(2\rho_1 - \rho_2)]}{3b}. \end{aligned} \tag{4.12}$$

If $\rho_2 \in \left(0, \frac{\rho_1}{2}\right)$, obviously one has

$$TE^{b*} - TE^{b} < 0$$

by (4.12), which means that the actual emissions of two firms in ETS_b are distorted after being implemented the emission discrimination policy (4.5). If $\rho_2 \in \left(\frac{\rho_1}{2}, \rho_1\right)$, from the assumption (4.8), we know

$$\alpha_2(2\rho_2 - \rho_1) - \alpha_1(2\rho_1 - \rho_2) \geq 0. \tag{4.13}$$

Obviously by (4.12), one has

$$TE^{b*} - TE^{b} \geq 0,$$

which suggests that the actual emissions of two firms in the ETS_b are not decreased by the discrimination policy. Hence the emission discrimination policy (4.5) is inefficient to improve the environmental effectiveness of the ETS_b.

Slight more intuitively, the policy implications of the above results can be explained as follows. After implementing the emission discrimination policy (4.5), the actual emissions of the firm with higher emission intensity are distorted and the actual emissions of the firm with lower emission intensity are increased. This difference provides the regulatory authority a simple and possible method to improve the environmental effectiveness of the ETS_b. However this simple method is efficient only when the difference of two firms' emission intensities is sufficiently vast. If the difference on their emission intensities is mild, then the regulatory authority should design a precise emission discrimination policy to the firms.

4.3. The actual emissions and emission permit allocations

In this subsection, we will compare the actual emissions of two firms in different *ETSs* after being implemented different emission discrimination policies.

Proposition 3

1. *When $\rho_2 \in \left(\frac{\rho_1}{2}, \rho_1\right)$, the regulatory authority can hardly find an appropriate emission discrimination policy such that the actual emissions of two firms in the ETS_b are less than that in the ETS_g.*
2. *When $\rho_2 \in \left(0, \frac{\rho_1}{2}\right)$, the actual emissions in the ETS_b would be less than that in the ETS_g if the regulatory authority enforces the following emission discrimination policy:*

$$\frac{e_{b_1}}{e_{b_2}} < \frac{\rho_1 - 2\rho_2}{2\rho_1 - \rho_2} \tag{4.14}$$

to the firms.

Proof. The difference of actual emissions can be expressed as:

$$\begin{aligned} TE^{b*} - TE^{g} &= 2P_c\rho_1 e_{b_1} + 2P_c\rho_2 e_{b_2} - P_c\rho_2 e_{b_1} - P_c\rho_1 e_{b_2} \\ &= P_c[\rho_1(2e_{b_1} - e_{b_2}) + \rho_2(2e_{b_2} - e_{b_1})] \end{aligned} \tag{4.15}$$

$$= P_c[e_{b_1}(2\rho_1 - \rho_2) - e_{b_2}(\rho_1 - 2\rho_2)] \tag{4.16}$$

in different *ETSs*. Hence if $\rho_2 \in \left(\frac{\rho_1}{2}, \rho_1\right)$, the following inequality holds constantly

$$TE^{b*} - TE^{g} < 0$$

by (4.16). Which means that the regulatory authority can hardly find proper reference emission levels e_{b_i} such that the actual emissions of two firms in the ETS_b are less than that in the ETS_g.

However if $\rho_2 \in \left(0, \frac{\rho_1}{2}\right)$, one has

$$TE^{b*} - TE^{g} < 0$$

by the assumption (4.14) and (4.15). Hence if the regulatory authority designs more precise reference emission levels to the firms, then the actual emissions of two firms in the ETS_b may be less than that in the ETS_g.

Slight more intuitively, the policy implications in Proposition 3 can be explained as follows. Before being enforced emission discrimination policies, the actual emissions of two firms in the ETS_b are constantly greater than that in the ETS_g, which means that the firms in the ETS_b are more harmful than they are in ETS_g to the environment. Since the ETS_g is immune to the emission discrimination policy, hence the regulatory authority is unable to decrease the actual emissions in the ETS_g by emission policies. However if the regulatory authority enforces a strict and precise emission policy to the firms in the ETS_b, then the actual emissions in ETS_b are remarkably decreased under mild conditions. From the opinion of policy efficiency, the ETS_b is a better choice for the regulatory authority to decrease the actual emissions and to improve the environmental effectiveness.

5. Concluding remarks

In this paper, we theoretically investigated that how emission discrimination affects the environmental effectiveness of carbon emission trading scheme under different emission permit allocation rules. We set up the duopoly model to characterize the environmental effectiveness of ETS, designed various emission discrimination policies to the firms and explored the connections between the environmental effectiveness of ETS and emission discrimination policies. Our results indicated that the actual emissions of firms in the ETS_g are immune to the emission discrimination policy. The regulatory authority can hardly facilitate the environmental effectiveness of ETS_g by enforcing an appropriate emission discrimination policy.

However in the ETS_b, our results revealed that the outputs of the firm with higher emission intensity are distorted, in contrast the outputs of the firm with lower emission intensity are increased. And then our results also suggested that the environmental effectiveness of ETS_b can be improved if the regulatory authority enforces a kind of appropriate emission discrimination policy to the firms. Finally, we compared the actual emissions of two firms in the carbon ETSs after being enforced different discrimination emission policies. We proved that under mild conditions, the actual emissions in ETS_b are remarkably decreased, if the regulatory authority enforces a strict emission discrimination policy to the firms. Hence we concluded that the ETS_b is more sensitive to different emission discrimination policies. The policy implication of our results is clear. From the viewpoint of policy efficiency, the ETS_b is a better choice for an 'active' regulatory authority to achieve the objective of carbon abatement.

The contributions of our papers are twofold. First, a duopoly model is set up to characterize environmental effectiveness of carbon emission trading schemes under different emission permit allocation rules. The research gap between environmental effectiveness and emission discrimination policy in emission trading schemes is filled. Hence our results update the environmental effectiveness theory of carbon emission trading scheme by developing a framework where we allow for policy discrimination and different emission permit allocations.

Second, our findings indicate that the emission discrimination policy is not valid to facilitate the environmental effectiveness of carbon emission trading scheme with grandfathering rule. However under benchmarking rule, the environmental effectiveness of carbon emission trading scheme can be remarkably improved by an appropriate emission discrimination policy. Hence our findings also provide policy makers with additional information that can be used to design efficient and effective carbon emission reduction policies for the purpose of carbon abatement.

Note

1. All the formulas in the subsection Basic models are cited from Wang and Zhou (2017). The authors thank one reviewer to point out this issue.

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Disclosure statement

No potential conflict of interest was reported by the authors.

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