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Market-based pollution regulations with damages Varying across space: When the adoption of clean Technology is socially optimal

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Abstract

For much of the pollution currently regulated by governments, resulting damages depend on the locations of emission sources. Market-based differentiated policies including differentiated taxes and differentiated emissions trading are designed to reflect spatially variant damages with differentiated emissions penalties. We evaluate differentiated policies from the perspective of clean technology adoption. In equilibrium, a firm may act as what regulator initially expects, which equates the firm's marginal damage to its marginal abatement cost; or else, the regulator sets a lower (higher) tax rate or trading ratio to stimulate the firm not to (to) adopt clean technology. Accordingly, differentiated policies lead to the socially optimal degree of adoption. And they provide greater incentives for firms in high damage locations to adopt clean technology. However, when imperfect information or uncertainty is considered, differentiated policies may not perform better than existing market-based policies. Overinvestment or underinvestment is possible. Moreover, we study a special case where marginal damages are constant. It shows differentiated taxes could still induce the socially optimal adoption even with incompleteness about abatement costs.

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Keywords: taxes, emissions trading, pollution regulation, technology adoption, environmental policy choice

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1 Introduction

Economists have long advocated employing market-based environmental policies such as emission taxes and tradable permits to regulate pollution, instead of command and control. The advantage of market-based regulations is their cost efficiency since the differences in marginal abatement costs across sources are considered (Dales 1968; Montgomery 1972; Baumol and Oates 1988). Netherland, Norway, Japan and Germany have implemented SO_2 taxes. The European Union emissions trading scheme was established in 2005 to control the emissions of CO_2. However, the existed market-based policies have some limitations, because they only work well for uniformly mixed pollutants (i.e. the damages caused by them don't depend on the locations of emission sources, just on the aggregate emissions level) such as CO_2 or widely dispersed pollutants. For non-uniformly mixed pollutants including SO_2, $PM_{2.5}$ and NO_x, these policies still generate deadweight loss since they don't take the interfirm differences in marginal damages into consideration.

Scholars and experts have recognized that market-based policies could be designed to reflect spatially variant damages. Baumol and Oates (1988) point out emission tax rate can be adjusted to equal the marginal damage at each source. With respect to emissions trading regime, numerous calibration options have been proposed. For example, Montgomery (1972) introduces ambient concentration permit market wherein firms have to buy ambient allowances in the area their emissions travel. Tietenberg (1980) suggests permits market can be divided into homogenous regions and one-for-one trading in each submarket is allowed. Unfortunately, these end in failure because of impracticality or thin trading. However, recent advances in integrated assessment models make it feasible to estimate the damages from a single source, which opens a new frontier for establishing permits market (Muller and Mendelsohn 2007, 2009; Muller et al. 2011; Fowlie and Muller 2013). Regulator could require emitters to hold differentiated amounts of permits for per unit of emissions. This differentiated requirement is typically called trading ratio, and it is proportional to source-specific marginal damage. The trading regime that features such trading ratios can move from cost efficiency to effectiveness, achieving pollution reductions through the minimization of both abatement costs and damages rather than merely minimizing abatement costs (Farrow et al. 2005; Muller and Mendelsohn 2009; Fowlie and Muller 2013; Holland and Yates 2015; Antweiler 2017).

Kneese and Schultze (1975) point out that, aside from effectiveness, the extent to which environmental policies provide incentives to adopt and develop new clean technology is another further important criterion for judging policy instruments. However, so far damage-based differentiated designs which are efficient to regulate pollution, have not been judged by the criterion. In this paper, we will fill the gap.

There are many literatures investigating the incentives created by environmental policy instruments for clean technology adoption, and thus attempting to rank the policies (Requate and Unold 2001, 2003; Requate 2005; Coria 2009; Perino and Requate 2012; D'Amato and Dijkstra 2015). And a main conclusion is drawn that under certain conditions, market-based undifferentiated policies (i.e. the existing market-based policies, which treat pollution emissions as if the damages caused by them are the same on a per-ton basis) always perform better than command and control. We continue to make a contribution by introducing differentiated policies into firms' investment incentives and exploring whether differentiated policies can further improve market-based pollution regulations. Throughout this paper, we also study a special case in which marginal damages are constant. It is necessary since a series of empirical results have indicated that the marginal damage of air pollution for a single emissions source is effectively constant (Muller and Mendelsohn 2007, 2009; Muller et al. 2011; Fowlie and Muller 2013).

A game model is built to analyze government's differentiated policy designs and firms' emissions reduction decisions. In equilibrium, a firm may act as what the regulator initially expects, which equates the firm's marginal damage to its marginal abatement cost; or else, the regulator sets a higher (lower) tax rate or trading ratio to stimulate the firm to (not to) adopt clean technology. And using the social optimum as a benchmark, it shows both differentiated taxes and differentiated emissions trading could lead to the socially optimal degree of adoption, while the extant undifferentiated policies couldn't. Accordingly, it demonstrates the comparative advantage of damage-based policy differentiation. Moreover, pollution regulation through differentiated policies facilitates firms in high damage locations to adopt clean technology better than the undifferentiated ones.

We then extend our base model to capture imperfect information about abatement costs and uncertainty about firm-specific damages. First, we follow Requate and Unold (2001, 2003) in studying the case where the regulator sets its policy without anticipating clean technology. It shows differentiated taxes may lead to overinvestment, while differentiated emissions trading may lead to either overinvestment or underinvestment. In comparison, differentiated designs don't perform better than undifferentiated policies. However, if the firms' marginal damages are assumed to be constant, differentiated taxes could still lead to the socially optimal adoption. Second, we study the case where the regulator is uncertain about firm-specific damages. Overinvestment or underinvestment is possible under these market-based policies.

In summary, the original contributions of this paper are as follows. First, we aim to evaluate marked-based pollution regulations from the perspective of clean technology adoption, where the regulations take spatially variant damages into account. It is absent in previous studies. Pollution damages as an important part of social costs often vary across sources, which should be incorporated into environmental policy designs. And in the long run, environmental policies are judged by an important criterion that is the extent to which they stimulate the adoption or development of clean technology. Through game analysis, a novel result is obtained: In equilibrium, a firm may act as what regulator initially expects; or else, the regulator sets a lower (higher) tax rate or trading ratio to stimulate the firm not to (to) adopt clean technology.

Second, we consider a special case in which the firms' marginal damages are constant. It is necessary since a series of empirical results have indicated that the marginal damage of air pollution for a single emissions source is effectively constant. Accordingly, the tax policy considering spatially variant damages can lead to the socially optimal degree of adoption even with incompleteness about abatement costs. To some extent, this policy is a better choice for the government to regulate pollution.

The remainder of the paper is organized as follows: In section 2, we set up the model and derive the socially optimal outcome. In section 3, we study differentiated policy designs and the incentives to adopt clean technology. In section 4, we extend the model to consider imperfect information about abatement costs and uncertainty about firm-specific damages. In section 5, conclusions are drawn.

2 The Model

2.1 Basic setting

Consider a competitive industry that consists of n firms. All these firms emit a homogenous pollutant. And a firm could reduce its pollution emissions by adopting a new clean technology to replace the old one. Every firm has its own abatement cost functions for the old and clean technologies, denoted by $C_i^0(e_i^0)$ and $C_i^I(e_i^I)$ respectively, where $e_i^j(j=0,I)$ refers to the pollution emissions from firm $i(i=1,\cdots,n)$ under technology j. Without any regulation, every firm has a maximal emission level, represented by $e_i^{j\max}$. The unregulated emission level for the clean technology is smaller, i.e., $e_i^{I\max} < e_i^{0\max}$. We raise the following usual assumptions about firms' abatement cost functions: $C_i^j(e_i^{j\max})=0$, and $C_i^j(e_i^j)>0$, $\partial C_i^j(e_i^j)/\partial e_i^j<0$, $\partial^2 C_i^j(e_i^j)/\partial e_i^{j2}>0$ for $e_i^j<e_i^{j\max}$.[2] And the marginal abatement cost curve for the clean technology is lower, i.e., $MC_i^I(e)=-\partial C_i^I(e)/\partial e < MC_i^0=-\partial C_i^0(e)/\partial e$ for $e<e_i^{0\max}$.[3] In addition, firm i needs to pay an extra fixed investment cost F_i when adopting the clean technology.

Emissions of the pollutant may lead to premature death, higher morbidity, impaired visibility, reduced yields of crops and timber, accelerated depreciation of

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[2] See Requate and Unold (2001, 2003) for reference.

[3] Amir et al. (2008) and Baker et al. (2008) show that the marginal abatement cost curves of old and clean technologies intersect at one point. For simplicity, but without loss of essential views, we only focus on the conventional assumption that clean technology leads to a lower marginal abatement cost curve.

artificial material and reduced entertainment services (Muller and Mendelsohn 2009). The health and environmental damages due to the emissions from firm i, evaluated in money terms, are expressed by the function $D_i(e_i)$. It involves the reduction in the utility of all the victims that are exposed to firm i's emissions. Ordinarily, compared with low-population rural areas, the damages caused by the same amounts of emissions are relatively high in large metropolitan areas.

With regard to the damage function, we assume it is non-negative, strictly increasing and convex for emissions, i.e., $D_i(0)=0$, and $D_i(e_i)>0$, $\partial D_i(e_i)/\partial e_i>0$, $\partial^2 D_i(e_i)/\partial e_i^2 \geq 0$ for $e_i>0$.[4] For convenience, firm i's marginal damage function is denoted by $MD_i(e_i)$, i.e., $MD_i = \partial D_i(e_i)/\partial e_i$. And the total social damages are the sum of the damages caused by each source.

2.2 The social optimum

We first explore the socially optimal outcome. It's necessary since it's used as a benchmark to evaluate the performance of environmental policy instruments. The social objective function aims at minimizing the total social costs which consist of all the firm's abatement costs for the two technologies, fixed investment costs and pollution damages:

$$\min_{e_i^j} : TSC = \sum_{i=1}^{n} SC_i = \sum_{i=1}^{n} [C_i^j(e_i^j) + F_i^j + D_i(e_i^j)](j=0,I)$$
$$F_i^j = \begin{cases} 0, & j=0 \\ F_i, & j=I \end{cases} \tag{1}$$

In fact, the total social costs represented by TSC are the sum of the social costs every firm contributes to. Obviously, $F_i^j = F_i$ if firm i should adopt clean technology in the social optimum, or else the fixed investment cost is zero. The first-order conditions for Eq. (1) show:

$$\frac{\partial TSC}{\partial e_i^j} = \frac{\partial C_i^j(e_i^j)}{\partial e_i^j} + \frac{\partial D_i(e_i^j)}{\partial e_i^j} = 0$$
$$MC_i^j(e_i^j) = MD_i(e_i^j) \tag{2}$$

The social optimum requires that every firm's marginal abatement cost should equal its marginal damage. Based on this, we shall continue to discuss the socially optimal adoption intuitively through Figure 1.

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4 See Holland and Yates (2015) for reference.

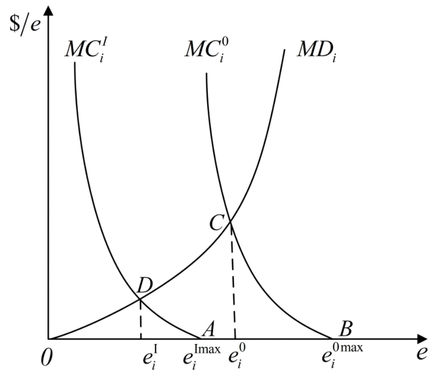

Figure 1: The socially optimal adoption for firm $i(i=1,\cdots,n)$

In Figure 1, $e_i^j\,(j=0,I)$ denotes the emission level that satisfies $MC_i^j(e_i^j)=MD_i(e_i^j)$. The intersection points of different curves are represented by A, B, C and D, which are used to mark the areas enclosed by related curves conveniently. In the social optimum, if firm i should switch from old to clean technology, its savings in damages and variable abatement costs is given by the area $S_{ABCD} \equiv \tilde{S}$.[5] Thus whether firm i should invest in clean technology depends on the comparison between $\tilde{S}$ and F_i. More specifically, we obtain the following result:

Proposition 1 *In the social optimum, the following holds:*

(i) If $\tilde{S} > F_i$*, firm* i *should adopt clean technology;*

(ii) If $\tilde{S} < F_i$*, firm* i *shouldn't adopt clean technology;*

(iii) *If* $\tilde{S} = F_i$*, firm* i *should be indifferent about whether or not to adopt.*

Consider a special case in which all the firms are the same except their locations. In other words, the firms' abatement cost functions and fixed investment costs are the same, while their damage functions are different. It can be seen that there is diversity upon the socially optimal adoption for the firms. However, all the firms would make the same investment decisions under the existing market-based policies. It is inconsistent with the social optimum and generates some deadweight losses. Thus it is essential to investigate differentiated policies for pollution regulation.

3 Differentiated environmental policies

In this section, we assume that the regulator knows the damages, abatement costs and fixed investment costs of all the firms with certainty. Although it is unlikely to

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[5] In Figure 1, $S_{ABCD} = \int_{e_i^0}^{e_i^{0\max}} MC_i^0(e)de + \int_0^{e_i^0} MD_i(e)de - \int_{e_i^I}^{e_i^{I\max}} MC_i^I(e)de - \int_0^{e_i^I} MD_i(e)de$.

be the case in practice, it is indispensable to the theoretical research. And we will have a discussion of information incompleteness in the next part.

Suppose the government announces a policy to regulate the pollutant and promises to hold its policy for long enough. After learning the regulator's setting of its policy, every firm decides whether or not to adopt clean technology. We use backward induction to find the equilibrium of this dynamic game. In other words, we first solve every firm's strategy and then the regulator's optimal policy-making.

3.1 Differentiated taxes

3.1.1 Stage two: firms' investment choices

For each firm, its investment decision depends on the comparison of the total costs it suffers in the cases of non-investment and investment:

$$TC_i = \min_{e_i^0, e_i^I}\left\{C_i^0(e_i^0) + \tau_i e_i^0, C_i^I(e_i^I) + \tau_i e_i^I + F_i\right\}(i = 1, \cdots, n) \tag{3}$$

where τ_i means the specific tax rate for firm i. Actually, the difference in the firms' tax rates stems from the different degrees of damages they cause. The total taxes that the firm needs to pay are the product of the tax rate and its emission level. The effective total cost for firm i, represented by TC_i, is obtained by taking the minimum value from the two cases:

(i) If $C_i^0(e_i^0) + \tau_i e_i^0 < C_i^I(e_i^I) + \tau_i e_i^I + F_i$, then $TC_i = \min_{e_i^0}[C_i^0(e_i^0) + \tau_i e_i^0]$. Firm i wouldn't adopt clean technology when it costs less in the case of non-investment. And:

$$\frac{\partial TC_i}{\partial e_i^0} = \frac{\partial C_i^0(e_i^0)}{\partial e_i^0} + \tau_i = 0$$
$$MC_i^0(e_i^0) = \tau_i \tag{4}$$

(ii) If $C_i^0(e_i^0) + \tau_i e_i^0 > C_i^I(e_i^I) + \tau_i e_i^I + F_i$, then $TC_i = \min_{e_i^I}\left[C_i^I(e_i^I) + \tau_i e_i^I + F_i\right]$. Firm i would adopt clean technology when it costs less in the case of investment. And:

$$\frac{\partial TC_i}{\partial e_i^I} = \frac{\partial C_i^I(e_i^I)}{\partial e_i^I} + \tau_i = 0$$
$$MC_i^I(e_i^I) = \tau_i \tag{5}$$

(iii) If $C_i^0(e_i^0) + \tau_i e_i^0 = C_i^I(e_i^I) + \tau_i e_i^I + F_i$, firm i would be indifferent about whether or not to adopt.

According to Eqs. (4) and (5), firm i's marginal abatement cost equals its specific tax rate in order to minimize its total cost. And the firm's emissions can be obtained once the tax rate is given. That is, $e_i^j(j = 0, I)$ can be expressed as

$e_i^j(\tau_i)$. Figure 2 rephrases the analysis intuitively and some results are obtained.

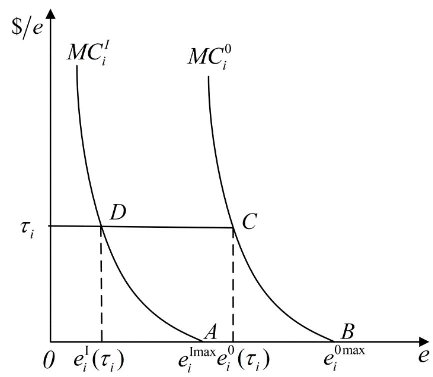

Figure 2: The investment choice of firm i under differentiated taxes

Given the tax rate, whether firm i would adopt clean technology relies on the comparison between F_i and the areas $S_{ABCD}(\tau_i)$.[6] It is obvious that $S_{ABCD}(\tau_i)$ gets larger strictly as τ_i increases. That is, the firm's investment incentives become stronger as its tax rate increases. And $S_{ABCD}(0)=0$. That is, the firm doesn't have any incentive to adopt clean technology under unregulated environment. Thus there exists only one tax rate $\tilde{\tau}_i$ so that $S_{ABCD}(\tilde{\tau}_i)=F_i$. That is, there exists only one tax rate that makes firm i be indifferent between investment and non-investment. And $F_i < S_{ABCD}(\tau_i)$ for $\tau_i > \tilde{\tau}_i$; $F_i > S_{ABCD}(\tau_i)$ for $\tau_i < \tilde{\tau}_i$. That is, firm i would invest in clean technology when its tax rate is greater than $\tilde{\tau}_i$; otherwise, it wouldn't.

3.1.2 Stage one: government's setting of tax rates

The regulator sets a specific tax rate for every firm, which is based on the total social cost minimization. Compared with the social optimum, the government needs to consider the firms' investment choices additionally when making its optimal strategy. In the following, we will depict in detail the government's setting of each firm's tax rate through Figure 3.

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[6] In Figure 2, $S_{ABCD}(\tau_i)=\int_{e_i^0(\tau_i)}^{e_i^{0\max}} C_i^0(e)de+\tau_i e_i^0(\tau_i)-\int_{e_i^I(\tau_i)}^{e_i^{I\max}} C_i^I(e)de-\tau_i e_i^I(\tau_i)$.

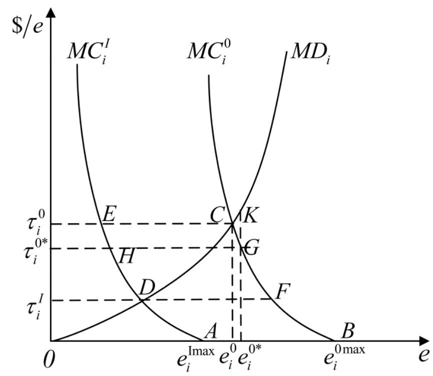

Figure 3: Government's setting of the specific tax rate for firm $i(i=1,\cdots,n)$

Before starting our analysis, we first clarify the notations in Figure 3. The corresponding tax rate is denoted by τ_i^0 (τ_i^I) when firm i's marginal abatement cost of old technology (clean technology) equals its marginal damage.

(i) If $F_i \geq S_{ABCD}$, firm i shouldn't adopt clean technology and its emission level is e_i^0 in the social optimum (see section 2.2). According to Eqs. (2) and (4), the regulator initially prefers to choose τ_i^0 as the firm's tax rate. But would firm i act as the social optimum for $\tau_i = \tau_i^0$? If not, how does the regulator set the specific tax rate for firm i?

(a) If $F_i \geq S_{ABCE}$, firm i would choose not to adopt clean technology when its tax rate is given as τ_i^0 (see section 3.1.1). It is in line with the social optimum. Thus the tax rate that the regulator sets for firm i is τ_i^0.

(b) If $S_{ABCD} \leq F_i < S_{ABCE}$, firm i would choose to adopt clean technology when its tax rate is given as τ_i^0 (see section 3.1.1). It is inconsistent with the social optimum. And it is obvious that the total social cost doesn't reach the minimum. The regulator needs to reconsider the setting of firm i's tax rate.

It can be demonstrated that the regulator will decrease the tax rate from τ_i^0 to the one that makes the firm just not invest. That is, the regulator lowers τ_i^0 until $S_{ABGH} = F_i$. The new tax rate is denoted by τ_i^{0*}. We briefly make an explanation. Compared to the social optimum, there is an extra part S_{CGK} for the social costs the firm contributes to when the tax rate is given as τ_i^{0*}. But importantly, the extra part S_{CGK} is the least compared with the regulator's other strategies.

It is of great economic significance. Due to the high fixed investment cost, the government sets a lower tax rate ($\tau_i^{0*} < \tau_i^0$) to stimulate the firm not to invest. And the firm's emission level is $e_i^{0*}(e_i^{0*} > e_i^0)$. That is, if environmental policy is less strict, not only the willingness to invest in clean technology becomes smaller, but also the firm emits more pollution.

(ii) If $F_i < S_{ABCD}$, a similar analysis is performed. If $F_i < S_{ABFD}$, the tax rate that the regulator sets for firm i is τ_i^I and the firm would adopt clean technology; if

$S_{ABFD} \le F_i < S_{ABCD}$, the regulator sets a higher tax rate $\tau_i^{I*}(\tau_i^{I*} > \tau_i^I)$ to stimulate the firm to invest as the fixed investment cost is too low.
Based on the above analysis, we could deduce the result as follow:
Proposition 2 *Under differentiated taxes, the government's setting of the specific tax rate for firm* $i(i = 1,\cdots,n)$ *belongs to one of the following three types:*
Type 1: $\tau_i = \tau_i^0$ *for* $\tilde{\tau}_i \ge \tau_i^0$;
Type 2: $\tau_i = \tilde{\tau}_i$ *for* $\tau_i^I \le \tilde{\tau}_i < \tau_i^0$;
Type 3: $\tau_i = \tau_i^I$ *for* $\tilde{\tau}_i < \tau_i^I$.

Proof: With the above preparations, it can be seen that $\tau_i = \tau_i^0$ for $F_i \ge S_{ABCE}$. And $F_i \ge S_{ABCE}$ is established when and only when $\tilde{\tau}_i \ge \tau_i^0$. So the tax rate for firm i is τ_i^0 for $\tilde{\tau}_i \ge \tau_i^0$. Similarly, $\tau_i = \tau_i^I$ for $\tilde{\tau}_i < \tau_i^I$. Besides that, $\tau_i = \tau_i^{0*}$ for $S_{ABCD} \le F_i < S_{ABCE}$; $\tau_i = \tau_i^{I*}$ for $S_{ABFD} \le F_i < S_{ABCD}$. Actually, τ_i^{0*} or τ_i^{I*} is equivalent to $\tilde{\tau}_i$. And $S_{ABFD} \le F_i < S_{ABCE}$ is established when and only when $\tau_i^I \le \tilde{\tau}_i < \tau_i^0$. So the tax rate for firm i is $\tilde{\tau}_i$ for $\tau_i^I \le \tilde{\tau}_i < \tau_i^0$.
Briefly, the government's setting of firm i's tax rate depends on three important values: τ_i^0, τ_i^I and $\tilde{\tau}_i$. $\tau_i^0(\tau_i^I)$ means firm i's marginal abatement cost of old (clean) technology equals its marginal damage; $\tilde{\tau}_i$ means firm i is indifferent between investment and non-investment.[7] Consider a special case in which firm i's marginal damage is constant. And we can obtain $\tau_i^0 = \tau_i^I$. Thus firm i's tax rate is equal to its constant marginal damage, which is consistent with Fowlie and Muller (2013).
Let's make a conclusion of the game analysis. In equilibrium, a firm may act as what the regulator initially expects, which equates the firm's marginal damage to its marginal abatement cost; or else, the regulator sets a lower (higher) tax rate to stimulate the firm not to (to) adopt clean technology since the fixed investment cost is too high (low). And after solving all the participants' strategies, we summarize the firms' investment behaviors: firm $i(i = 1,\cdots,n)$ wouldn't invest in clean technology if $F_i \ge S_{ABCD} = \tilde{S}$; it would invest if $F_i < S_{ABCD} = \tilde{S}$. By comparing with Proposition 1, we obtain a satisfactory result as below:
Proposition 3 *Pollution regulation through differentiated taxes can lead to the socially optimal degree of clean technology adoption.*

3.2 Differentiated emissions trading
3.2.1 Stage two: firms' investment choices
It can be seen that under differentiated taxes, every firm only needs to consider its own investment decision regardless of the others' once its specific tax rate has

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[7] In fact, we implicitly assume a firm chooses to be green of investment behavior that makes its social cost lower if it is indifferent between investment and non-investment.

been given. However, a firm's decision is influenced by the others under differentiated emissions trading, because the others' investment decisions significantly affect the market price of permits. At the early stage, the price of permits is higher, since fewer firms have invested and the market demand of permits is larger. All the firms know this information and think it is unwise to act first. So we assume that all the firms make their decisions at the same time. Or, they make the investment decisions independently and buy (sell) permits in the market simultaneously. Similarly, a firm's objective function is expressed as below:

$$TC_i = \min_{e_i^0, e_i^I}\{C_i^0(e_i^0) + p(r_i e_i^0 - w_i), C_i^I(e_i^I) + p(r_i e_i^I - w_i) + F_i\}(i = 1, \cdots, n) \tag{6}$$

In the above, r_i denotes the specific trading ratio for firm i. By definition, firm i needs to hold $r_i e_i$ units of permits when its emission level is e_i. In fact, the trading ratios dominate the exchange of emissions. p denotes the market price of permits. w_i denotes the initial endowment of permits for firm i. And $\sum w_i \le W$, where W means the total permit supply. So $p(r_i e_i - w_i)$ means the costs firm i needs to pay in the permit market. It can be negative as well, which means the revenue firm i receives through selling its excess permits. Moreover, if the market is clearing, we can get such equation:

$$W = \sum_{i=1}^{n} r_i e_i \tag{7}$$

Similar to section 3.1.1, firm i's investment choice depends on the comparison between F_i and σ_i, where σ_i means the firm's savings in the variable costs when switching from old to clean technology.

$$\sigma_i = C_i^0(e_i^0) + p(r_i e_i^0 - w_i) - C_i^I(e_i^I) - p(r_i e_i^I - w_i) = C_i^0(e_i^0) + p_i e_i^0 - C_i^I(e_i^I) - p_i e_i^I \tag{8}$$

where p_i identically equal $r_i p$, which can be regarded as the price of per unit of pollution emissions from firm i. In essence, p_i and τ_i are the same. Thus we can solve the firms' strategies through the same analysis as differentiated taxes, and will not elaborate it again here.

3.2.2 Stage one: government's setting of trading ratios and total permit supply

Given every firm's strategy, the government selects the trading ratios and total permits to minimize the total social costs. And according to Eq. (7), the total permit supply can be obtained based on all the firms' trading ratios and emissions expected by the regulator. In the following, we solve the regulator's optimal strategy through Figure 4.

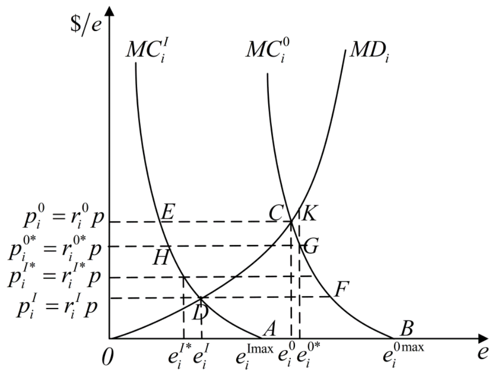

Figure 4: Government's setting of the specific trading ratio for firm $i(i=1,\cdots,n)$

In essence, there is no difference between Figure 4 and Figure 3. And the analysis here is similar with section 3.1.2. Nevertheless, we should notice that r_i and p are considered as a whole in the analysis. So in equilibrium, r_i and p could have a variety of possibilities as long as p_i satisfies certain value. In order to highlight the uniqueness, we construct each firm's trading ratio as $r_i = \dfrac{p_i}{(p_1 + \cdots p_n)/n}$. Then the equilibrium price of permits can be obtained: $p = p_1/r_1 = p_2/r_2 = \cdots = p_n/r_n$. Moreover, the aggregate permits can be obtained: $W = \sum_{i=1}^{n} r_i e_i$, where $e_i = e_i^0(e_i^{0*})$ for $r_i = r_i^0(r_i^{0*})$ and $e_i = e_i^I(e_i^{I*})$ for $r_i = r_i^I(r_i^{I*})$.

And similar to section 3.1.2, we obtain the following results:

Proposition 4 *Under differentiated emissions trading, the government's setting of the specific trading ratio for firm* $i(i=1,\cdots,n)$ *belongs to one of the following three types:*

Type 1: $r_i = r_i^0$ *for* $\tilde{p}_i \ge p_i^0$;

Type 2: $r_i = \tilde{r}_i$ *for* $p_i^I \le \tilde{p}_i < p_i^0$;

Type 3: $r_i = r_i^I$ *for* $\tilde{p}_i < p_i^I$.

And the total permit supply of the market set by the government is: $W = \sum_{i=1}^{n} r_i e_i$.

In type 2, $\tilde{r}_i$ is obtained on the basis of $p_i = \tilde{p}_i$. It is r_i^{0*} or r_i^{I*} in our analysis. Consider that all the firms' marginal damages are constant, i.e., $MD_i(e_i) = \delta_i (i=1,\cdots,n)$. So it is obvious that $p_i = \delta_i$. And it becomes easy to get the trading ratios: $r_i = \dfrac{\delta_i}{(\delta_1 + \cdots + \delta_n)/n}$. At this point, the setting of the trading ratios is independent of the firms' abatement cost functions.

Proposition 5 *Pollution regulation through differentiated emissions trading can* *lead to the socially optimal degree of clean technology adoption.*

3.3 High-damage firms vs. low-damage firms

Compared with the existed policies, differentiated policies make firms' investment incentives rely on their own damages additionally. In order to explore the particular character deeply, the investment incentives of high-damage and low-damage firms are comparatively analyzed (see Figure 5).

Without loss of generality, we consider two firms that just differ in the damages they cause. To be specific, we assume $MC_h^j(e) = MC_l^j(e)(j = 0, I)$ and $F_h = F_l$, while $MD_h(e) > MD_l(e)(e > 0)$. Pollution emissions from firm h cause higher damages than firm l. According to section 3.1 and 3.2, if $F_h = F_l \geq S_{ABEF}$, neither firm h nor firm l would adopt clean technology under any differentiated policy; if $S_{ABCD} \leq F_h = F_l < S_{ABEF}$, firm h would adopt clean technology, while firm l wouldn't; if $F_h = F_l < S_{ABCD}$, both of them would adopt.

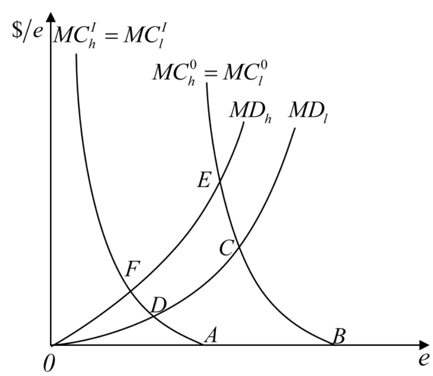

Figure 5: High-damage and low-damage firms' investment incentives under differentiated policies

Proposition 6 *All other conditions being equal, differentiated policies provide greater incentives for a high-damage firm to adopt clean technology than a low-damage firm.*

This result is exactly what we would like to see: differentiated policies can preferentially stimulate high-damage firms to invest. However, undifferentiated policies would make the two firms have the same investment incentives regardless of the difference in their damages. Thus, differentiated policies facilitate high-damage firms to invest in clean technology better than undifferentiated policies. The comparative advantage of differentiated policies is further expanded.

4 Extensions

In this part, the assumptions that the firms' abatement costs of both technologies and the damages caused by each firm are known by the government are relaxed. In real life, the regulator may not anticipate the arrival of clean technology when its policy is being designed, since the commitment period of a policy is usually extremely long. For example, the third phase of the EU emissions trading system starts from 2013 and ends at 2020, which is independent of technological development. And besides, the estimation of marginal damage parameters still remains highly uncertain even in the most advanced integrated assessment model. Based on these facts, we extend our simple model. In Section 3, we have shown under perfect information, differentiated policies lead to the socially optimal degree of adoption. Using the social optimum or the case of perfect information as a baseline, how about this section?

4.1 Adoption incentives under formerly optimal policy commitment

We begin with a discussion of differentiated taxes. From Figure 3, it can be seen that if the regulator sets the tax rates optimally without anticipating clean technology, the specific tax rate for firm $i(i=1,\cdots,n)$ is τ_i^0. Then firm i would adopt clean technology if and only if $F_i < S_{ABCE}$. But under complete information, firm i makes no investment in clean technology for $S_{ABCD} \le F_i < S_{ABCE}$. By comparison, this case leads to overinvestment. The intuition behind it is easy to be understood. Under perfect information, if $F_i < S_{ABCE}$, the regulator's setting of firm i's tax rate belongs to τ_i^I or $\tilde{\tau}_i$ and we know $\tau_i^I \le \tilde{\tau}_i < \tau_i^0$. That is to say, every firm's optimal tax rate here is higher than that under complete information. In a word, overinvestment is caused by the higher tax rate which is optimal for the regulator to set in this case.

Additional insights on differentiated taxes can be obtained from constant marginal damages. According to Proposition 2, the condition that the firms' marginal damages are constant makes the setting of tax rates independent of the abatement cost functions. Then the firms' optimal strategies here are consistent with that under complete information.

With respect to differentiated emissions trading, it is complicated to analyze the issue. Compared to the case of complete information, both overinvestment and underinvestment are possible. This is because the trend of some firms' trading ratios may rise and the others' may fall, although every firm may have a higher value of p_i which is essentially equal to τ_i.[8] And on the other hand, the trend change of the market's total permit supply is also uncertain.[9] Based on these two

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[8] A higher value of p_i doesn't mean firm i's trading ratio always increases, since $r_i = \dfrac{p_i}{(p_1+\cdots+p_n)/n}$ which states r_i also depends on $p_j(j \ne i)$.

[9] The regulator sets the market's total permits as $W=\sum_{i=1}^{n} r_i e_i$, where e_i means firm i's emissions

channels of uncertainty, it is difficult to tell whether the market price of permits here is higher or lower than that under perfect information, let alone the adoption of clean technology.

If the firms' marginal damages are constant, the above analysis becomes easy. According to Proposition 4, the setting of the firms' trading ratios is only relevant to the constant marginal damages. So even though clean technology isn't available, every firm's trading ratio set by the regulator is the same with that in the case of complete information. On the other side, the regulator sets a higher ceiling of the aggregate permits, which leads to a lower market price of permits.[10] Thus it induces underinvestment since the firms here may prefer to buy permits in the market rather than invest in clean technology.

Thus we obtain the following result:

Proposition 7 *If the government makes its policy optimally without anticipating clean technology, pollution regulation through differentiated taxes may lead to overinvestment, while differentiated emissions trading may lead to either overinvestment or underinvestment. For a further discussion in which all the firms' marginal damages are constant, differentiated taxes could still lead to the socially optimal adoption of clean technology, while differentiated emissions trading may lead to underinvestment.*

Requate and Unold (2001, 2003) show undifferentiated taxes may lead to overinvestment because of high tax rate, and undifferentiated emissions trading may lead to underinvestment. Actually, every firm's trading ratio can be regarded to be fixed to one under undifferentiated emissions trading. As well, the trading ratios are fixed in the case of constant marginal damages under differentiated emissions trading. They both only involve the change of the aggregate permits. So the results in the two emissions trading policies are the same.

By comparison, differentiated policies here don't perform better than the undifferentiated ones. Nevertheless, consider the special case where the firms' marginal damages are constant, and we obtain differentiated tax policy is superior to the other market-based policies. In fact, the result of constant marginal damages has been reported in many literatures. For example, Muller and Mendelsohn (2009) calculated the marginal damages of six pollutants from nearly 10000 sources in America. And they stated the marginal damage of a single pollutant from a single source is constant. At this point, the government prefers differentiated taxes to

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expected by the regulator. And the trend changes of e_i's are similar to r_i's, in which some may rise and the others may fall.

[10] With non-anticipation of clean technology, the regulator thinks the emission level of firm $i(i=1,\cdots,n)$ is e_i^0 which satisfies $MC_i^0(e_i^0)=MD_i$. And the regulator completely ignores the possibility of $e_i^I(e_i^I<e_i^0)$ which satisfies $MC_i^I(e_i^I)=MD_i$. Thus the aggregate permits ceiling is set as $W=\sum_{i=1}^{n} r_i e_i^0$.

regulate pollution.

4.2 Adoption incentives with damage uncertainty

For simplicity without affecting the relevant result, we construct a simple two-firm model in which these two firms have the same abatement cost functions and fixed investment costs, but they differ in the constant marginal damages. We assume that $D_i(e_i) = \delta_i e_i (i = h,l)$, and $\delta_h > \delta_l > 0$. However, the regulator is uncertain about δ_i ex ante and only knows their joint density function $f(\delta_h, \delta_l)$.[11]

We start by discussing taxes. In order to minimize the expected total social cost, the regulator's setting of firm i's tax rate under differentiated taxes is $\tau_i = E[\delta_i]$ and the single tax rate under undifferentiated taxes is set as $\tau = E[\frac{\delta_h + \delta_l}{2}]$.[12] And if the true damage parameter of each firm is greater than the expected, differentiated taxes may lead to underinvestment in these two firms. In contrast, undifferentiated taxes may lead to underinvestment in firm h and overinvestment in firm l, or underinvestment in both firms. If the true damage parameter of each firm is smaller than the expected, differentiated taxes may lead to overinvestment of the two firms, while undifferentiated taxes may lead to underinvestment of firm h and overinvestment of firm l, or overinvestment of both firms. If the true damage parameter of one firm is greater than the expected and the other's is smaller than the expected, similar discussions could be performed. In short, both differentiated taxes and undifferentiated taxes may induce underinvestment or overinvestment, which ascribes to the difference between the true damage parameter and the expected.

Now consider the emissions trading programs. Under differentiated emissions trading, firm i's trading ratio is set to be $r_i = \frac{E[\delta_i]}{(E[\delta_h] + E[\delta_l])/2}$. And the price of per unit of pollution emissions from firm i, i.e. p_i, is equal to $E[\delta_i]$ which amounts to τ_i. Under undifferentiated emissions trading, the market price of permits, i.e. p, is equal to $E[\frac{\delta_h + \delta_l}{2}]$ which amounts to τ. Thus the discussion about the incentives created by the emissions trading programs for technology adoption can be translated into a discussion in the case of tax policies. And both overinvestment and underinvestment are possible.

Thus we could obtain the following result:

Proposition 8 *If the government is uncertain about firm-specific damages, both differentiated taxes and differentiated emissions trading may lead to either overinvestment or underinvestment.*

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[11] Accordingly, we obtain the expected marginal damage of firm i as $E[\delta_i] = \iint \delta_i f(\delta_h, \delta_l) d\delta_h d\delta_l$.

[12] The result is obtained through backward induction.

When studying the above result, we make a strongly specific assumption about the firms' damages. For more generalized damage functions, it is obvious that the result still holds. Realistically, the elimination of the uncertainty comes with a high cost. Thus, damage uncertainty may prevent differentiated policies from performing better than the extant market-based policies.

Furthermore, if the expected ranking of marginal damage parameters is the reverse of the true one, differentiated policies would be reduced to absolute inferiority. More specifically, if the regulator designs its policy based on the expectation that $E[\delta_h] < E[\delta_l]$, firm l would have greater investment incentives than firm h. In other words, differentiated policies preferentially promote the low-damage firm to invest. This is not conducive to environmental protection.

Differentiated policies may be not desirable to regulate pollution nowadays due to the lack of information. However, we shouldn't deny the advantages of differentiated policies which have been analyzed in section 3. And along with the increase of public environmental protection awareness, people would like to evaluate pollution damages with higher monetary value. Differentiated emissions penalty becomes increasingly necessary. Thus, what should also be done is to improve the accuracy of all parameters as much as possible, especially damage parameters, at appropriate cost.

5 Conclusions

This paper compares the performance of market-based environmental policies through clean technology adoption, when damages vary across firms. We focus on differentiated policies including differentiated taxes and differentiated emissions trading, which are designed to take spatially variant damages into account. Using the social optimum as a baseline, differentiated policies perform better than the existing policies under certain conditions. Once information incompleteness or uncertainty is built into the model, the advantage created by policy differentiation in clean technology adoption becomes ambiguous.

More specifically, game theory is used to analyze the incentives provided by differentiated policies for clean technology adoption. In equilibrium, a firm may act as what the regulator initially expects, which equates the firm's marginal damage to its marginal abatement cost; or else, the regulator sets a lower (higher) tax rate or trading ratio to stimulate the firm not to (to) adopt clean technology since the fixed investment cost is too high (low). This provides a foundation for our further research. We find the degree of clean technology adoption in equilibrium is socially optimal. Moreover, differentiated regulations can give greater incentives for high-damage firms to invest in clean technology.

Practical consideration concerns information constraints that extend our baseline model. We consider incomplete information about abatement costs and uncertainty about firm-specific damages. It turns out that differentiated policies may lead to either overinvestment or underinvestment. Compared to the existed market-based policies, differentiated designs show no advantages in technology adoption. However, when all the firms' marginal damages are constant, differentiated taxes could still induce the socially optimal adoption even with incompleteness about abatement costs. This is because the specific tax rate for each firm is set equal to its constant marginal damage, which is independent of firms' abatement cost functions.

Differentiated policies indeed promote the evolution of market-based pollution regulations, but just in certain conditions. For the case of constant marginal damages which have been reported in many literatures, differentiated tax policy is superior to the other market-based policies under the incomplete abatement cost information. Besides that, our findings demonstrate the importance of information constraints in determining the adoption consequences of differentiated designs. Particularly, the government should improve the quality of marginal damage estimates as much as possible. These theoretical results can give governments useful insights to regulate pollution. And they provide important implications for future empirical research.

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