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# Implementing Optimal Rewards for Economic Regulation using Tradable Share Permits

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## Abstract

This paper presents a simple system for efficient regulation under asymmetric information. Each firm's income is controlled by a tax that depends on the firm's own output and on a parameter construed as a share permit. These "shares of total expected output" lower a firm's tax burden and are acquired in a competitive market. By employing this scheme, the planner only requires knowledge of marginal damage to induce the first-best outcome. Relative to a traditional cap-and-trade approach the system increases expected social welfare. If incentives for strategic behavior in the market exist, their impact may be scaled down.

*Keywords:* Asymmetric information; Taxation; Tradable permits;

*JEL classification:* Q58, H41, D82

## 1 Introduction

As a planning instrument, *price controls* had been considered superior to *quantity regulation* for decades until the publication of Weitzman's (1974) article, "Prices vs. Quantities." The prevailing view among economists today is that either instrument may prove superior over the other. In most cases, however, when information is held asymmetrically, both of these single modes of control fail to attain the optimal outcome. To obtain such efficiency, a scheme combining tax and quantity regulation might be used. A scheme in that line is proposed by Weitzman (1978). In his "Optimal Rewards for Economic Regulation" model, he uses a quadratic function to penalize each firm for deviating from a prescribed individual quota target. Because this penalty function does not induce a strictly monotonic demand for quotas, however, quota holdings cannot be subject to voluntary exchanges between firms. The fact that each optimal quota value must therefore be explicitly determined by the planner levies a rather heavy informational burden on him/her.

In this article, we fill a gap in the theory of regulation by introducing a hybrid system of taxation and tradable share permits. This system differs

from Weitzman's (1978) original model by the argument of the marginal tax function facing each firm.<sup>1</sup> While he uses a difference ( $e_i - q_i$ ) where  $e_i$  is a firm  $i$ 's emissions and  $q_i$  its quota target, we plug in a quotient ( $e_i/s_i$ ) where  $s_i$  is a share permit parameter. This distinction implies that we are able to reduce the planner's information needs. Operating with a share parameter, interpreted as the expected emissions of the firm divided by the total expected emissions of the industry, lessens the planner's informational burden because he/she is not required to form any expectation at all regarding total emissions in absolute quantity terms. And because the tax becomes a strictly decreasing function of the individual share permit holding, the shares we define are tradable. Hence, by employing a market for share permits the planner may also avoid having to estimate an efficient distribution of shares.

All in all, when the planner is able to perfectly observe emissions and share permit holdings at the firm level, he/she must only be aware of the marginal damage to be able to implement our hybrid system of taxation and tradable share permits. Competitive behavior in the permit market will then ensure an *ex post* optimal distribution of share permits. As in Weitzman's (1978) scheme, each firm will then face a tax schedule that internalizes the damage it causes and the firm will therefore also select the emission level that makes its outcome *ex post* efficient. In this equilibrium, the amount that each firm is willing to allocate for permits *and* the amount that it pays for its emissions add up to the total amount the company would spend when facing a full information Pigouvian unit tax.

Roberts and Spence's (1976) mixed system of tradable quantities and linear taxation may also achieve *ex post* efficiency when information is limited to marginal damage. However, because the planner must rely on linear tax segments to approximate the damage function, he/she must employ a multiple of these segments to accurately emulate the damage function. This appears difficult from a practical standpoint because it requires that the planner issues a continuum of license types that would each clear at different prices.

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<sup>1</sup>Weitzman also assumes that the damage a firm imposes on the environment by discharging emissions is independent of the damage caused by other firms. We, on the other hand, follow the standard approach that the industry creates environmental damages that, in monetary terms, are a strictly convex function of the sum of emissions across firms.

Alternatively, each type of permit could be rented at various prices (Collinge and Oates, 1982), or a menu of options could be issued (Unold and Requate, 2001).<sup>2</sup>

Compared to the alternatives mentioned above, the scheme we propose is unique in that it uses a traditional market mechanism to achieve the *ex post* efficiency goal. Arguably, such an exchange market is easier to use in practice. As is customary, that market is continuously open for trades, there is only a single type of license, and the supply of licenses is fixed.

A fixed supply of permits does not always ensure competitive behavior. As Hahn (1984) and Westskog (1996) show for the case of a traditional permit market, welfare losses may accrue due to the strategic behavior of dominating firms. Comparably, however, it turns out that our modification may reduce the ability of the big polluters to exercise market power.

Some of the mechanisms proposed in the literature (e.g. Dasgupta et al., 1980; Montero, 2008) have the advantage of being able to implement an efficient allocation of permits in dominant strategies. On the other hand, such strategy-proof mechanisms belong to a category of designs that can be applied solely at discrete points in time where at each instant the planner has to communicate with firms. These methods are certainly suitable for implementing an initial allocation of permits, but they might be costly if they were to be used repeatedly.<sup>3</sup>

Section 2 is the main section of this paper. It spells out in detail the scheme we propose under the assumption of optimizing and price taking behavior on the part of all firms. The two next sections are dedicated to a comparison of the system with the traditional cap-and-trade approach. Section 3 focuses on the implications for social welfare, while Section 4 focuses on the efficiency of the system if some firms are allowed to behave strategically in the permit market. Before the last section concludes, it presents a

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<sup>2</sup>Some other approaches to the same end require each firm to have complete information on certain (static or dynamic) Nash equilibrium outcomes. In the scheme suggested by Kim and Chang (1993) it pertains to the sum of emissions across other firms, in Duggan and Roberts' (2002) proposal it pertains to the emission of the firm's "neighbor", while in Varian's (1994) scheme it concerns the Pigovian tax level.

<sup>3</sup>Strategy-proof methods can be wasteful because the process of gathering and handling information when there are many agents in practice can be very resource intensive.

discussion of the mechanism and outlines an application to greenhouse gas mitigation policies.

## 2 Mixing fees and share permits

There is a finite number  $n$  of firms, each of which emits a homogeneous pollutant into (local or global) commons. We assume that each firm is an entity that maximizes profits by being well-informed about the data pertaining directly to itself. In the absence of regulation, company  $i$  ( $= 1, \dots, n$ ) has benefits  $B_i^0$  of discharging emissions  $e_i^0 \geq 0$ . When firms are subject to control, each firm  $i$  reduces emission to  $0 \leq e_i \leq e_i^0$ . The remaining private gross benefits are then given by the function  $B_i(e_i)$  which satisfies  $B_i(e_i^0) = B_i^0$ ,  $B_i'(e_i) > 0$  and  $B_i''(e_i) < 0$ , and furthermore, Inada conditions  $B_i'(0) = \infty$  and  $B_i'(\infty) = 0$ .<sup>4</sup>

We write  $e := \sum e_i$  as shorthand for the aggregate emission level. Let aggregate economic damage caused by emissions as measured in monetary terms be given by the function  $D(e)$  where we assume that  $D(0) = 0$ ,  $D' > 0$  and  $D'' > 0$ .<sup>5</sup>

A full-information welfare optimum solves the problem

$$\max_{e_i \geq 0, \forall i} \sum B_i(e_i) - D\left(\sum e_i\right). \quad (1)$$

The necessary optimality condition for interior solutions is

$$B_i'(e_i) = D'(e) \quad (2)$$

for all  $i$ . Since the objective in problem (1) is strictly concave, condition (2) is also sufficient, and the optimum is unique.

Environmental regulation is performed by a benevolent central planner bestowed with the authority to implement an efficient enforcement system of

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<sup>4</sup>The Inada conditions are included for simplicity as they ensure interior solutions in some of the optimization problems that follows.

<sup>5</sup>The case in which  $D'' = 0$  is trivial. It is well known that the first-best optimum in this case is attained by a linear tax equal to  $D'$ .

his/her own design. In this endeavor, he/she must contend with only knowing the damage function  $D(\cdot)$ . Since each benefit function  $B_i(\cdot)$  represents private information, the planner will a priori only have a vague idea (or have no knowledge at all) about optimal emission levels. We posit, though, that he/she can perfectly observe each firm  $i$ 's discharge  $e_i$  in the aftermath.

We introduce an important part of our mechanism, a specific tax function, by looking at three increasingly weaker assumptions about the control position:

Case 1: The regulator's task would be relatively straightforward if only one firm were polluting. Then, by charging  $\int_0^e D'(x)dx = D(e)$  as a total indemnity, the company would internalize the damage it creates and voluntarily choose the optimal emission.<sup>6</sup>

Case 2: If the planner, in the case of an industry with  $n$  equal firms, had simply charged each of them for their share of total damages  $1/nD(e)$ , the tax amount levied on each firm would have been dependent on the action of other firms. Consequently companies would have faced strategic concerns and thus played a game where the outcome would have been an inefficient Nash equilibrium. To avoid such behavior, each tax levied should depend solely on a firm's own emissions. Thus, in the " $n$  equal firms"-case, the solution is to let the regulator specify individual tax functions as  $\int_0^{e_i} D'(nx)dx = 1/nD(ne_i)$ . Noticing that equal  $e_i$ 's would assure  $e = ne_i$ , we can discern that firm  $i$  in this case would face the same tax rate  $D'(ne_i)$  as the regulated company in a one-polluter industry. As a result, optimal discharges would be realized.

Case 3: A broader interpretation can be conjectured. If the planner were in the possession of adequate information to perfectly foresee the relation between the *ex post* optimal emissions of firms, - the share  $1/n$  introduced above would be replaced by an optimal parameter  $s_i$  that the planner would be able to assign for each firm. That parameter should be interpreted as firm

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<sup>6</sup>This is proposed by Loeb and Magat (1979) in the context of regulating the output of a monopoly.

$i$ 's holding of *share permits*, or its allocated share of the total expected emissions of the industry<sup>7</sup>, of which there is a total of  $\sum s_i := 1$ . The individual tax function is now formulated as<sup>8</sup>

$$t_i = T(e_i, s_i) := \int_0^{e_i} D' \left( \frac{x}{s_i} \right) dx = s_i D \left( \frac{e_i}{s_i} \right) \quad (3)$$

where, as previously stated,  $e_i$  is the amount of pollutant emitted by firm  $i$ . This tax function - together with the optimal share distribution - would, as in the " $n$  equal firms" case, ensure a series of optimal choices within the industry.

As assumed in this paper, however, the planner knows nothing about the firms' benefit functions. Therefore, he/she cannot directly expedite an efficient share distribution. But the planner can circumvent the information problem. Recall that  $D' > 0$ . This implies that the rate of the tax (3) levied upon firm  $i$ ,  $\partial t_i / \partial e_i = D'(e_i/s_i)$ , increases with its argument  $e_i/s_i$  so that a higher  $s_i$  value for constant  $e_i$  means a lower marginal tax. Thus, a high  $s_i$  is worthwhile to the firm. We can then presume the following mechanism.

First of all, the tax function (3) that the planner will commit to is announced to the parties. Then an initial allocation of the fixed supply  $\sum s_i = 1$  of share certificates is effectuated, e.g., through an auction or they may be given away for free (grandfathering). Subsequently, exchanges may take place on a permit market. Firm  $i$ 's holding of  $s_i$  is verifiable from a central register at the moment the planner finally calculates the tax (3) on realized emissions.

In this two-stage sequential mechanism, in the second stage firm  $i$  chooses emissions according to

$$V_i(s_i) = \max_{e_i \geq 0} [B_i(e_i) - T(e_i, s_i)]. \quad (4)$$

where  $V_i(s_i)$  is the value of share holding  $s_i$ . The necessary optimality con-

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<sup>7</sup>A more formal definition of this parameter is presented in the next section.

<sup>8</sup>This tax function formulation is valid for  $s_i > 0$ . When  $s_i = 0$  and  $e_i = 0$  then  $t_i = T(0, 0) = 0$ , and when  $s_i = 0$  and  $e_i > 0$  then the tax  $t_i = T(0, e_i)$  should be set as high as possible.



dition for interior solutions to (4) using (3) is

$$B'_i(e_i) = D' \left( \frac{e_i}{s_i} \right) \quad (5)$$

which defines  $e_i = e_i(s_i)$ . Since the objective in problem (4) is strictly concave, condition (5) is also sufficient, and the optimum is unique.

Assume there are a sufficient number of firms, each small enough that it is a reasonable approximation to treat them as price-taking agents. In the first stage firm  $i$  trade shares in the market solving the decision problem<sup>9</sup>

$$\max_{s_i \geq 0} \{V_i(s_i) - \mu s_i\} \quad (6)$$

where  $\mu$  is the market-clearing price per unit of  $s_i$ . The necessary optimality condition for interior solutions<sup>10</sup> to (6) is  $\mu = V'_i(s_i)$ , which, by the Envelope Theorem applied to (4) using (3), is equal to

$$\mu = \frac{e_i}{s_i} D' \left( \frac{e_i}{s_i} \right) - D \left( \frac{e_i}{s_i} \right) \quad (7)$$

which is positive by the strict convexity of  $D$ . Since  $V''_i(s_i) = -D''(e_i/s_i) e_i^2/s_i^3 < 0$  it follows that the objective in problem (6) is strictly concave. Hence, condition (7) is both necessary and sufficient, and the optimum unique.

**Proposition 1** *Suppose the constraint  $\sum s_i = 1$  is perfectly enforced. Then, for all  $i$ ,  $s_i$  will be distributed among firms such that consistency is obtained. That is,*

$$e = \frac{e_i}{s_i} \text{ for all } i. \quad (8)$$

**Proof.** Let  $a_i := e_i/s_i$  (emissions per share). Equation (7) expresses  $\mu$

<sup>9</sup>We can ignore any specification of the initial allocation of permits because it is irrelevant for a competitive market (Montgomery, 1972).

<sup>10</sup>Inada conditions on  $B$  ensures an interior solution to (4), i.e.  $e_i > 0$ . Then  $s_i = 0$  can be ruled out as an optimal solution to (6) because in our case we assume that the tax  $t_i = T(e_i, 0)$  should be set as high as possible (see footnote 7).

by  $a_i$ . Note that

$$\frac{d\mu}{da_i} = a_i D''(a_i).$$

From  $D''(a_i) > 0$  it follows that price  $\mu$  is monotonically increasing with  $a_i$ . Because  $\mu$  is constant across firms, firms equate  $a_i = a$ . If shares sum to unity this implies  $a = e$ . The desired assertion follows. ■

Equation (7) is the inverse demand function for share permits for firm  $i$ . The demand depends on its emission and consistency (8) implies that in equilibrium no firm buys more share permits than it needs. The result (8) also implies that (2) is equivalent to (5) for all  $i$ . This entails

**Proposition 2** *The tax rule (3) and the enforcement of  $\sum s_i = 1$ , yields a socially optimal level of pollution for all  $i$ .*

Note that consistency (8) also implies

$$\mu = eD'(e) - D(e) \tag{9}$$

wherefrom follows

**Proposition 3** *For each firm, the fee (3) plus expenses for  $s_i$  is equal to*

$$T(e_i, s_i) + \mu s_i = D'(e) e_i. \tag{10}$$

*This sum matches the tax that each firm would pay facing the full-information Pigouvian unit tax  $\tau := D'(e)$ .*

As illustrated in Figure 1, if competitive firms demand rights to pollute according to the inverse demand function  $P(e)$ , they end up paying  $\mu + D(e)$  for pollution  $e$ ; they pay  $\mu$  in shares (the area above the  $D'(e)$  curve) and  $D(e)$  in taxes (the area below the  $D'(e)$  curve). So what the planner does by employing the mechanism is to create a perfectly competitive market on the supply side. The supply of emission permits is as if it were coming from competitive suppliers with marginal production cost  $D'(e)$ . In this perfectly

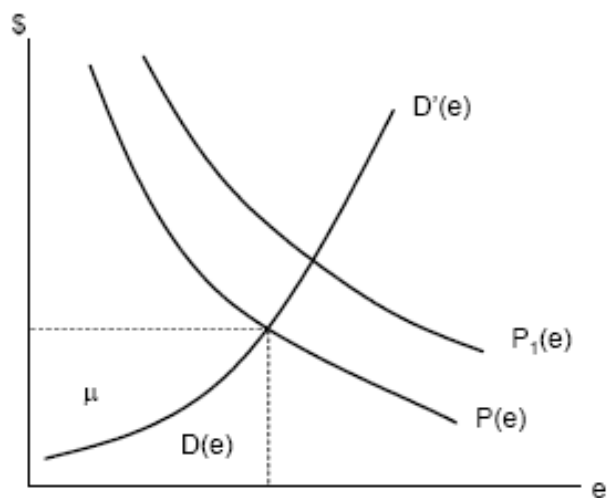


Figure 1:

competitive market consuming firms (i.e., consumers of rights) trade in the market along their true demand for emissions,  $P(e)$ , like in any other perfectly competitive market and not along any misreported demand curve like  $P_1(e)$  or something lower for that matter.<sup>11</sup>

### 3 Welfare effects

In order to compare welfare consequences for our suggested reform with traditional quantity regulation, we want to start with a setting in which initial allocations of permits are given free to firms. Then, both in a traditional cap-and-trade system and in the system we propose, subsequent financial transactions due to purchases and sales on the market can only flow between firms. Hence, for the planner, the regulatory budget with respect to the trade process is neutral for both systems. While under the traditional quantity system there are no further transactions going on,<sup>12</sup> our proposal in Section 2 stipulates that each firm will always pay a tax to the authorities for emissions. Comparing the systems might therefore be easier if our current

<sup>11</sup>The author is grateful to Juan-Pablo Montero for suggesting this interpretation.

<sup>12</sup>We assume then, of course, that all firms comply with their final permit holdings.

scheme is extended to incorporate a personal rebate.

First, let us be more specific about the share permit  $s_i$  held by firm  $i$ . It is defined as  $s_i := q_i/q$  where  $q_i$  is the quota holding of firm  $i$  and where  $q := \sum q_i$  is the total amount of quotas issued. The personal rebate we request should ensure that the payment (3) from firm  $i$  to the authorities is nullified when the firm happens to comply with its permit  $q_i$ . Such a rebate is equal to the amount determined by the tax function  $s_i D(e_i/s_i)$  when  $e_i = q_i$ . This sum

$$r_i = R(s_i; q) := s_i D(q) \quad (11)$$

is to be subtracted from firm  $i$ 's original payment (3) to the regulator. So, instead of the scheme in Section 2, which solely levies a tax on firms, the current regime now consists of deducting the individual positive or negative sum

$$f_i = F(e_i, s_i; q) := T(e_i, s_i) - R(s_i; q). \quad (12)$$

Because the rebate (11) is solely (and linearly) dependent on  $s_i$ , this merely causes an increase  $\partial r_i / \partial s_i = D(q)$  in the price of the share quota. Denoting this new price as  $\lambda$  the altered inverse demand function for share permits can be written as  $\lambda = \mu + D(q)$  where  $\mu$  is the "pure tax system" price given by equation (7). With the rebate being independent on  $e_i$ , it is easy to show that Proposition 1 still holds ground, and consequently, Proposition 2 does also. The corresponding Proposition 3, indicating that  $f_i + \lambda s_i = D'(e) e_i$ , is also true.

Propositions 1 and 2 are valid, of course, even if the subject of exchange is the permit itself  $q_i$  (rather than the share permit  $s_i = q_i/q$ ). The permit price is then given by  $p = \lambda/q$ , thus rendering the equation (10) of Proposition 3 in this case as  $f_i + pq_i = D'(e) e_i$ . If realizations in that latter case happen to be  $e_i = q_i$  for all  $i$ , the price  $p$  would be equal to the permit price that arises in a conventional cap-and-trade system with  $q$  as the total amount of quotas issued.

As mentioned above, when initial quotas are given free to firms in a cap-and-trade system, the regulatory budget thereafter is *null*. The total amount of quotas issued with optimal use of this traditional instrument would be the

quantity that maximizes expected welfare (Weitzman, 1974). This *ex ante* optimal quantity might also be a natural choice for a planner aiming to minimize the expected deviation between  $q$  and the realized outcome  $e = \sum e_i$  in our regime. But this choice of  $q$  in the rebated scheme, which will give the planner an anticipated distribution of total pollution around the expected value, will not be budget-neutral for him/her in the long run. The expected budget will be strictly positive simply because each firm's tax (the deducted amount (12) when  $f_i > 0$ ) for exceeding the quota  $q_i$  by a certain quantity is higher than the reward (the deducted amount when  $f_i < 0$ ) for emitting the quota less the same amount. So a switch to our *ex post* efficient rebated scheme (12) with grandfathering on average generates revenue for the regulator. Comparably this means an increase in expected social welfare.

That expected gain would of course also be present if, for instance, permits are initially allocated through an auction. Applying the "pure tax" regime of Section 2 would also make no difference in this respect. The rebate (11) is just a tool for the redistribution of welfare from the government to the industry. The planner may for instance want to transfer all the extra expected profit to the industry to avoid the prospect that firm owners and/or employees will oppose the implementation of the scheme (Buchanan and Tullock, 1975). The planner can then simply increase the grandfathered amount  $q$  to the level which leads to the expected budget-neutrality for the authorities.

## 4 Imperfect permit markets

The previous assumption that all firms exhibit price taking behavior in a market with a fixed supply may sometimes be a reasonable approximation, as in the case of controlling emissions in industries under the European Union Emission Trading Scheme (EU ETS).<sup>13</sup> The suggested implementation might,

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<sup>13</sup>"The EU ETS was launched on January 1, 2005 as a cornerstone of EU climate policy towards its Kyoto commitment and beyond. Through the EU ETS, Member States allocate part of the efforts towards their Kyoto targets to private sector emission sources (mostly utilities). Over 2008–12, emissions from mandated installations (about 40% of EU emissions) are capped on average at 6% below 2005 levels." Kossoy and Ambrosi (2010).

however, also be useful if firms were allowed to exercise market power. It is a fact that strategic behavior might lead to inefficiencies in any market with a uniform price. Nevertheless, given the same initial distribution of permits, losses due to market power can be lower with our system compared to the levels that for instance Hahn (1984) and Westskog (1996) predicts for the traditional cap-and-trade system. A simple argument supporting this view is that the competitive fringe of firms in our regime has the option to utilize the flexibility of the system for their own benefit. This option might be used in following way:

**Proposition 4** *If the price of share permits is higher (lower) than in competitive equilibrium, a rational price-taking firm will buy a lower (higher) amount of share permits than the amount that corresponds to the quantity it chooses to emit.*

**Proof.** For all firms, the condition (5)  $B'_i(e_i) = D'(e_i/s_i)$  implicitly defines the emission reaction function  $e_i(s_i)$ . Differentiation of this function with respect to  $s_i$  as well as manipulation to obtain the elasticity of  $e_i$  with respect to  $s_i$  yields

$$El_{s_i}(e_i) = \frac{s_i}{e_i} e'_i(s_i) = \frac{D''(e_i/s_i)}{D''(e_i/s_i) - s_i B''_i(e_i)}$$

Since  $D'' > 0$  and  $B''_i < 0$ , the elasticity  $El_{s_i}(e_i)$  is always less than one. Hence, the emissions level is relatively inelastic with respect to a change in the share permit holding. Because a competitive firm only buys more share permits than the amount that corresponds to what it emits when the price is lower than in competitive equilibrium and vice versa, the desired assertion follows. ■

As explained by Hahn (1984), a dominant buyer (seller) of permits in a traditional quantity system may find it profitable to understate (overstate) his demand in order to force down (up) the price of permits below (above) the competitive price. Relative to a conventional system that undertakes a one-to-one relationship between individual emissions and permits, a competitive fringe that behaves as predicted by Proposition 4 is less inclined to sell

share permits at low prices, as well as less inclined to buy share permits at high prices. The strategic firm anticipates this and will comparably lower its tendency to understate (overstate) demand in the first place. Hence, a dominant firm's manipulation efforts within our scheme can only be less successful.

## 5 Discussion and conclusion

This paper introduces a simple yet powerful tool for controlling a multiple-firm industry creating strictly convex damages. When individual emissions can be observed and the market for share permits is fully competitive, a regulator can induce the first-best optimum by merely knowing the marginal damage on the environment. Each firm can act devoid of problems with information and strategic choice. While taxation leads firms to internalize environmental costs, the market mechanism of the scheme ensures optimal distribution of damage payments.

Even though the tax function facing an individual firm is non-linear, its total payment equals that caused by the linear Pigouvian tax that would have been used by a planner having full knowledge of private benefits. The overall scheme can thus be construed as a linear tax regime in which firms themselves choose the optimal total emissions and thereby also the optimal linear tax level. An alternative interpretation is that the supply of permits is as if it were coming from competitive suppliers with marginal production cost equal to marginal damage.

In the case in which some firms have market power, we demonstrate that the proposed system might be more efficient compared to the traditional cap-and-trade system. This is due to the fact that small firms may find it more profitable to deviate from the quota-emission relationship, rather than being exploited by the manipulative tactics of big polluters. So importantly, the introduction of our scheme does not make possible new types of strategic firm behavior in the permit market. On the contrary, if incentives for such behavior exist, the impact of them may be scaled down.

When we in Section 3 introduce a rebate that depends on *ex ante* ex-

pected emissions, we show that our proposal may be regarded as a traditional cap-and-trade system that makes use of optimal rules for enforcement. The original concept of cap-and-trade is rapidly gaining acceptance worldwide as the main principle for handling externalities when information is imperfect and held asymmetrically. The idea has political appeal because, among other things, the binding commitment to not exceed a predetermined emission level provides an easily perceived *ex ante* measure of environmental progress. In practice, however, a strategy for enforcement has to be designed. Traditionally such enforcement consists of imposing a financial penalty on a firm that exceeds its quota holding. Under our assumption about perfect observations this fine should be equal to the damage caused by the offense (Polinsky and Shavell, 2000). But this is exactly what our rebated scheme prescribes. In addition we find that the optimal enforcement regime also implies that the planner should grant a reward to those firms that realize emissions below their targeted amount.

Compared side-by-side with a traditional cap-and-trade system where all firms comply, we show that a switch to a regime with optimal enforcement rules increases social welfare. Since the scheme uses shares of total expected discharges as the unit for trade on the market, the planner is not required to form any expectation at all about the outcome in absolute quantity terms. But as said, he/she may use that information to determine a rebate that together with grandfathering becomes a tool that redistributes gain from the authorities to the industry.

What we can say about the efficiency of the system differs only slightly in the case in which we allow for (independent) uncertainty about damage caused by the industry. The damage function we use throughout this article would then have to be replaced by a function of the expected damage caused by the total of realized emissions, and the outcome would be second-best efficient rather than first-best (Kaplow and Shavell, 2002)<sup>14</sup>.

One application of our system might be to tackle climate change. Due to the generic feature of greenhouse gases as stock pollutants it is often as-

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<sup>14</sup>Kaplow and Shavell (2002) investigate the case of regulating a one-firm industry with a non-linear tax.



sumed that the marginal damage curve is relatively flat in the relevant range of emission reductions. Then, in accordance with Weitzman (1974), price control is preferred to quantity regulation. In fact, simulations by Pilzer (2002) indicate that expected welfare gain may be *five times higher* with an optimal price policy than with its quantity policy counterpart. Despite this, and as already mentioned above, policy makers still tend to regard quantity regulation as more appealing. A rationale for such a choice might be based on two arguments. Firstly it seems to be an agreement between climate researchers that the probability of irreversible, abrupt and catastrophic damages as global temperature rises is nonnegligible. There is therefore a chance that the sum of a specific year's discharges of greenhouse gases into the atmosphere breaches the critical concentration threshold causing dramatically increased damages such as the loss of the Greenland ice sheet and the West Antarctic ice sheet (Notz, 2009). This corresponds to an expected damage function which is strictly convex and is smooth due to the uncertainty about the threshold level. So again in accordance with Weitzman (1974), to assume the presence of catastrophic events can reverse the preference for price control. Secondly plausible scenarios of statistical dependence between firms' marginal benefits and marginal damages consist to a greater extent of examples of positive rather than negative correlation (Stavins, 1996). And positive correlation may indeed tip the preference in favor of quantity controls (Weitzman, 1974).

A country which has ratified the Kyoto Protocol may give high priority to comply with the agreement by minimizing the difference between realized emissions and the targeted amount (Quirion, 2010). But this is precisely the goal that governs our optimal enforcement regime. Since polluters are often unable to control their emissions with any great degree of accuracy, a regime only imposing fines to firms that exceeding their quota amount may to a lesser degree be able to fulfill that goal.

Although our instrument is presented in the static context of limiting a homogeneous pollutant discharged by an industry with multiple firms, the scheme may apply equally well when marginal damage varies across space (Montgomery, 1972; Muller and Mendelson, 2009). It might be applicable to

other types of economic activities in need of regulation under the presence of asymmetric information including e.g. the “dual” problem of regulating effects of positive externalities. And our approach might be useful in a dynamic context, for instance as a tool for regulating catches in demersal fisheries (This Author, 2010).

With our proposal we advance Weitzman’s (1978) mechanism by introducing share permits that can be traded on a market. Our scheme’s flexibility might be invaluable for regulatory practice; moreover, it improves social welfare. Furthermore, the system has low information requirements while being as potentially easy to implement as a traditional cap-and-trade system. The latter argument is a unique feature of our *ex post* efficient implementation method.

None of the options suggested in the literature for implementing *ex post* efficient systems have to our knowledge been adapted for practical use. One reason for this gap perhaps can be traced to a common understanding that the proposed methods may result in "considerable administrative difficulties" (Myles, 1995). The scheme proposed in this paper hopefully reverses this conception.

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