TRADING FOR THE FUTURE
Signaling in Permit Markets[*]

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Abstract

Tradable permits are celebrated as a political instrument since they allow (i) firms to equalize marginal abatement costs through trade and (ii) the government to distribute the burden of the policy in a politically fair and feasible way. These two concerns, however, conflict in a dynamic setting. Anticipating that high-cost firms will receive more permits in the future, firms purchase excessive amounts of permits to signal high costs. This raises the price above marginal costs and distorts abatements. In fact, it is better with non-tradable permits if the heterogeneity between the firms is small, if the (shadow) price for permits is large, and if the government redistributes permits frequently.

Key words: Tradable permits, private information, signaling

1. Introduction

Pollution markets are becoming the most important instrument for solving our most important problem. In order to curb global climate change, in January, 2005, the European Union introduced the Emission Trading System (ETS) for carbon dioxide, the largest contributor to the greenhouse effect. ETS is a two-step procedure where, first, permits worth €38 billions annually were distributed to more than 12 thousand large point sources in 25 countries. Thereafter, the firms owning the permits are allowed to trade them at the ETS market. Permit markets have a longer history in the US, starting with the Clean Air Act in 1974, allowing trade in sulfur dioxide allowances in specific cases. Since then, the market for such permits have been enlarged in several steps (Hahn, 1989), allowing extensive trading after the 1990 Amendments. A regional market for nitrogen oxides emissions was created in 2003 and, in these days, several US states consider setting up an emission trading system for carbon dioxide, similar to the ETS (The Economist, 2006).

Tradable permits are celebrated as a political instrument. Traditional economic instruments, such as emission taxes, are often difficult to implement for political reasons: it may be judged unfair if firms that, in the past, had the right to pollute, loose this right over night. Or, firms may have political and bargaining power if they, for example, are able to relocate to a friendlier regulatory environment. For such reasons, policy-makers often hesitate introducing new taxes, relying instead on 'command-and-control' policies where emission quotas are distributed for free. Large polluters typically receive more quotas for free, since these would otherwise suffer the most from tough regulation. A system of tradable permits has been celebrated as a compromise, combining the efficiency properties of a market with the government's concern for redistribution.

These two concerns conflict in a dynamic setting, however. When the government frequently intervenes in the market, the firms trade accordingly. In particular: if firms that prove to have high costs of reducing pollution are given more permits in the future, the firms have an incentive to purchase more permits to signal such a high cost. The market for permits may then be distorted, and these distortions can be so large that prohibiting trade is actually better.

We present a simple multi-period model where, in each period, the government distributes permits and the firms trade.[1] The government is inclined to divide the burden evenly across the firms, implying that high-cost firms receive larger quotas than low-cost firms.[2] The government cannot commit to future policies, and it does not observe the firms' costs directly. However, the pattern of trade reveals some information, and the government updates its beliefs accordingly. Anticipating this, firms purchase more permits than what

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[1] A frequent reallocation of the permits is consistent with the ETS. The permits under the ETS are issued for a three year period (2005-2007), while the periods will be of five year length starting 2008. A frequent reallocation of the permits has been advocated to ensure flexibility: Noll (1982, p. 123) writes "reissuing permits...gives regulators continuing opportunities to adjust total emissions".

[2] There is ample evidence of governments distributing more pollution quotas to heavy polluters. In fact, under the 'National allocation plans' of the ETS, some nations give electric utilities more generous allowances if they use coal than if they use natural gas. Others apply standards based on best available technology (Zetterberg *et al.*, 2004). For implementing the Clear Air Act, Schmalensee *et al.* (1998, p. 54) states that "units are given fixed numbers of tradable permits...that depend primarily on historic emissions and fuel use". Such a procedure is advocated by Noll (1982).

they would find optimal in a static setting, thereby signaling their need for permits. This raises the permit price above marginal costs and the market ends up being distorted.

As this argument suggests, and the analysis below proves, the market for permits may be distorted. In fact, the distortions may be so large that a system of non-tradable permits is better, even though such a command-and-control policy fails to equalize marginal costs across the firms. To be specific: Prohibiting trade is better if the heterogeneity between the firms is small, the social loss of pollution is large, and if the government intervenes frequently in the market.[3]

Due to the short history of tradable permits in practice, there is not a lot of empirical material. Thus, many of the studies are based on experiments and simulations. These have suggested that the gains from trade are huge, with cost-savings that in some cases exceed 90 percent of the abatement costs compared to 'command-and-control' (Tietenberg, 1992. See also Carlson *et al.*, 2000; Burtraw *et al.*, 2005). However, compared with observed abatement, they find that only parts of the potential savings are realized. Our theory contributes to explain this puzzle. Moreover, our model is consistent with the large drop in price and trading volume in the ETS market late April, 2006 (Section 8 discusses some anecdotal evidence).

Normatively, our analysis issues a warning to the combination of trade and a frequent redistribution of free pollution permits. The warning is more important for the Europe's ETS, where every period is just a few years. In the American sulfur dioxide market, the distributed allowances last 30-45 years. Based on our model, the US market ought to be more efficient that the ETS.[4]

There is a large literature comparing policy instruments in public and environmental economics (for overviews, see Baumol and Oates, 1988; Cropper and Oates, 1992). Going back to Pigou (1920), economists have typically favoured emission taxes since they directly let the firms face the social cost of their emissions. Weitzman (1974) shows that whether quotas or taxes are best depends on the uncertainty and the slope of the cost curves,[5] but the choice is in practice typically determined by political considerations. Buchanan and Tullock (1975) observed that, from a political point of view, it is often more acceptable to distribute quotas for free, since these are viewed as less confiscatory.[6] Although restricting pollution is always costly to a firm, with free quotas the firm is not required to pay a tax in addition. Quotas, however, do not guarantee that the firms' marginal costs of cleaning are equalized. Dales' (1968) idea of making the permits tradable is viewed as a great compromise, combining the efficiency of markets with the concern for redistribution.

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[3]Thus, efficiency, as a function of the frequency of intervention, is U-shaped in our model: Frequent interventions make the market perform worse, down to the point at which it is better to abandon the market altogether.

[4]The US NO_x market is more similar to the ETS: permit distribution is delegated to the individual states and there are more examples of frequent updating.

[5]Technical standards, on the other hand, are never efficient unless accompanied by output taxes (Eskeland, 1994).

[6]This explanation is confirmed by the evidence. Discussing the Clean Air Act, Schmalensee *et al.* (1998, p. 56) write: "Allowances were given to utilities rather than sold because there was no way that a sales-based program could have passed Congress". Evaluating a possible carbon dioxide market in the US, Burtraw *et al.* (2005) state: "the primary justification for the free allocation of allowances is compensation for the adverse impacts of the cap-and-trade program on generators".

Since Dales, many public economists have viewed taxes and tradable permits as equivalent in terms of efficiency (see e.g. Tietenberg, 1992). We accept (and take as given) the government's incentive to distribute permits for free, and shows that this concern distorts the market, possibly making non-tradable permits better. This breaks the equivalence to an emission tax which, in our model, would implement the first-best.[7,8]

Just a few studies criticize pollution markets, and then typically by pointing to standard market failures. For example, a firm with market power would restrain its quota demands if being a buyer, but restrain its supply if being a seller (Hahn, 1984). The firms may also be able to collude and trade in a way which induces the government to issue a larger total number of permits in the future (Andersson, 1997). Moledina *et al.* (2003) observe that the firms may have incentives to raise the permit price to get more permits in the future, but they assume that there are few (two) firms, there is only aggregate uncertainty, and the government does not realize that firms are strategic. Our model, however, assumes a large number of firms and types that are firm-specific. The government is rational, but it cannot commit to future policies.[9]

The paper is organized as follows. The next section presents the static version of the model. This generates benchmark results to which we later can refer, and it makes it easy to introduce the dynamic model in Section 3. Section 4 derives the market equilibrium of the model, taking the policies as given, while equilibrium policies are derived in Section 5. Sections 4-5 assume that the permits are tradable, while Section 6 makes a comparison to non-tradable permits and derives conditions under which this is efficient. While our model is very simple, Section 7 argues that it is robust to several generalizations. The final section concludes and discusses some anecdotal evidence. The Appendix shows that distortionary signaling arise even under permit taxes, if some quotas are exempt from the tax.

2. The Static Version of the Model

The one-period version of the model is particularly simple. There is a large number of firms, approximated by a continuum of mass one. Each firm i decides how much to pollute, x_i, and its gross profit is given by

$$\pi_i = \theta_i x_i - x_i^2/2.$$

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[7]Some papers critisizes grandfathering since it distort pollution in advance (Fischer and Fox, 2006), complementing our focus on signaling.

[8]Our analysis thus strenghtens the arguments in favour of the 'polluter pays principle'. OECD's (1975) interpretation of this principle states that polluters should pay for their own pollution control, but it does not require that polluters pay for those remaining emissions that are within the allowed bounds of standards or quotas.

[9]Other weaknesses with tradable permit markets may be that (i) markets are not efficient unless permits can be traded (or banked) over time; (ii) quotas distributed on the basis of firms' outputs represent distorting subsidies (Burtraw *et al.* 2006); (iii) the environmental impact of emission may vary geographically (Montgomery, 1972). The latter argument is important for sulfur dioxide emission, requiring certain 'exchange rates' for permits to be traded efficiently across areas. This is not necessary for CO2 emission, leading Burtraw *et al.* (2005, p. 282) to conclude that "CO2 would seem a perfect pollutant for a uniform cap-and-trade program".
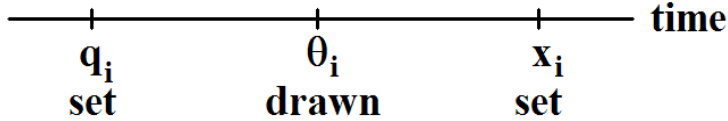
Figure 2.1: Timing of events

Thus, $\theta_i - x_i$ is firm i's marginal benefit of polluting or, equivalently, its marginal *cost* of *reducing* pollution. This marginal cost decreases in the amount of pollution and increases in the firm's type, θ_i. With no restrictions on x_i, firm i would set the marginal cost equal to zero:

$$x_i = \theta_i.$$

Clearly, a firm that has high cost of reducing emission (large θ_i) chooses to pollute more.

From a social point of view, it is valuable to reduce pollution further. Let the marginal value of reducing pollution be constant and equal to $v > 0$. The socially optimal solution maximizes $\pi_i - vx_i$,

$$\max_{x_i} \left(\theta_i x_i - x_i^2/2 - vx_i \right) \Rightarrow x_i^* = \theta_i - v. \tag{2.1}$$

We assume that a benevolent government distributes pollution permits for free. Distributing permits, or quotas, with the number $q_i = \theta_i - v$ would be first best.[10] The problem for the government is that θ_i is unknown. It only knows that $\theta_i \in \left\{ \underline{\theta}, \overline{\theta} \right\}$ and $\Pr\left(\theta_i = \underline{\theta} \right) = k_i \in (0,1)$. However, the government has two means of approaching (2.1): It may try to distribute the quotas according to all available information (the k_is), and the firms might be allowed to trade the permits after the initial distribution. In fact, one may disentangle the government's problem in three parts: (i) determining the total number of permits, (ii) their distribution across firms, and (iii) whether they should be tradable.

Together with the timing in Figure 2.1, the game is now easily solved by backward induction. Since the government is benevolent, equilibrium policies are also optimal. Parameters without subscript i represent the average and total value across the is, such that $q = \int_i q_i di$.[11]

Proposition 1. (i) *The equilibrium (and optimal) q is given by (2.2) whether the permits are tradable or not. For any q, however:*
(ii) *non-tradable permits are distributed according to (2.3);*
(iii) *for tradable permits, marginal costs are equalized across firms for any distribution of*

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[10]Throughout the paper, we assume that $x_i \leq q_i$ binds if there is no trade in permits, such that firms always want more quotas in equilibrium. In the static model, this requires that for any i, $\theta_i \geq \mathrm{E}\theta_i - v \Rightarrow v \geq (1 - k_i)\left(\overline{\theta} - \underline{\theta} \right)$.

[11]For such integrals to exist, we must assume that q_i is peacemal continuous in i. In equilibrium, it is always possible to order the is such that this is indeed the case.

the q_is, and the permit price is given by (2.4).

$$q = \theta - v \tag{2.2}$$
$$q_i = E\theta_i - (\theta - q) \tag{2.3}$$
$$p = \theta - q \tag{2.4}$$

Proof: (ii) Let λ be the Lagrange multiplier to the constraint $q = \int_i q_i di$.

$$\max_{q_i} E \int \left(\theta_i q_i - q_i^2/2 - vq_i\right) di \ \ \text{s.t.} \ \int q_i di = q \Rightarrow \tag{2.5}$$

$$E\theta_i - q_i - v = \lambda \Rightarrow \tag{2.6}$$
$$\int_i (E\theta_i - q_i - v) di = \theta - q - v = \lambda. \tag{2.7}$$

Substituting the second equation of (2.7) into (2.6) gives (2.3).
(iii) From each firm's maximization problem,

$$\theta_i - x_i = p \Rightarrow \tag{2.8}$$
$$\int_i (\theta_i - x_i) di = \theta - q = p.$$

(i) With trade, $q = \theta - v$ gives the first-best. Without trade, one might simply summarize the q_is from (2.6) without the constraint ($\lambda = 0$), or substitute the q_is from (2.3) into (2.5) and maximize over q. Both give (2.2). *QED*

When the permits are non-tradable, a firm should be given more quotas if its expected cost of cleaning is high. In fact, (2.3) requires a uniform emission-cut for all firms, compared to what they would be expected to pollute without restrictions. This is efficient, but it is *not* first-best since the government does not know the firms' actual costs. The expected cost of cleaning for firm i is different from its actual cost, $E\theta_i = k_i \underline{\theta} + (1 - k_i)\overline{\theta} \neq \theta_i \in \{\underline{\theta}, \overline{\theta}\}$.

By allowing for trade, however, high-cost firms can buy permits from low-cost firms, thereby minimizing total costs in equilibrium. Since there is a large number of firms, each firm take the permit price as given. The equilibrium with trade is thus first-best, and trade is always recommendable.

Notice that the initial distribution of the quotas, the q_is, have no impact on efficiency if the permits are tradable. Given q, the government is indifferent to how the quotas are distributed across the firms. Therefore, by adding just a mild preference for one distribution rather than another, this would be the actual outcome. Such preferences may exist, indeed. Consider the following possibilities:

a. Fairness: Suppose the government wants to allocate the burden of the policy evenly across firms.[12] Likely high-cost firms should then be given a larger q_i.

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[12] Hahn and Stavins (1992, p. 466) argue that beyond cost-effectiveness, "other legitimate criteria of success should be considered, principal among these being the relative distributional equity or fairness associated with specific policies".

b. Participation constraints: Suppose that, in the beginning of the period, firms can move to another country without the policy in place, and that the cost of moving is the same across firms. Firms with a low k_i are then more inclined to move, unless they receive a larger q_i.

c. Bargaining: Suppose the distribution of the quotas are decided in a bargaining game between the firms and the government, and let the Nash bargaining solution characterize the outcome. For example, each firm might be associated with "its own" political legislator or district, negotiating on its behalf. Negotiators representing likely high-cost firms are then less willing to agree unless they get a larger q_i.

d. Market failures: Suppose that the firms do not trade permits with probability $\epsilon > 0$, $\epsilon \to 0$.[13] Managers may be time-constrained or the mere transfer of permits could entail substantial transaction costs. Market power could lead to other market failures.

With such concerns, the distribution (2.3) is strictly preferred even when the permits can be traded:[14]

Proposition 2. *Suppose either a, b, c or d holds. The initial quotas are distributed according to (2.3), whatever q is.*

Proof: *a.* With no regulation, i's profit is simply $\theta_i^2/2$. With tradable permits, i's profit becomes (substitute (2.8) and rewrite):

$$\theta_i x_i - x_i^2/2 - p(x_i - q_i) = (\theta_i - p)^2/2 + pq_i. \tag{2.9}$$

The expected burden of the policy is the same across all is if the expected change in profit equals some constant κ:

$$
\begin{aligned}
\mathrm{E}\left(\theta_i^2/2 - (\theta_i - p)^2/2 - pq_i\right) &= \kappa \Rightarrow \\
\mathrm{E}\theta_i p - p^2/2 - pq_i &= \kappa \Rightarrow \tag{2.10}
\end{aligned}
$$

$$\int_i \left(\mathrm{E}\theta_i p - p^2/2 - pq_i\right) di = \theta p - p^2/2 - pq = \kappa. \tag{2.11}$$

Substituting (2.11) into (2.10) gives (2.3).
b. Suppose the moving cost is κ. Then, a firm does not move if the expected profit change $\mathrm{E}\theta_i p - p^2/2 - pq_i \le \kappa$. If this fails to hold for i, it must be given a larger q_i to stay. Then, some other firm j must receive a smaller q_j to keep q constant. If the inequality ends up binding for all firms, (2.10) must hold and so must therefore (2.3).
c. Suppose, for a moment, there is a finite number of firms, n, and these are bargaining before their types are realized. The Nash bargaining solution is given by maximizing the Nash Product, NP,

$$NP = \prod_i \left(\tilde{v} - \left[\mathrm{E}\theta_i p - p^2/2 - pq_i\right]\right) \text{ s.t. } \sum q_i/n = q,$$

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[13] "[M]any participants opted out of the market", Carlson *et al.* (2000, p. 1319) state when explaining why only parts of the potential cost savings are realized. Also Hahn and Stavins (1992, p. 465) write that "transaction costs in tradable permit markets can be substantial".

[14] Supporting high-cost firms by other means than giving them more permits would not change the results in this paper.

where $\widetilde{v}$ is each firm's benefit of the agreement (e.g. equal to the penalties it otherwise faces, or equal to vq/n if it is represented by a local legislator) and the term in the brackets is i's reduction in profit (from (2.10)). Letting λ be the Lagrange multiplier on the constraint $\sum q_i = qn$, the first-order conditions are:

$$\frac{p\left(\mathrm{E}\theta_i - q_i\right)}{\widetilde{v} - \left[\mathrm{E}\theta_i p - p^2/2 - pq_i\right]} NP = \lambda \Rightarrow$$

$$\mathrm{E}\theta_i p - p^2/2 - pq_i = \frac{\lambda\widetilde{v}/NP - p^2/2}{1 + \lambda/NP} = \kappa,$$

for some constant κ, independent of i. Again, this gives (2.10) which implies (2.3). Clearly, this holds also when $n \to \infty$.

d. For a given ϵ and q, the government solves:

$$\max_{q_i} \epsilon \mathrm{E} \int_i \left(\theta_i q_i - q_i^2/2 - vq_i\right) di + (1-\epsilon)\,\mathrm{E}\int_i \left((\theta_i - p)^2/2 + pq_i\right) di \ \text{s.t.} \ q = \int_i q_i di$$

where the last term is found by integrating (2.9). Since the distribution of the q_is only affect the first term, the problem is identical to (2.5), with solution (2.3). *QED*

3. The Dynamic Model

The dynamic model consists of an infinite number of periods, and everyone's discount factor is $\delta \in (0,1)$. The timing within each period is given by Figure 1, and the firms cannot store their permits from one period to the next (there is no "banking"). Firm types are partially persistent: for each firm i, its type in the next period is the same as that in the current period with probability $s \in (0,1)$. With probability $1-s$, however, the firm's type is drawn again and, then, $\Pr(\theta_i^+ = \underline{\theta}) = k$. Superscript "+" and "-" are, respectively, added to all parameters representing the next and the previous period (this way, we do not need subscripts for periods). It follows that firm i is low-cost with probability

$$k_i = \left\{ \begin{array}{l} s + (1-s)k \ \text{if} \ \theta_i^- = \underline{\theta} \\ (1-s)k \ \text{if} \ \theta_i^- = \overline{\theta} \end{array} \right\}. \tag{3.1}$$

The government cannot commit to future policies, and starts every period by distributing quotas to the firms. Even though the distribution of the q_is does not affect $\pi - vq$, the government may still be tempted to distribute more quotas to likely high-cost firms, just as argued for the static model. If so, q_i may be a function of $\mathrm{E}\theta_i$ and thus of $\mathrm{E}\theta_i^-$, written $q\left(\mathrm{E}\theta_i^-\right)$. Define $\underline{q} \equiv q\left(\underline{\theta}\right)$, $\overline{q} \equiv q\left(\overline{\theta}\right)$ and

$$\Delta \equiv \overline{q} - \underline{q}.$$

$\underline{q}$ and $\overline{q}$ are, respectively, the quotas distributed to firms that proved to be of low cost and high cost in the previous period. The arguments above suggest $q(.)$ to be a strictly increasing function, implying $\Delta > 0$.[15] For most of our results, we do not need to further

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[15] This is stronger than necessary: It is enough that $q(.)$ is weakly increasing. The proofs below require $\partial q(\mathrm{E}\theta_i^-)/\partial \mathrm{E}\theta_i^- > 0$ at $\mathrm{E}\theta_i^- = \overline{\theta}$, but the results would hold even if this were relaxed.

specify Δ, and we therefore abstain from formalizing the mechanism that could lead to $\Delta > 0$. This way, we keep the model general and consistent with several explanations and interpretations. For example, if one of the assumptions *a, b, c* or *d* hold, then Proposition 2 suggests that the initial distribution is given by (2.3).[16] Together with (3.1), (2.3) implies that:

$$
\begin{aligned}
\underline{q} &= q - s\left(\theta - \underline{\theta}\right) \\
\overline{q} &= q + s\left(\overline{\theta} - \theta\right) \\
\Delta &= s\left(\overline{\theta} - \underline{\theta}\right).
\end{aligned}
\tag{3.2}
$$

This is in line with Noll (1982, p. 122), suggesting that one "basis for the provisional allocation is the estimated competitive (cost-minimizing) allocation". Thus, at various stages below, we can refer to (3.2) to get additional results.

Games with infinite horizons often have a large number of equilibria, and we need refinements. In particular, we limit attention to Markov strategies, such that strategies only depend on the history through its effect on types and beliefs. This prevents, for example, a firm from threatening to buy a lot of permits (hurting itself and thus the government) whenever it does not receive a large quota. Furthermore, we restrict attention to sequential equilibria (Kreps and Wilson, 1982), implying that strategies are best responses after all histories, and that beliefs are consistent with Bayes' rule. Finally, we rule out equilibria that fail the Intuitive Criterion (Cho and Kreps, 1987). Roughly, this implies that if a firm pollutes $\overline{x}$, and this never can be optimal for a low-cost firm, then the government should conclude that the firm has high cost and, in the next period, it should receive the quota $\overline{q}$.

For the case of tradable permits, the next section solves the market equilibrium of the game, and the following section derives equilibrium and optimal policies. Section 6 makes a comparison to non-tradable permits, and specifies conditions under which this is better. While our model is very simple, Section 7 argues that the results continue to hold if the government receives exogenous signals about firm types; if the firms have observable differences in e.g. size; if the types are endogenous; and if we relax the equilibrium refinement.

4. The Market Equilibrium

In the static model, each firm sets its marginal cost of reducing pollution equal to the permit price, implying

$$x_i = \theta_i - p.$$

Observing x_i and p, the government learns firm i's type. If there were a next period, the government would then distribute $\underline{q}$ to low-cost firms and $\overline{q}$ to high-cost firms. Anticipating this, low-cost firms would be tempted to imitate the high-cost firms' strategy, particularly if $\Delta \equiv \overline{q} - \underline{q}$ were large.

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[16]In fact, if one of *a-d* holds and trade is (believed to be) efficient, then (2.3) is the optimal and equilibrium distribution for the same reasons as in Proposition 2. If trade is expected to be inefficient, as it might be in analysis below, then assumption *d* still implies (2.3) while assumptions *a-c* would make the optimal q_is somewhat more complex. In any case, $\Delta > 0$ would still hold.

This intuition is true also in the dynamic model. Since purchasing permits is more beneficial for high-cost firms, polluting signals cost.[17] And, since signaling a high cost may lead to more permits in the future, there is a greater value of polluting in a dynamic setting. A low-cost firm might also, naturally, be tempted to imitate high-cost firms to receive more permits in the next period. To signal its type credibly, therefore, a high-cost firm may have to pollute more than it would otherwise have preferred. We start by characterizing firms' behavior taking p, q and Δ as given.

Proposition 3. (i) *There is a unique equilibrium.*
(ii) *The emission levels are given by (4.1) for low-cost firms and (4.2) for high-cost firms.*
(iii) *The average marginal cost (4.3) is strictly less than the price if (4.4) holds.*

$$\underline{x} = \underline{\theta} - p \tag{4.1}$$

$$\overline{x} = \overline{\theta} - p + \max\left\{0, \sqrt{2\delta\Delta p^+} - (\overline{\theta} - \underline{\theta})\right\} \tag{4.2}$$

$$\theta - x = p - \max\left\{0, (1-k)\left[\sqrt{2\delta\Delta p^+} - (\overline{\theta} - \underline{\theta})\right]\right\} \tag{4.3}$$

$$(\overline{\theta} - \underline{\theta}) < \sqrt{2\delta\Delta p^+} \tag{4.4}$$

Proof: We first prove (ii). If the equilibrium is separating, a low-cost firm does not want to imitate high-cost firms and cannot get less than $\underline{q}$ in the next period. Thus, taking $\underline{q}$ as given:

$$\underline{x} = \arg\max_x \left(\underline{\theta}x - x^2/2 + p(q-x) + \delta\underline{q}p^+\right) = \underline{\theta} - p.$$

A high-cost firm pollutes $\overline{x}$. An equilibrium $(\underline{x}, \overline{x})$ fails the Intuitive Criterion if there exists another alternative x' which is worse for the low-cost firm (even if it should receive a quota $\overline{q}$ in the next period) but better for the high-cost firm if the government, after observing x', concludes that the firm has high cost. Thus, in a separating equilibrium, $\overline{x}$ must be given by:

$$\overline{x} = \arg\max_x \left(\overline{\theta}x - x^2/2 + p(q-x) + \delta\overline{q}p^+\right) \quad \text{s.t.}$$

$$\underline{\theta}x - x^2/2 + p(q-x) + \delta\Delta p^+ \leq \underline{\theta}\underline{x} - \underline{x}^2/2 + p(q-\underline{x}) \tag{4.5}$$
$$= (\underline{\theta} - p)^2/2 + pq.$$

If the low-cost type's incentive constraint (4.5) does *not* bind, the solution is

$$\overline{x}_n = \overline{\theta} - p,$$

but if $x = \overline{x}_n$ does not satisfy (4.5), x must must increase until (4.5) binds, requiring:

$$\overline{x}_b = \underline{\theta} - p + \sqrt{(p-\underline{\theta})^2 - \left((\underline{\theta}-p)^2 - 2\delta\Delta p^+\right)} = \underline{\theta} - p + \sqrt{2\delta\Delta p^+}.$$

Clearly, $\overline{x}_b > \overline{x}_n$ if (4.4) holds, and $\overline{x} = \max\{\overline{x}_n, \overline{x}_b\}$, giving (4.2).
(iii) Simply take the weighted average of (4.1) and (4.2) and rearrange.

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[17]Technically, this is true because the firms' objective functions satisfy the single-crossing property in the space (x, q^+).

(i) From the proof of (ii), there is a unique separating equilibrium. If there were a pooling or a semi-pooling equilibrium where both some low-cost and some high-cost firms polluted x', $q'(.) > 0$ implies that their future quota would be some $q' < \overline{q}$. But such an equilibrium does not satisfy the Intuitive Criterion since some x which is never attractive for a low-cost firm,

$$\underline{\theta}x - x^2/2 + p(q - x) + \delta\left(\overline{q} - q'\right)p^+ < \underline{\theta}x' - x'^2/2 + p(q - x'), \qquad (4.6)$$

is still attractive for the high-cost firm if the government concludes that such a firm must have high cost, thereby giving it $\overline{q}$ in the next period. It is easy to see that if $x > x'$ is such that (4.6) binds with equality (making the low-cost firm indifferent), the high-cost firm is strictly better off. Thus, the equilibrium would fail the Intuitive Criterion. *QED*

If (4.4) does *not* hold, the difference between firm types is so large that low-cost firms are not tempted to imitate high-cost firms, even when the latter simply set $\overline{x} = \overline{\theta} - p$ and receive more allowances in the next period. Maximizing static profit is then sufficient to signal high cost, and marginal costs are equalized across firms in equilibrium.

If Δ is large, however, high-cost firms receive much more allowances than low-cost firms in the next period. And if the future price p^+ is large, this is very valuable. If, at the same time, the discount factor δ is large, then the next period is so important that low-cost firms are tempted to imitate high-cost firms in order to get a larger quota in the future. Polluting $\overline{\theta} - p$ is then not sufficient to demonstrate a high type. Instead, high-cost firms are forced to pollute more to credibly signal their need for permits. This implies that their static marginal benefit of polluting is smaller than the price. Equivalently, the price is larger than the marginal cost of cleaning, since polluting is beneficial for two reasons. Not only is cleaning costly, it also reveals low cost of cleaning to the government. Thus, the equilibrium price for permits is higher than the marginal cost of cleaning since the price also reflects the reputational value of signaling to the government.

The equilibrium price for permits can now easily be derived:

Proposition 4. *If (4.4) holds, p is given by (4.7); if (4.4) does not hold, p is given by (2.4).*

$$\sqrt{p} = (1-k)\sqrt{\delta\Delta/2} + \sqrt{(1-k)^2\delta\Delta/2 + \underline{\theta} - q} \qquad (4.7)$$

Proof: If (4.4) does not hold, marginal costs equal the price which, as in Proposition 1, is given by (2.4). If (4.4) holds, equalizing demand and supply implies:

$$k\underline{x} + (1-k)\overline{x} = q \Rightarrow$$
$$k\left(\underline{\theta} - p\right) + (1-k)\left(\overline{\theta} - p + \sqrt{2\delta\Delta p^+}\right) = q \Rightarrow$$
$$p = \underline{\theta} + (1-k)\sqrt{2\delta\Delta p^+} - q. \qquad (4.8)$$

Since all periods are identical, $p^+ = p$. Solving for $\sqrt{p} > 0$ gives (4.7). *QED*

The price p increases in Δ and δ but decreases in k and q. It is more tempting to signal high costs if the quota-difference Δ is large and the future close (δ large). Then, the

reputational gain from polluting is high, and this is reflected in a high price. Naturally, the price is lower if few firms pollute excessively (k large) and if q, the supply of permits, is large.

The equilibrium described above is clearly inefficient. For any q, total costs would be minimized if the firms equalized marginal costs. Instead, high-cost firms pollute more than the optimal amount, and since they have to purchase permits from low-cost firms, these pollute too little. Thus, high-cost firms are buying too many permits compared to what is optimal.[18]

Proposition 5. *Suppose (3.2) and (4.4) hold. There is too much trade in permits.*

Proof: In the first-best outcome,

$$\bar{\theta} - \bar{x}^* = \underline{\theta} - \underline{x}^* = \underline{\theta} - \frac{q - (1-k)\bar{x}^*}{k} \Rightarrow$$
$$\bar{x}^* = q + k\left(\bar{\theta} - \underline{\theta}\right).$$

Since $\bar{x}^* > \bar{q}$, high-cost firms should purchase permits. In equilibrium,

$$\bar{x} = \underline{\theta} - p + \sqrt{2\delta\Delta p^+} = \bar{x} = q + k\sqrt{2\delta\Delta p^+},$$

which is larger than $\bar{x}^*$ under (4.4). Thus, high-cost firms are purchasing more permits in equilibrium than what is optimal. Equivalently, low-cost firms sell more permits than what is optimal. *QED*

We close this section by discussing condition (4.4), taking the price into account. The condition says that costly signaling arises if the (next-period) price is sufficiently high, while the equilibrium is first-best if the price is sufficiently low. Since the price itself is higher in the former case, the condition might hold when there is signaling while, at the same time, it might fail if the equilibrium is first-best. It that case, we have multiple equilibria.[19]

Proposition 6. (i) *If (4.9) holds, an equilibrium exists in which trade is efficient and (4.4) does not hold.*
(ii) *If (4.10) holds, an equilibrium exists in which trade is inefficient and (4.4) holds.*
(iii) *If both (4.9) and (4.10) hold, both equilibria exist.*

$$\left(\bar{\theta} - \underline{\theta}\right) \geq \sqrt{2\delta\Delta\left(\theta - q\right)} \tag{4.9}$$

$$\left(\bar{\theta} - \underline{\theta}\right) < \sqrt{2\delta\Delta}\left((1-k)\sqrt{\delta\Delta/2} + \sqrt{(1-k)^2\delta\Delta/2 + \underline{\theta} - q}\right) \tag{4.10}$$

Proof: Suppose (4.4) does not hold and set $p = \theta - q$, giving (4.9). Suppose, instead, (4.4) does hold and substitute (4.7) for the price in (4.4), giving (4.10). The price is higher in

---

[18]The result that there will be too much trade holds because the equilibrium is in separating strategies, which is due to the Intuitive Criterion. Without that, Section 7 argues that the equilibrium can be in pooling strategies, implying too little trade.

[19]The possibility of multiple equilibria does not contradict Proposition 3 (i), which characterized firms' behavior taking p as given.

the latter case (simply because demand is higher in the signaling equilibrium), implying that both conditions may hold simultaneously. *QED*

Condition (4.10) is necessary and failing (4.9) is a sufficient condition for signaling to occur. When both (4.9) and (4.10) hold, there are multiple equilibria. If the firms believe that the price of permits will be low, there is no desire to signal. If the firms believe that the price will be high in the future, signalling takes place and the price will be high, indeed.

5. Policies, Permits and Prices

So far, we have taken the government's policy as given and only studied firms' equilibrium behavior. Anticipating this, what should the government do? In particular, choosing the total number of permits q determines the equilibrium price p and, in turn, each firm's amount of pollution.

Proposition 7. *The optimal number of permits is $q = \theta - v$, whether they are tradable or not, and whether (4.4) holds or not.*

Proof: If (4.4) does not hold, trade is efficient and q is given by (2.2), as in Proposition 1. If (4.4) holds and the permits are traded, the government's problem is to maximize $\pi - vq$, which is:

$$k \left(\underline{\theta} \underline{x} - \underline{x}^2/2 \right) + (1-k) \left(\overline{\theta} \overline{x} - \overline{x}^2/2 \right) - v \left(k\underline{x} + (1-k)\overline{x} \right)$$

Since p is a function of q, choosing q is equivalent to choosing p. And since $\partial \underline{x}/\partial p = \partial \overline{x}/\partial p = -1$ (taking the next-period q^+ and p^+ as given), the first-order condition is:

$$k \left(\underline{\theta} - \underline{x} \right) + (1-k) \left(\overline{\theta} - \overline{x} \right) - v = 0 \Rightarrow (2.2).$$

QED

Thus, the total number of permits should be the same whether trade is efficient or distorted. Although the total cost of cleaning (for each q) is larger in the latter case, the marginal cost with respect to q is the same.[20]

Substituting the optimal q into the price function (4.8), we can state the optimal policy in terms of the price instead of the quantity (taking as given the next-period policy and price).

Proposition 8. *The optimal price of permits is given by (5.1).*

$$p = v + \max \left\{ 0, (1-k) \left(\sqrt{2\delta \Delta p^+} - \left(\overline{\theta} - \underline{\theta} \right) \right) \right\} \tag{5.1}$$

---

[20]This is due to the quadratic profit function, and it simplifies the comparison to non-tradable permits in the next section. In general, the optimal q could be larger or smaller if trade is allowed or if trade is inefficient: that would depend on the profit function.

Thus, $p > v$ whenever (4.4) holds. The intuition is straightforward: If the market for permits is distorted, the equilibrium price is higher than the average marginal cost of reducing pollution. The latter should be equal to the marginal value, v, which thus must be less than the equilibrium price. It is therefore wrong, as is typically presumed, that the number of quotas should be such that the price reflects the social value of cleaning. The price is excessively high because of the reputational effect, and it should thus be higher than the value of cleaning.[21]

The initial distribution of permits is also a political variable. If this is determined by (3.2), we can easily compare the firms' actual pollution levels to the quotas they will receive in equilibrium.

Proposition 9. *If (3.2) holds, $\underline{q} > \underline{x}$ while $\overline{q} < \overline{x}$.*

Proof: With tradable permits under (4.4), note that $\overline{x} - \underline{x} = \sqrt{2\delta p^+ \Delta}$ implies

$$
\begin{aligned}
\underline{x} &= q - (1-k)\sqrt{2\delta p^+ \Delta} \\
\overline{x} &= q + k\sqrt{2\delta p^+ \Delta}.
\end{aligned}
\tag{5.2}
$$

We can thus write from (3.2),

$$
\begin{aligned}
\overline{q} &= q + s\left(\overline{\theta} - \theta\right) = \overline{x} - k\sqrt{2\delta p^+ \Delta} + s\left(\overline{\theta} - \theta\right) \\
&= \overline{x} - k\left(\sqrt{2\delta p^+ \Delta} - s\left(\overline{\theta} - \underline{\theta}\right)\right) < \overline{x} \text{ under (4.4).} \\
\underline{q} &= q - s\left(\theta - \underline{\theta}\right) = \underline{x} + (1-k)\sqrt{2\delta p^+ \Delta} - s\left(\theta - \underline{\theta}\right) \\
&= \underline{x} + (1-k)\left(\sqrt{2\delta p^+ \Delta} - s\left(\overline{\theta} - \underline{\theta}\right)\right) > \underline{x} \text{ under (4.4).}
\end{aligned}
$$

QED

More permits are given to firms that polluted a lot in the past, but the difference is not as large as their actual emission levels. The government realizes that high-cost firms polluted more than what were optimal, and their future quota will thus be less that their emission levels. Low-cost firms, on the other hand, polluted less than optimal, so they will receive more permits compared to their emission levels. In addition, the firms' types might change over time, which pushes the optimal quotas further towards the average.

6. Tradable or Non-Tradable Permits?

The distortions in the market for permits suggest that trade in permits may not be as desirable as previously thought. But what about the alternative? Since, in the model, firms' costs are private information, it seems consistent to assume that the government

---

[21]While the government is benevolent and rational in our model, it may not be expected that (5.1) is anything like the existing price for permits. In the ETS, for example, the price is very low due to an excessive number of permits being issued by the governments. This suggests, perhaps, that the firms were successful in signaling their need for permits prior to the distribution, without the governments realizing the signaling that took place.

does not learn the firms' costs if they cannot signal by their emission levels. Thus, prohibiting trade would imply that $q_i = q$ for all firms. While prohibiting trade would prevent low-cost firms from optimally selling their permits to high-cost firms, it would also prevent high-cost firms from polluting too much in order to signal their types. Is it possible that the costs of signaling outweigh the benefits from trade?

Proposition 10. *Whatever is q,*
(i) *allowing trade is good if and only if (6.1) holds;*
(ii) *under (3.2), the corresponding condition is (6.2).*

$$2\left(\overline{\theta} - \underline{\theta}\right)^2 \quad > \quad \delta\Delta p \tag{6.1}$$

$$2\left(\overline{\theta} - \underline{\theta}\right) \quad > \quad \delta sp \tag{6.2}$$

Proof: Since q is the same under both regimes, we only need to compare firms' profit. Without trade, these are:

$$\int_i \left(\theta_i q - q^2/2\right) di = \theta q + q^2/2. \tag{6.3}$$

With tradable permits, summing over the π_is gives (letting $p = p^+$ and using (5.2)):

$$
\begin{aligned}
& k\left(\underline{\theta}\underline{x} - \underline{x}^2/2\right) + (1-k)\left(\overline{\theta}\overline{x} - \overline{x}^2/2\right) \\
= & \ \theta q - q^2/2 - k\underline{\theta}(1-k)\sqrt{2\delta p\Delta} - k\left(-2q(1-k)\sqrt{2\delta p\Delta} + (1-k)^2 2\delta p\Delta\right)/2 \\
& + (1-k)\overline{\theta}k\sqrt{2\delta p\Delta} - (1-k)\left(2qk\sqrt{2\delta p\Delta} + k^2 2\delta p\Delta\right)/2 \\
= & \ \theta q - q^2/2 + k(1-k)\sqrt{2\delta p\Delta}\left[(\overline{\theta} - \underline{\theta}) - \sqrt{\delta\Delta p/2}\right].
\end{aligned}
$$

Compared to (6.3), trade is good if the last term is positive, requiring (6.1). Substituting from (3.2) gives (6.2). *QED*

If (4.4) does *not* hold, trade is first-best and (6.1) always hold. Otherwise, the distortions from signaling in trade must be compared to the cost of uniform emission standards. The cost of uniform standards is, naturally, increasing in the heterogeneity $(\overline{\theta} - \underline{\theta})$, making trade relatively better.[22] However, if the future is close (δ large), the quota-differential Δ large, and the permit-price high, it is very tempting to signal high costs and the resulting distortions are higher than the cost of uniform standards. Therefore, trade is good only if $(\overline{\theta} - \underline{\theta})$ is large while δ, Δ and p are small.

If Δ is set according to (3.2), prohibiting trade is good if s is large. Intuitively, a large s means that firm types are stable and less likely to change. This motivates the government to increase the quota difference between the firms and this, in turn, increases the incentive

---

[22] This trade-off is similar to that in Harstad (2007), studying whether uniformity (and side payments) are good in a bargaining context with private information. In both that paper and this, uniformity is better for small heterogeneity, since it reduces the cost of signaling. Otherwise, the models, the mechanisms and the results are very different.
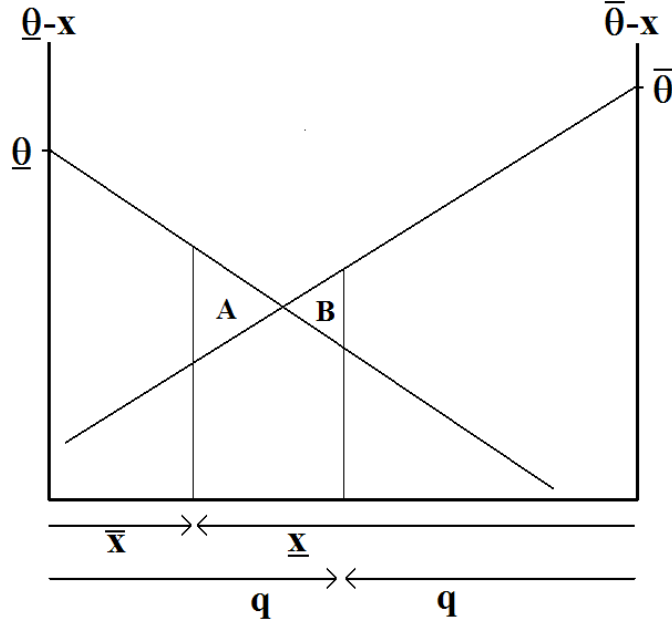
Figure 6.1: If the social loss of signaling (A) is larger than the gains from trade (B), trade should be prohibited.

to signal by purchasing permits. Note that the effect of s somehow complements the effect of δ: if the government frequently redistributes the quotas, then the discount factor δ is large and, at the same time, firms' types are less likely to change (implying that s is large). For both reasons, then, trade is bad.[23]

Conditions (6.1)-(6.2) are, for simplicity, written for a fixed price p, although we have solved for p above. From (4.7), p increases in δ and Δ, reinforcing the effects just described. In addition, p decreases in q which, from Proposition 7, decreases in v. Thus, for more important environmental problems, where v is large, the permits should not be traded.

Our description of non-tradable permits might be overly pessimistic. There might be ways in which the government can learn firms' types even if the permits are not traded. For example, if the firms did trade in the previous period, the government learned their types then, and this is useful information when distributing the permits now. Or, to take another example, the quotas might be enforced by a fee f, to be paid for each unit of pollution x_i exceeding a firm's quota q_i. A firm may then be able to signal its type by polluting more than its allowance (thereby paying $f(x_i - q_i)$ in penalties). Such a signal is credible for x_i sufficiently large, because low-cost firms are less tempted to pay fees for polluting more. The government can then conclude that firms paying large fees have high costs, and they will receive more quotas in the next period. This intuition is confirmed in the Appendix, analyzing this situation. When $f \to \infty$, $x_i \to q$ and the quotas are strictly enforced, but the government are still able to distinguish low and high cost firms.

---

[23]We may write $s = \widehat{s}^t$ and $\delta = \widehat{\delta}^t$ if $\widehat{s}$ is the annual stability-probability, $\widehat{\delta}$ is the annual discount factor, and t is the number of years for which the government distributes the quotas. Clearly, s and δ are both decreasing in t.

For these reasons, it may be more reasonable to assume that even without trade in permits, the government is able to distinguish low and high cost firms at the end of the period. In the next period, quotas are distributed according to $\underline{q}$ and $\overline{q}$, just as argued above. Pollution levels are then not completely uniform across firms, and this reduces the inefficiency of the non-trade system. Hence, the following conditions for when trade is preferable are stronger than the corresponding conditions in Proposition 10. The comparative statics are the same, however.

Proposition 11. *Suppose the government learns firms' types at the end of every period, even without trade. Whatever q is,*
(i) trade is good if and only if (6.4) holds;
(ii) under (3.2), the corresponding condition is (6.5).

$$\left(\overline{\theta} - \underline{\theta}\right)^2 \left(1 + \sqrt{1 - s^2}\right)^2 \;>\; 2\delta\Delta p \tag{6.4}$$

$$\left(\overline{\theta} - \underline{\theta}\right)\left(1 + \sqrt{1 - s^2}\right)^2 \;>\; 2\delta sp \tag{6.5}$$

Proof: If the government knows the firms' types in the previous period, then firms that had low costs then receive low quotas now. The sum of the π_is is thus:

$$
\begin{aligned}
& k(s\underline{\theta} + (1-s)\theta)\underline{q} + (1-k)(s\overline{\theta} + (1-s)\theta)\overline{q} - k\underline{q}^2/2 - (1-k)\overline{q}^2/2 \\
=\; & (1-s)\theta q + ks\underline{\theta}\underline{q} + (1-k)s\overline{\theta}\overline{q} - k\underline{q}^2/2 - (1-k)\overline{q}^2/2 \\
=\; & (1-s)\theta q + k\underline{q}\left(s\underline{\theta} - \underline{q}/2\right) + (1-k)\overline{q}\left(s\overline{\theta} - \overline{q}/2\right) \\
=\; & (1-s)\theta q + k\left((s\underline{\theta})^2 - (q - s\theta)^2\right)/2 + (1-k)\left((s\overline{\theta})^2 - (q - s\theta)^2\right)/2 \\
=\; & \theta q - q^2/2 - (s\theta)^2/2 + k(s\underline{\theta})^2/2 + (1-k)(s\overline{\theta})^2/2 \\
=\; & \theta q - q^2/2 + s^2 k(1-k)\left(\overline{\theta} - \underline{\theta}\right)^2/2.
\end{aligned}
$$

Compared to trade, trade is better if

$$
\begin{aligned}
k(1-k)\sqrt{2\delta p\Delta}\left[\left(\overline{\theta} - \underline{\theta}\right) - \sqrt{\delta p\Delta/2}\right] \;&>\; k(1-k)s^2\left(\overline{\theta} - \underline{\theta}\right)^2/2 \Rightarrow \\
\sqrt{2\delta p\Delta}\left[2\left(\overline{\theta} - \underline{\theta}\right) - \sqrt{2\delta p\Delta}\right] \;&>\; s^2\left(\overline{\theta} - \underline{\theta}\right)^2.
\end{aligned}
$$

Unless trade is first-best, (4.4) implies $\sqrt{2\delta p\Delta} > \left(\overline{\theta} - \underline{\theta}\right)$ and the possibility to write the above equation as:

$$
\begin{aligned}
\left(\overline{\theta} - \underline{\theta}\right)^2\left(1 - s^2\right) \;&>\; \left(\sqrt{2\delta p\Delta} - \left(\overline{\theta} - \underline{\theta}\right)\right)^2 \Rightarrow \\
\left(\overline{\theta} - \underline{\theta}\right)\sqrt{1 - s^2} \;&>\; \sqrt{2\delta p\Delta} - \left(\overline{\theta} - \underline{\theta}\right) \Rightarrow (6.4).
\end{aligned}
$$

Substituting for (3.2) gives (6.5). *QED*

If $s \to 0$, condition (6.4) becomes identical to (6.1) since, then, it does not matter whether the government learns. If $s \to 1$, (6.4) becomes the converse of (4.4) since, then, the non-tradable system approaches the first-best and trade can be good only if this is first-best as well.

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7. Robustness and Extensions

This section briefly discusses some robustness issues and possible extensions.

(i) To follow up on the last paragraph in the previous section, one could allow for other ways in which the government might learn the firms' types. As long as such a signal would be imperfect, however, the firms would still have an incentive to signal their types. The results above would then continue to hold, qualitatively. For example, suppose that, at the end of each period, the government receives a signal $\widehat{\theta}_i \in \{\underline{\theta}, \overline{\theta}\}$, which is informative with probability $z \in (0, 1)$. If it is not informative, the government learns nothing. Thus, with Bayesian updating, $E\theta_i^+ = zs\widehat{\theta}_i + (1 - zs)\theta$. The signal does not change the situation when permits are tradable: Since the signal is imperfect, it is still necessary and desirable for high-cost firms to separate themselves from low-cost firms. This will reveal the firms' types, and the government can ignore the imperfect signal. Without trade, however, a more precise signal allows the government to distribute the quotas better in the next period. This makes non-tradable better compared to tradable permits. Following a similar reasoning as in the proof of Proposition 11, trade is good if and only if:
$$\left(\overline{\theta} - \underline{\theta}\right)\left(1 + \sqrt{1 - z^2 s^2}\right) > \sqrt{2\delta\Delta p}.$$
Clearly, the comparative static is the same as before.

(ii) Throughout the paper, we have assumed that firms appear to be identical, except for their chosen emission levels. However, observable heterogeneity would not affect the results. Suppose, for example, that k were known to vary across firms. Then, $\overline{q}$ and $\underline{q}$ may as well vary across firms, and should be written $\overline{q}_i$ and $\underline{q}_i$. Nevertheless, the results above would be identical if just $\overline{q}_i - \underline{q}_i$ were the same for all firms. This would actually be the case under (2.3), implying that (3.2), and thus all the results, would continue to hold. If firms were of different sizes, to take another example, we could simply let the profit function, and all the variables above, be measured per unit of capital (or firm size). Maximizing profit is equivalent to maximizing the profit per unit of capital, and the results above would therefore be unaffected.

(iii) We have also simplified by assuming that there are only two possible types. If there were more types and these were eventually revealed, the government would be inclined to distribute different quotas to each type. In a separating equilibrium, each firm would need to ensure that the neighboring type, which has slightly smaller costs, is not better off by imitating the firm's strategy. All firms, except for the lowest-cost firms, must therefore credibly signal their types by polluting more than what they would like in a static setting. The intuition from the analysis above would survive, but the comparative static would be much more complicated.

(iv) Although firm types are exogenous in our model, endogenizing θ_i would strengthen our results. Suppose that firm i can make some investment that affect its probability of becoming a low-cost firm. A successful investment implies that the firm is penalized in the form of a smaller quota, particularly if the outcome is observable. Thus, the firm has too low incentives to reduce its cost of cleaning or, equivalently, it has too high incentives to increase its cleaning costs. The incentives are heavily distorted if the government intervenes frequently, making a non-tradable system better.

(v) Our equilibrium concept is crucial. In particular, the Intuitive Criterion implies that there is a unique equilibrium, which is in separating strategies. This criterion is sometimes criticized since it implies that high-cost firms undertake costly signaling even when almost all firms have high cost (see e.g. Bolton and Dewatripont, 2005, p. 110). For this reason, the separating equilibrium in Spence's (1973) labor market may be Pareto-dominated by a pooling equilibrium where no-one undertakes costly education. This critique, however, does not have bite in the present model. By combining (5.1) and (4.1), as $k \rightarrow 1$, $p \rightarrow v$, and almost all firms pollute optimally. Similarly, by combining (5.1) and (4.2), as $k \rightarrow 0$, $\overline{x} \rightarrow \overline{\theta} - v$, and almost all firms pollute optimally.

Without imposing the Intuitive Criterion, one could easily have equilibria in pooling strategies. For example, there is a sequential equilibrium in which all firms pollute $\overline{x}_n = \overline{\theta} - p$ (maximizing a high-cost type's profit), and where the government interprets any deviation as evidence of low cost. Under (4.4), this would induce all firms to pollute $\overline{x}_n$. Thus, Proposition 5 would be reversed: there would be too little trade in this equilibrium. The other results would survive, however, qualitatively: demand would still be higher than what is optimal, this time for the low-cost firms, since these would not want to pollute less and reveal their low costs. The price would still be above marginal costs, and the market would be distorted. If the distortions were large, prohibiting trade would be better.

8. Conclusions

Tradable pollution permits are celebrated as a political instrument. The system supposedly combines the efficient features of a market with the government's sense for fairness. We show, however, that these two goals conflict in a dynamic setting. Our model relies on two assumptions that both fit well with the reality: (i) the government redistributes permits over time and (ii) it is inclined to distribute the burden equally across the firms (thereby giving a larger quota to high-cost firms). As a consequence, trade in permits is distorted and the price is above marginal cost in equilibrium. In fact, a system of non-tradable permits is better if the heterogeneity between firms is small, if the social cost of pollution is high, and if the government intervenes frequently. Thus, the analysis suggests that important environmental problems should not be solved by tradable permits unless the government can commit not to intervene.

It is immensely important to understand the dynamic effects of pollution markets, since they are becoming increasingly important for solving global environmental problems. But due to their short history, it is not much empirical evidence to draw upon. We have already mentioned that the gains from trade, while large, has not been of the magnitude that earlier simulations suggested. Our analysis may contribute to explaining this puzzle. Our model also predicts that the price is above marginal costs, contrasting earlier theories, but more in line with the evidence.[24] Finally, our model predicts that there may be multiple

---

[24] Theoretically, Cason (1993) suggests that bidders (in the EPA's auction) have an incentive to understate their value of the permit. While supported by experiments (Cason, 1995), his prediction is not supported by the "real-world" empirical evidence. Joskow *et al.* (1998, p. 682) find that bidders instead overstate the reservation prices, and state: "The most plausible explanation seems to be that some utilities use the EPA auction process to demonstrate to regulators that they could not sell their allowances

equilibria for the permit price, which perhaps can explain the sharp drop in price at the ETS market late April, 2006.[25]

Theoretically, the analysis provides lessons for the old debate on plan versus markets. While a perfect market would be first-best in our setting (with no redistribution), frequent intervention distorts the market allocation. The more frequently the government intervenes, the worse the market performs. At some point, it is better to abandon the market altogether and rely completely on command-and-control; prohibiting trade in permits. This suggests that efficiency, as a function of regulatory intervention, may be U-shaped. Mixing plans and markets might be worse than either.[26]

Of course, our simple framework has many shortcomings. In particular, (i) we have taken the political instruments as given (without explaining, for example, why emission taxes are not available), (ii) we have not modelled why the government is unable to commit to future policies and, despite these shortcomings, (iii) we have assumed that the government is benevolent. Future research should formalize how voters and the political institutions determine the politicians' preferences and their possibilities to commit. Deriving optimal and equilibrium policies, given these constraints, may bring us closer to the best possible environmental regulation.

9. Appendix: Combining Quotas and Fees

This section studies the equilibrium if the government imposes some fee f on pollution x_i exceeding a firm's emission allowance, q_i. Just as before, we denote by $\underline{q}$ and $\overline{q}$ the levels of quota distributed to firms that were previously of low and high type, respectively. If, given the quota, current low-cost firms behaved similar to high-cost firms, the government cannot distinguish them and they receive the same quota $q' < \overline{q}$ in the next period. The high-cost firm will receive $\overline{q}$, however, if it is able to separate itself from the low-cost firm. Since the profit functions fulfil the single-crossing property in the space (x, Δ), high cost firms are indeed able to signal their type, just as in the model above. Thus, low-cost firms have no chances of convincing the government that they have high costs, and they solve the problem:

$$\underline{x} = \arg \max_x \left(\underline{\theta} x - x^2/2 - \max \{0, f(x - q_i)\} \right) = \max \{q_i, \underline{\theta} - f\}.$$

A high-cost firm's problem is thus:

$$\overline{x} = \arg \max_x \left(\overline{\theta} x - x^2/2 - \max \{0, f(x - q_i)\} \right) \text{ s.t.}$$

at prices above those prevailing in the private market".

[25] Within three weeks, the price dropped from €30 to €10, while the trading volume per day dropped from 20m to 1m tonn. In our framework, this may corresponds to a change from an equilibrium with signaling, high prices and a lot of trade, to the other equilibrium with low prices and less trade (Proposition 6). The switch in equilibrium was triggered by news revealing that governments had issued more permits than their companies needed (Financial Times, 2/11/2006, p. 29).

[26] Another interpretation of our results is that the first and the second welfare theorems may conflict in a dynamic setting. While the first welfare theorem states that the market equilibrium is first-best, the second states that any market equilibrium can be achieved by a proper reallocation of initial endowments. This is sometimes interpreted as suggesting that the combination of plan and markets can achieve remarkable outcomes, both in terms of efficiency and equality. This proved to be wrong in our dynamic model. Anticipating future intervention, the market is distorted accordingly.

$$\underline{\theta}x - x^2/2 - \max\left\{0, f\left(x - q_i\right)\right\} + \delta b\left(\underline{q}, \Delta\right) \leq \max\left\{\underline{\theta}\underline{q} - \underline{q}^2/2, \left(\underline{\theta} - f\right)^2/2 + fq_i\right\} \equiv \underline{V},$$
$$(9.1)$$

where $b\left(\underline{q}, \Delta\right)$ is a low-cost firms expected value of receiving $\underline{q} + \Delta$ instead of only $\underline{q}$ next period. If the constraint does *not* bind, the solution is

$$\overline{x}_n = \overline{\theta} - f,$$

since $\overline{x} = q_i$ surely makes the constraint bind. If the constraint binds, however, $\overline{x}$ is given by:

$$\overline{x}_b = \underline{\theta} - f + \sqrt{\left(\underline{\theta} - f\right)^2 - 2\left(\underline{V} - \delta b\left(\underline{q}, \Delta\right) - fq_i\right)}$$

Thus, $\overline{x} = \max\left\{\overline{x}_n, \overline{x}_b\right\}$. It follows directly:

Proposition 12. *Pollution levels are first-best if and only if* (i) $f = v$, (ii) $\underline{q}, \overline{q} \leq \underline{\theta} - v$, *and* (iii) $\overline{\theta} - \underline{\theta} \geq \sqrt{\left(\underline{\theta} - v\right)^2 - 2\left(\underline{V} - \delta b\left(\underline{q}, \Delta\right) - vq_i\right)}$.

Proof: If $\underline{q} = \overline{q}$, there is no incentive to signal, $\overline{x}_n > \overline{x}_b$ and $f = v$ is necessary for the first-best, clearly. If $\underline{q} < \overline{q}$, $f = v$ is necessary for all low-cost firms to pollute optimally, and then $\overline{x} = \overline{x}_n$ is optimal, requiring $\overline{x}_n \geq \overline{x}_b$, giving condition (iii). *QED*

By setting $f = v$, firms face the right incentive to pollute, unless they need to separate themselves from low cost firms, which is condition (iii). If Δ is large, however, it is so tempting to signal high costs that high-cost firms need to pollute excessively to signal their types credibly. The result shows that the first-best is possible, even if $\Delta > 0$, if just f is set appropriately and the quotas are not that large.

If, however, the quotas are set according to (2.3), such that (3.2) holds, then the first-best is never achievable, since $\underline{q}, \overline{q} > \underline{\theta} - v$, implying that low-cost firms pollute too much. The fixed-quota system can always be approximated, however, by letting f grow very large. If f grows, (9.1) binds ($\overline{x}_n < \overline{x}_b$) and (9.1) can be rewritten as:

$$\overline{x} - q_i = \frac{\underline{\theta}\overline{x} - \overline{x}^2/2 + \delta b\left(\underline{q}, \Delta\right) + \underline{\theta}\underline{q} - \underline{q}^2/2}{f}.$$

Clearly, as $f \to \infty$, $\overline{x} \to q_i$, and the fixed quota system is strictly enforced, although the equilibrium is in separating strategies.

Proposition 13. *If $f \to \infty$, each firm's pollution level approaches its quota, tough the types are still separated in equilibrium.*

This implies that in the fixed quota systems, where the quotas are enforced by fees, the government learns the firms' types at the end of each period. This intuition underlies Proposition 11 above.

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