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Trading for the Future
Signaling in Permit Markets

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Trading for the Future: Signaling in Permit Markets*

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7 February 2007

Abstract

Tradable pollution 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. Prohibiting trade is better if the heterogeneity between the firms is small, if the (shadow) price for permits is large, and if the government redistributes permits frequently. Thus, important environmental problems should not be solved by tradable permits unless the government can commit not to intervene.

JEL classification: H23, Q58, P48, D82

Key words: Political instruments, governmental intervention, tradable permits, private information, signaling

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1. Introduction

Pollution markets are becoming the most important instrument for solving our most important problem. 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: First, permits are distributed to more than 12,000 large point sources in 25 countries. Thereafter, the permits can be traded at the ETS market. By 2008, the governments will distribute permits again, this time for a period of five years. Permit markets have a longer history in the United States. Already in 1974, the Clean Air Act allowed trade in sulfur dioxide allowances in specific cases. Since then, the market for such permits has been enlarged in several steps (Hahn, 1989). A regional market for nitrogen oxides emissions was created in 2003 and now several U.S. states consider setting up an emission trading system for carbon dioxide, similar to the ETS.

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 lose this right over night. Or, firms may have political and bargaining power if, for example, they are able to relocate to a friendlier regulatory environment. For such reasons, policy-makers often hesitate to introduce new taxes and rely instead on "command-and-control" policies in which emission quotas are distributed for free. Large polluters typically receive more quotas for free, since these would otherwise suffer the most from tough regulation. By making the permits tradable, its supporters argue, one combines the efficiency properties of a market with the government's concern for redistribution.

These two concerns, however, conflict in a dynamic setting. When the government frequently intervenes to redistribute quotas, 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 it is actually better to prohibit trade.

We present a simple multi-period model in which, 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

[1] The permits under the ETS are issued for a three-year period (2005-2007), while the periods will be of a five-year length starting in 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". Hence, the allowances are different from property rights in that "Congress can change the number of allowances issued or do away with them altogether without raising a constitutional claim for compensation" (Joskow and Schmalensee, 1998, p. 39).

[2] Although the European Commission recommends the allocation of permits not to be based on recent history, in practice the permits *are* distributed according to *both* recent emission and projections for future need (Buchner *et al.*, 2006). Also for the Clear Air Act, "units are given fixed numbers of tradable permits...that depend primarily on historic emissions and fuel use" (Schmalensee *et al.*, 1998, p. 54). Such a procedure is advocated by Noll (1982).

than what 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. 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. Trade in permits should be prohibited if the heterogeneity between the firms is small, the social loss of pollution is large and the government intervenes frequently.[3]

Theoretically, the analysis contributes to the old debate on plan versus markets: Unregulated pollution markets (with no redistribution) would be first-best in our setting. The more often the government intervenes (redistributes), the worse the market performs. At some point, it is better to abandon the market altogether and rely completely on command-and-control. Mixing plans and markets might be worse than either.

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 EU's ETS, where every period is just a few years long. In the American sulfur dioxide market, the distributed allowances last 30-45 years. Based on our model, the U.S. market ought to be more efficient than the ETS.[4]

Empirically, there is not a lot of material due to the short history of tradable permits in practice. Thus, many of the studies are based on experiments and simulations. These studies 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; Carlson *et al.*, 2000; Burtraw *et al.*, 2005). Compared with observed abatement, however, the authors find that only parts of the potential savings are realized. Our theory contributes to explaining this puzzle.

A large literature compares 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 favored emission taxes, because 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 from a political point of view, Buchanan and Tullock (1975) observed that it is more acceptable to distribute quotas for free, since this is viewed as less confiscatory. For the Clean Air Act, "Allowances were given to utilities rather than sold because there was no way that a sales-based program could have passed Congress" (Schmalensee *et al.*, 1998, p. 56). 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. 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 tendency to distribute permits for free, and show how it distorts the market,

[3] The government, as a principal, would thus be better off if it could not observe the agents' actions (as in Prat, 2005), e.g. if the market were anonymous (as in Bisin and Rampini, 2006). It would be hard to control (and monitor) anonymous pollution markets, however.

[4] The U.S. NO_x market is more similar to the ETS: Permit distribution is delegated to the individual states, and it is more typical with frequent updating.

[5] On the other hand, emission standards (per unit of output) are never efficient unless accompanied by output taxes (Eskeland, 1994).

possibly making non-tradable permits better. This breaks the equivalence to an emission tax which, in our model, would implement the first-best.[6]

Only a few studies criticize pollution markets, and these typically point to standard market failures. For example, a firm with market power would restrain its quota demands as a buyer, but restrain its supply as a seller (Hahn, 1984). The firms also may be able to collude and trade in a way that 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 there are only two firms, no firm-specific 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.[7]

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. Equilibrium policies are derived in Section 5. Sections 4 and 5 assume the permits are tradable, while Section 6 makes a comparison to non-tradable permits and derives conditions under which this is preferable. Although our model is simple, Section 7 argues that it is robust to several generalizations. The final section concludes and discusses some anecdotal evidence.

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

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

Thus, $\theta_i - x_i$ is firm i's marginal benefit of polluting or, equivalently, its marginal *cost* of cleaning or *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 a high cost of reducing emission (large θ_i) chooses to pollute more.

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

[6] Our analysis thus strenghtens the arguments in favor 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 them to pay for the remaining emissions.

[7] Other weaknesses with tradable permit markets arises (i) if "grandfathering" delays capital turnover (Maloney and Brady, 1988); (ii) if permits can not be traded (or banked) over time; or (iii) if the environmental impact of emission 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".

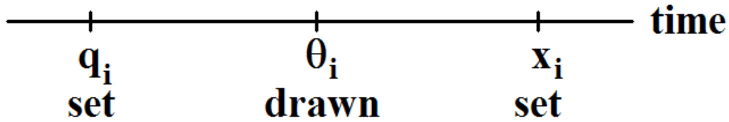

Figure 2.1: Timing of events

solution maximizes $\pi_i - vx_i$,

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

Suppose 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. 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 ways of approaching the optimal solution (2.1): It can try to distribute the quotas according to the best available information (the k_is), and the firms might be allowed to trade the permits after the initial distribution.

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 $q = \int_i q_i di$.[8]

Proposition 1. (i) *Non-tradable permits are distributed according to (2.2).*
(ii) *For tradable permits, marginal costs are equalized across firms for any distribution of the q_is, and the permit price is given by (2.3).*
(iii) *The equilibrium (and optimal) q is given by (2.4) whether the permits are tradable or not.*

$$\begin{aligned} q_i &= \mathrm{E}\theta_i - (\theta - q) & (2.2)\\ p &= \theta - q & (2.3)\\ q &= \theta - v & (2.4) \end{aligned}$$

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

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

$$\begin{aligned} \mathrm{E}\theta_i - q_i - v &= \lambda \Rightarrow & (2.6)\\ \int_i \left(\mathrm{E}\theta_i - q_i - v\right) di &= \theta - q - v = \lambda. & (2.7) \end{aligned}$$

[8]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.

Throughout the paper, we assume that $x_i \le q_i$ 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, $\theta_i \ge \mathrm{E}\theta_i - v \Rightarrow v \ge (1 - k_i)\left(\overline{\theta} - \underline{\theta}\right)$.

Substituting the second equality in (2.7) into (2.6) gives (2.2).
(ii) From each firm's maximization problem,

$$\begin{aligned} \theta_i - x_i &= p \Rightarrow \\ \int_i (\theta_i - x_i)\, di &= \theta - q = p. \end{aligned} \tag{2.8}$$

(iii) 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 (2.2) into (2.5) and maximize over q. Both give (2.4). *QED*

When the permits are non-tradable, a firm should be given more quotas if its expected cost of cleaning is high. Thus, in the EU, "projections became necessary because no Member State wished to deviate far from expected emissions in deciding the total to allocation to installations" (Buchner *et al.*, 2006, p. 9). In fact, (2.2) requires a uniform emission cut for all firms, compared to what they would be expected to pollute without restrictions. While this is in principle efficient, (2.2) is *not* first-best since the government does not know the firms' realized costs.

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 takes 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, a government maximizing efficiency 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. Since such preferences may be reasonable, they should be taken into account. Consider the following possibilities:

a. Fairness: Suppose the government wants to allocate the burden of the policy evenly across firms. Likely high-cost firms should then be given a larger q_i.[9]

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 is decided in a bargaining game between the firms and the government, and let the Nash bargaining solution characterize the outcome.[10] For example, each firm might be associated with a 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.[11]

[9] 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".

[10] The Nash bargaining solution coincides with the equilibrium in the non-cooperative multilateral bargaining game studied by Krishna and Serrano (1996); see their Theorem 1'.

[11] In the EU, "the allocation process can best be described as an extended dialogue between the government and industry" (Buchner *et al.*, 2006, p. 7).

d. Market failures: Suppose that the firms do not trade permits with some (arbitrary) small probability $\epsilon > 0$. Managers may be time or credit-constrained or the mere transfer of permits could entail substantial transaction costs.[12]

With any of these concerns, distributing the quotas according to (2.2) is strictly preferred even when the permits can be traded:

Proposition 2. *Suppose either a, b, c or d holds. The equilibrium (and optimal) distribution of the quotas is given by (2.2), also if they are tradable.*

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

$$\begin{aligned} \mathrm{E}\left(\theta_i^2/2 - (\theta_i - p)^2/2 - pq_i\right) &= \kappa \Rightarrow \\ \mathrm{E}\theta_i p - p^2/2 - pq_i &= \kappa \Rightarrow \qquad (2.10) \\ \int_i \left(\mathrm{E}\theta_i p - p^2/2 - pq_i\right) di &= \theta p - p^2/2 - pq = \kappa. \qquad (2.11) \end{aligned}$$

Substituting (2.11) into (2.10) gives (2.2).
b. Suppose the moving cost is κ. Then a firm does not move if the expected profit change $\mathrm{E}\theta_i p - p^2/2 - pq_i \leq \kappa$. 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 therefore so must (2.2).
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,

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

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:

$$\begin{aligned} \frac{p(\mathrm{E}\theta_i - q_i)}{\widetilde{v} - [\mathrm{E}\theta_i p - p^2/2 - pq_i]} NP &= \lambda \Rightarrow \\ \mathrm{E}\theta_i p - p^2/2 - pq_i &= \frac{\lambda\widetilde{v}/NP - p^2/2}{1 + \lambda/NP} = \kappa, \end{aligned}$$

[12] "[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", which create an "efficiency justification for politicians' typical focus on initial allocation" (Stavins, 1995, p. 133).

for some constant κ, independent of i. Again, this gives (2.10), which implies (2.2). Clearly, this holds also when $n \to \infty$.
d. For a given ϵ and q, the government solves:

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

where the last term is found by integrating (2.9). Since the distribution of the q_is only affects the first term, the problem is identical to (2.5), with solution (2.2). *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 2.1, and the firms cannot store their permits from one period to the next.[13] 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

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

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

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

Respectively, $\underline{q}$ and $\overline{q}$ are 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 $\Delta > 0$. For most of our results, we do not need to further 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* holds, then Proposition 2 suggests that the initial distribution is given by (2.2).[14] Together with

[13] It is still possible with "banking" of permits over time within the same period. In any case, relaxing this assumption would not change the results (firms would *not* want to bank permits in the model).

[14] In fact, if one of *a*-*d* holds and trade is (believed to be) efficient, then (2.2) 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 the analysis below, then assumption *d* still implies (2.2), while assumptions *a*-*c* would make the optimal q_is somewhat more complex. In any case, $\Delta > 0$ would still hold.

(3.1), (2.2) 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 exactly as suggested by Noll (1982, p. 122), that one "basis for the provisional allocation is the estimated competitive (cost-minimizing) allocation". Thus, at various stages below, we can refer to the specification (3.2) to get additional results.

Games with infinite horizons typically have a large number of equilibria, and we need refinements. In particular, we limit attention to Markov strategies, such that strategies depend only 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 receives a small 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 finds conditions under which this is better. Although our model is simple, Section 7 argues that the results continue to hold if (i) the government receives exogenous signals about firm types, (ii) the firms have observable differences in e.g. size, (iii) there is more than two types, (iv) types are endogenous or (v) the equilibrium concept is relaxed.

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.

This intuition is true also in the dynamic model. Since purchasing permits is more beneficial for high-cost firms, polluting signals cost.[15] A low-cost firm might also, of course, 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

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

it would otherwise prefer, thereby separating itself from the low-cost firm. 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.*

$$\begin{aligned} \underline{x} &= \underline{\theta} - p & (4.1)\\ \overline{x} &= \overline{\theta} - p + \max\left\{0, \sqrt{2\delta\Delta p^+} - \left(\overline{\theta} - \underline{\theta}\right)\right\} & (4.2)\\ \theta - x &= p - \max\left\{0, (1-k)\left[\sqrt{2\delta\Delta p^+} - \left(\overline{\theta} - \underline{\theta}\right)\right]\right\} & (4.3)\\ \left(\overline{\theta} - \underline{\theta}\right) &< \sqrt{2\delta\Delta p^+} & (4.4) \end{aligned}$$

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' that 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:

$$\begin{aligned} \overline{x} &= \arg\max_x \left(\overline{\theta}x - x^2/2 + p(q-x) + \delta\overline{q}p^+\right) \quad \text{s.t.} \\ \underline{\theta}x - x^2/2 + p(q-x) + \delta\Delta p^+ &\leq \underline{\theta}\underline{x} - \underline{x}^2/2 + p(q-\underline{x}) & (4.5)\\ &= \left(\underline{\theta} - p\right)^2/2 + pq. \end{aligned}$$

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:

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

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.

(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, because some x that 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 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 the marginal cost of reducing polluting is smaller than the price. Not only is cleaning costly, but it also reveals low cost of cleaning to the government. Thus, the equilibrium price for permits is higher than the marginal cost of cleaning, because 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 (2.3), just as in the static setting.*

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

Proof: If (4.4) does not hold, marginal costs equal the price, which, as in Proposition 1, is given by (2.3). If (4.4) holds, equalizing demand and supply implies:

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

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 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 clearly is 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.[16]

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

Proof: In the first-best outcome,

$$\begin{aligned}\overline{\theta} - \overline{x}^* &= \underline{\theta} - \underline{x}^* = \underline{\theta} - \frac{q - (1-k)\overline{x}^*}{k} \Rightarrow \\ \overline{x}^* &= q + k\left(\overline{\theta} - \underline{\theta}\right).\end{aligned}$$

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

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

which is larger than $\overline{x}^*$ 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.[17]

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.*

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

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

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 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 two equilibria. If the firms believe 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, signaling takes place and the price will be high, indeed. Thus, in one equilibrium there is signaling in every period; in the other there is never any signaling.

[16] 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.

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

5. Policies, Permits and Prices

So far, we have taken the government's policy as given and studied only 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 (2.4), as in Proposition 1. If (4.4) holds and the permits are traded, the government's problem is to maximize $\pi - vq$, which is:

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

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:

$$k\left(\underline{\theta} - \underline{x}\right) + (1-k)\left(\overline{\theta} - \overline{x}\right) - v = 0 \Rightarrow (2.4).$$

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.[18]

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).*

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

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, although 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.[19]

[18] 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, this would depend on the profit function.

[19] Although 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.

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,* $\underline{x} < \underline{q} < \overline{q} < \overline{x}$.

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 was optimal, and their future quota will thus be less than 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 toward 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 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. Although 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 to signal their types. Is it possible that the costs of signaling outweigh the benefits from trade?

Proposition 10. (i) *Allowing trade is good if and only if (6.1) holds.*
(ii) *Under (3.2), the corresponding condition is (6.2).*

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

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

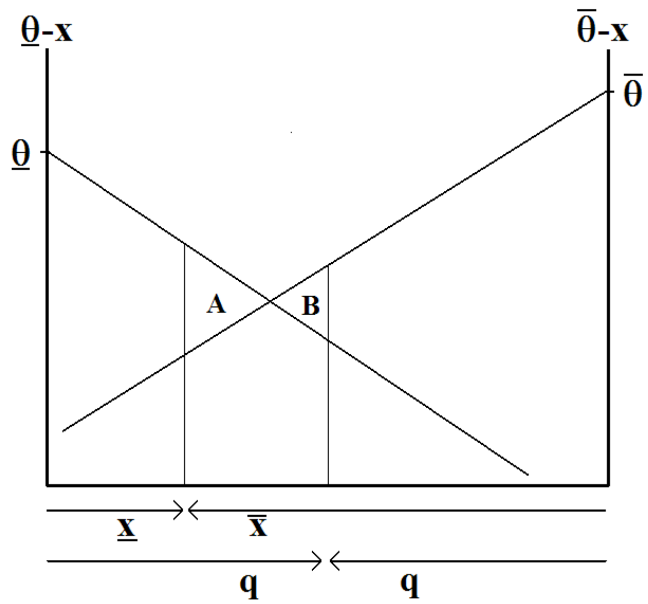

Figure 6.1: If the social loss of signaling (A) is larger than the gains from trade (B), trade should be prohibited (the figure presumes $k = \frac{1}{2}$).

Proof: Since q is the same under both regimes, we need only 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)):

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

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 holds. Otherwise, the distortions from signaling in trade must be compared to the cost of uniform emission standards. The cost of uniform quotas is, naturally, increasing in the heterogeneity $\left(\overline{\theta} - \underline{\theta}\right)$, making trade relatively better.[20] However, if the future is close (δ large), the quota-differential Δ

[20] 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.

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 $\left(\overline{\theta} - \underline{\theta}\right)$ is large while δ, Δ and p are small. Note that the result holds for any q.

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 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. Formally, if s_a and δ_a are the annual stability probability and discount factor, then $s = s_a^t$ and $\delta = \delta_a^t$ where t is the number of years in each period. Clearly, s and δ are both decreasing in t.

Corollary 1. *If the government distributes quotas frequently, it is better to prohibit trade.*

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.

Corollary 2. *The more important is the environmental problem, the more likely it is that trade should be prohibited.*

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 then learned their types, providing useful information when distributing the permits now. Or, to give another example, the non-tradable permits 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 that they should receive more quotas in the next period. This intuition is confirmed in our working paper version: When $f \to \infty$, $x_i \to q$ and the quotas are strictly enforced, but the government is still able to distinguish low- and high-cost firms.

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.*

(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 receive low quotas now. The sum of the π_is is thus:

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

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

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. But as long as such a signal would be imperfect, high-cost firms would still find it necessary and desirable 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 permits better relative to tradable permits.

(ii) Throughout this 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 (2.2), implying that (3.2), and thus all the results, would continue to hold. If firms were of different sizes, to give 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 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 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 affects its probability of becoming a low-cost firm. A successful investment implies that the firm is penalized in the form of a smaller quota, with an immediate effect 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 more frequently the government intervenes, the more the incentives are distorted.

(v) Our equilibrium concept is crucial. In particular, the Intuitive Criterion implies there is a unique equilibrium, which is in separating strategies. This criterion is sometimes criticized because 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 $k \to 1$, $p \to v$, and almost all firms pollute optimally. Similarly, by combining (5.1) and (4.2), as $k \to 0$, $\overline{x} \to \overline{\theta} - v$, 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.[21] 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.

[21] This is related to the ratchet effect (see e.g. Freixas *et al.*, 1985).

However, the other results would survive 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 desire to be fair. We show, however, that these two goals conflict in a dynamic setting. Our model relies on two assumptions that both match 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). In equilibrium, the permit price is above marginal costs of cleaning, and trade is distorted. 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 in solving environmental problems. But due to their short history, there is not much empirical evidence to draw upon. We have already mentioned that the gains from trade, although large, have 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, different from earlier theories, but more in line with the evidence.[22] Finally, our model predicts there may be multiple equilibria for the permit price, which perhaps can explain the sharp drop in price at the ETS market late April, 2006.[23]

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 often 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.[24]

[22] Theoretically, Cason (1993) suggests that bidders (in the EPA's auction) have an incentive to understate their value of the permit. Although 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 conclude: "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 at prices above those prevailing in the private market".

[23] 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 correspond 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).

[24] Our analysis is also a reminder that the first and the second welfare theorems may conflict in a dy-

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 formalized 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.

namic 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 is not true when the plan is based on manipulable characteristics (see e.g. Roberts, 1984). If, in our model, the distributions of permits were based on the firms' past types (which are non-manipulable), there would be no distortions. However, the distributions are based on the expectation over types, and these are manipulable by the firms.

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