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Optimal design of a phase-in emissions trading program

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Abstract

This paper studies a phase-in emissions trading program with voluntary opt-in possibilities for non-affected firms and derives optimal permits allocations to affected and opt-in firms when the environmental regulator has incomplete information on individual unrestricted emissions and control costs. The regulator faces a trade-off between production efficiency (minimization of control costs) and information rent extraction (reduction of excess permits allocated to opt-in firms). The first-best equilibrium can be attained if the regulator can freely allocate permits to affected and opt-in firms; otherwise a second-best equilibrium is implemented. The latter is sensitive to uncertainty in control costs and benefits. © 2000 Elsevier Science S.A. All rights reserved.

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1. Introduction

In recent years we have witnessed a significant increase in the attention given by environmental policy makers to market-based instruments, particularly tradeable

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emissions permits.¹ The sulfur dioxide (SO₂) emissions trading program under Title IV of the 1990 Clean Air Act Amendments is the largest experience with the use of tradeable permits ever implemented. Furthermore, it is the first emissions trading program to include a voluntary participation provision — the Substitution provision — in its first phase of implementation.² Electric utility units not affected by the emissions limits of Phase 1 can voluntarily *opt-in* and receive tradeable permits.³

Although the Substitution provision was primarily designed to allow those *non-affected* electric units with low control cost to opt in, Montero (1999) explains that a large number of non-affected units opted in because their unrestricted or counterfactual emissions (i.e. emissions that would have been observed in the absence of regulation) were below their permit allocation. In other words, they had received *excess permits*. While shifting reduction from high-cost *affected* units to low-cost non-affected units reduces aggregate compliance costs, excess permits may lead to social losses from higher emissions than had the voluntary provision not been implemented.

As with any other regulatory practice, the optimal design of a phase-in emissions trading program with opt-in possibilities for non-affected firms is subject to an asymmetric information problem in that the regulator has imperfect information on individual unrestricted emissions and control costs. Furthermore, if we believe that either for practical or political reasons, phase-in or less than fully comprehensive trading systems are likely to be the rule rather than the exception in future environmental policy, the same sort of issues observed in the SO₂ emissions trading program are likely to arise in attempts to implement tradeable permit schemes in practice. In fact, a salient example is provided by current emissions trading proposals in dealing with global warming that call for early carbon dioxide restrictions on OECD and few other countries with voluntarily opt-in possibilities with the rest of the world (see Tietenberg and Victor (1994), and The Kyoto Protocol to the Convention on Climate Change).⁴ In this paper I study the welfare implications and implications for instrument design of this particular asymmetric information problem.

As shown below, in a world with perfect information and no transaction costs, a

¹For the theory and practice of tradeable permits see Tietenberg (1985) and Hahn and Hester (1989).

²In Phase 1 (1995 through 1999), the ‘dirtiest’ 263 electric utility units are mandatorily affected, while in Phase 2 (2000 and beyond), more than 2000 additional units become affected. For more details, see Joskow and Schmalensee (1998).

³Tradeable permits are called *allowances* in this particular trading program. In this paper, however, I will use the term *permits* throughout.

⁴As mentioned by a referee, another interesting example in the context of global warming might be the possibility of ‘early voluntary reduction credits’ in the US prior to the binding target on carbon dioxide emissions in 2008. Although the pre-2008 and post-2008 agents may appear to be the same, if the ‘voluntary credits’ are used to increase the binding target, the same sort of problems discussed in this paper will be present.

regulator would issue permits to opt-in firms equal to their unrestricted emissions in each period. In practice, however, the environmental regulator cannot anticipate the level of unrestricted emissions. Yet, s/he must establish a permit allocation rule in advance that cannot be changed easily even if new information would suggest so.⁵ Thus, we must recognize that a voluntary program is subject to an asymmetric information or adverse selection problem in that firms reducing emissions below their permit allocation independent of the environmental legislation will receive excess permits.⁶ In deciding how to set the allocation rules for affected and opt-in firms, the regulator faces the classical trade-off in regulatory economics between production efficiency (minimization of aggregate control costs) and information rent extraction (reduction of excess permits). For instance, a too restrictive allocation rule for opt-in firms may inefficiently leave too many low-cost firms outside the program.

The regulator's problem reduces to that of finding the permit allocations for affected and opt-in firms that maximizes social welfare under conditions of imperfect information, distributional concerns and cost and benefit uncertainty. To my knowledge there is no paper addressing the issue of adverse selection and optimal design of a phase-in program. Montero (1999) identifies and tests the issue empirically but does not derive optimal permit allocations. In this paper, I study the optimal design problem following literature on the economics of regulation (Laffont and Tirole, 1993), instrument choice under uncertainty (Weitzman, 1974; Stavins, 1996), and optimal environmental regulation under imperfect information (Kwerel, 1977; Dasgupta et al., 1980; Spulber, 1988).

One of the results of the paper is that if the regulator has two instruments — the permit allocation to originally affected firms and to opt-in firms — in the absence of income effects and distributional concerns, s/he can achieve the first-best outcome. This result is similar to those of Kwerel (1977), Dasgupta et al. (1980), and Spulber (1988) in that information asymmetries may not prevent the environmental regulator from achieving the social optimum. If the regulator, however, cannot make 'permit transfers' from affected to opt-in firms, so that s/he has only one instrument — the permit allocation to opt-in firms — s/he achieves a second-best outcome in which the opt-in allocation is lower than the first-best opt-in allocation to the point where gains from information rent extraction are just offset by the productive efficiency losses of leaving low-cost non-affected firms outside the program. I also find that the second-best result is sensitive to

⁵The regulator may not want to use information too close to the compliance period in order to prevent strategic behavior on the part of the firms. In fact, in the Substitution provision of the SO₂ trading program, the EPA sets the permit allocation of opt-in electric units approximately equal to their 1988 emissions level — 7 years before compliance.

⁶As shall become clear later in the paper, it may happen that, on aggregate, opt-in firms do not receive excess permits (still opt in because their low marginal control costs) if the allocation rule is too tight.

uncertainty in aggregate control costs and benefits. If benefit and cost uncertainties are correlated negatively or not at all, the regulator always benefits from setting the opt-in rule slightly above the ‘certain’ second-best allocation.

The remainder of the paper is organized as follows. In Section 2, I present the model and explain the trade-off between production efficiency and information rent extraction. In Section 3, I derive the social optimum or first-best permit allocation rules for affected and opt-in firms when the regulator lives in a world of complete information and certainty. In Section 4, I derive the optimal design when the regulator has incomplete information on individual unrestricted emissions and marginal control costs, but still she has two instruments and there are no income effects from permit allocation transfers between affected and opt-in firms. Although the results in Sections 3 and 4 can be demonstrated graphically (and are), I also develop analytical proofs to structure subsequent sections. In Section 5, I include distributional concerns and restrict the analysis of Section 4 to the optimal design when the regulator has only one instrument — the permit allocation to opt-in firms. In Section 6, I study the effect of benefit and cost uncertainty on instrument design. Concluding remarks are in Section 7.

2. The model

There are two periods, $t = 0, 1$, and a continuum of polluting firms of mass 1. I do not consider pollution in period 0, and without loss of generality, we let emissions in period 0 to be equal across firms and equal to u_0 . In period 1, each firm’s unrestricted emissions u^i (i.e. emissions that would have been observed in the absence of the regulation) are expected to be equal to u_0 , but they can be higher, the same as, or lower than that. In addition, each firm can reduce emissions at a constant marginal cost c^i . Values of u^i and c^i are firm’s private information, but their cumulative distributions are common knowledge. The regulator implements an emissions trading program to control pollution in period 1.

I assume that $u \in [\underline{u}, \bar{u}]$ and is independently identically distributed according to an arbitrary cumulative distribution $F(u)$, with density $f(u)$ and mean u_0 (this is for both affected and non-affected firms). Similarly, I assume that c is independently identically distributed according to an arbitrary cumulative distribution $G(c)$, with density $g(c)$. Let intervals of c differ among affected and non-affected firms; in particular I make $c \in [\underline{c}, \tilde{c}]$ for affected firms and $c \in [\underline{c}, \bar{c}]$ for non-affected firms. Thus, the regulator knows a priori whether non-affected firms have, on average, higher or lower control costs than affected firms.

The timing of the problem is as follows (hereafter I omit the sub-index i). In period 0, the regulator designates a fraction $\alpha < 1$ of firms to be mandatorily affected, which are referred to as *affected* firms. I discuss neither why only some firms are mandatorily affected in the first place nor the criteria used to select these

affected firms.⁷ In that period, the regulator also establishes a reduction target (\bar{q}) to be imposed upon affected firms (through the allocation of permits a_A), and the opt-in allocation rule, a_{OP} , to *non-affected* firms that voluntarily opt in — the so-called *opt-in* firms.⁸ In period 1, non-affected firms opt in after observing their unrestricted emissions u , marginal control cost c , and the market clearing price of permits p .⁹ The regulator cannot tell firms' marginal costs and unrestricted emissions apart, but knows aggregate figures so he can deduce p and aggregate emissions for a target \bar{q} and an opt-in allocation a_{OP} .

Let us first illustrate the trade-off between control cost minimization and information rent extraction with the aid of Fig. 1. The horizontal axis indicates the amount q by which total emissions are reduced below their unrestricted level, $B'(q)$ represents the marginal social benefit of emissions reduction,¹⁰ and $C'_A(q)$ represents the marginal control cost of emissions reduction from affected firms.¹¹ As usual, I assume that $B'(q) > 0$, $B''(q) < 0$, $C'(q) > 0$, $C''(q) > 0$, $B'(0) > C'(0)$, and $B'(q) < C'(q)$ for q sufficiently large.

Let for the moment \bar{q} be the emissions reduction target, not necessarily optimal, chosen by the authority to be imposed upon affected firms.¹² Aggregate control costs are then given by the area under $C'_A(q)$ from 0 to \bar{q} . When the regulatory agency implements the voluntary program and issues, to opt-in firms, permits equal to their historic emissions u_0 , the new marginal control cost curve shifts downward with the inclusion of low-cost opt-in firms. Let $C'_{AOP}(q)$ be the aggregate marginal control costs from affected and opt-in firms. If it happens that period 1 unrestricted emissions of all opt-in firms are equal to u_0 and hence to the permit allocations, the reduction target \bar{q} remains the same, aggregate control costs reduce to the area under $C'_{AOP}(q)$ from 0 to \bar{q} , and savings from the voluntary opt-in program are given by $A(\text{ABFG})$, where $A(\cdot)$ denotes area. In short, there is no adverse selection and no need for information rent extraction.

When some opt-in firms have reduced their unrestricted emissions below historic levels and in this case below the permit allocation, the original reduction target \bar{q} reduces to $\bar{q} - EA$, where EA is the excess allocation of permits to opt-in firms.¹³ Permits EA are used to cover reductions that would have occurred had the

⁷Joskow and Schmalensee (1998) explain the political economy of the selection of mandatory electric units in Phase 1 of the SO_2 emissions trading program.

⁸Hereafter subindexes A , NA , and OP will refer to affected, non-affected and opt-in firms, respectively. It should be emphasized that an opt-in firm is a non-affected firm that voluntarily chose to opt-in.

⁹This seems to be a strong assumption since opt-in firms affect p as well, but aggregate information allows any agent to predict the equilibrium price for a given a_A and a_{OP} .

¹⁰Note that this is equivalent as using a damage function $D(e = u - q)$, where e are emissions.

¹¹ $C'_A(q) = c^i$ such that $q = \int_c^i \int_u^u u' dF dG$.

¹²Note that when reductions are imposed only upon affected firms the optimum would be obtained by making $B'(q) = C'_A(q)$.

¹³Next section shows how to estimate EA .

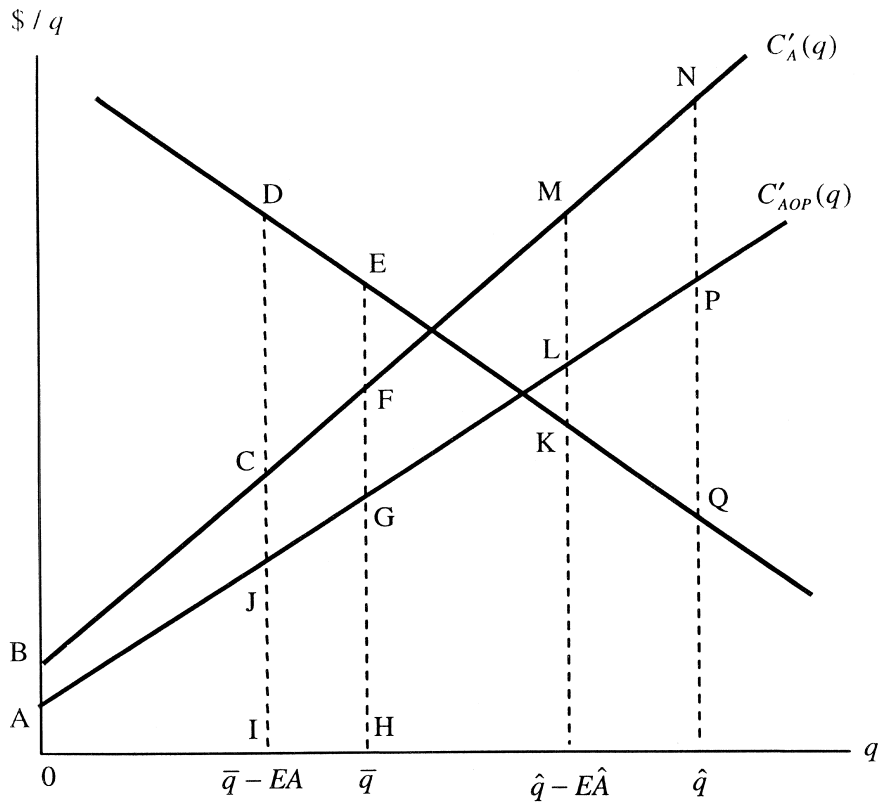


Fig. 1. Net benefits from voluntary opt-in.

voluntary program not been implemented. The adverse selection effect is represented by this shift of the original reduction target to the left.

Aggregate control costs are now given by the area under $C'_{AOP}(q)$, from 0 to $\bar{q} - EA$. While savings from lower cost reductions are given by $A(ABCJ)$, savings from avoided reductions are given by $A(ICFH)$. On the other hand, emissions will be larger than otherwise by an amount equal to EA . The social cost attached to these additional emissions is given by the area under $B'(q)$ from $\bar{q} - EA$ to \bar{q} , which is $A(IDEH)$.

The total savings or net benefits associated with the voluntary program are given by $A(ABCJ) - A(CDEF)$, which can be positive or negative, depending on the slope of the $B'(q)$ and $C'(q)$ curves, how much reduction substitution between affected and opt-in firms is economically available, and where the original reduction target \bar{q} is situated. As we move the reduction target \bar{q} to the right, marginal costs increase while marginal benefits decrease, and so does the negative effect of excess permits.

For instance, if a new reduction target, \hat{q} , is located to the far right, the adverse selection effect from excess permits may have no deleterious welfare effects, but the opposite. For clarity in exposition let us say that in Fig. 1, $C'_{AOP}(q)$ is still the aggregate marginal control costs from affected and opt-in firms when \hat{q} is the original reduction target and the permit allocation to opt-in firms is, again, equal to u_0 .¹⁴ By the same arguments stated before, it is not difficult to see that given the new reduction level $\hat{q} - E\hat{A}$ (where $E\hat{A}$ is the new level of excess permits), total benefits from the voluntary program are equal to $A(\text{ABML}) + A(\text{KMNQ})$, which is obviously positive.

In the following sections, I will solve the regulator's optimization problem under different conditions. I start with the case where the regulator lives in a world of complete information and certainty.

3. Optimal design under complete information

Here I assume that the regulator observes individual unrestricted emissions in period 1, or equivalently, that they are equal to emissions in period 0, and has perfect knowledge about the aggregate benefit and aggregate control costs curves for affected and non-affected firms. There is no adverse selection. The objective of a risk-neutral regulator is to determine the optimal emission reduction target q to be achieved from reductions of affected and non-affected firms (q_A and q_{NA} , respectively) by solving

$$\max_{q_A, q_{NA}} W = B(q) - C_A(q_A) - C_{NA}(q_{NA}) \quad (1)$$

subject to

$$q = q_A + q_{NA}. \quad (2)$$

Replacing (2) into (1), the solution is given by the first-order conditions

$$B'(q^* = q_A + q_{NA}) = C'_A(q_A) = C'_{NA}(q_{NA}) = p^*. \quad (3)$$

To implement the social optimum or first-best solution (q^*, p^*) , the regulator must impose a reduction target upon affected firms \bar{q} — through the allocation of permits a_A — and define an allocation rule a_{OP} for opt-in firms such that the market clearing price of permits $p = p^*$. The allocation rule for opt-in firms must be such that all non-affected firms with marginal costs below or equal to p^*

¹⁴Rigorously, it shifts downward. Given the higher equilibrium price, low-cost firms that did not opt in before because of high unrestricted emissions may now opt in. This will become clearer in the following sections.

voluntarily opt in. In other words, a_{OP} must be such that for all non-affected firms with $c \leq p^*$ we have¹⁵

$$\pi = p^* a_{OP} - cu \geq 0 \quad (4)$$

where π are opting-in profits. Because an opt-in firm obtains profits by either having unrestricted emissions below the permit allocation or by producing permits at a cost below the market price, there may be also firms opting in if $c > p^*$ as long as $a_{OP} > u$.

In order to define the optimal a_{OP} , the regulator would not want to let $a_{OP} < u$, because that would inefficiently prevent firms with $p^* a_{OP}/u < c < p^*$ from opting-in. Neither would she want to set $a_{OP} > u$, because high-cost non-affected firms ($c > p^*$) would opt in without making any reduction. Although in the latter situation the regulator could still achieve the first-best by reducing the allocation of affected firms, s/he rather sets the optimal allocation rule $a_{OP} = u$.

Furthermore, since $a_{OP} = u$, we have that $EA = 0$. The first-best reduction target imposed over affected firms is $\bar{q} = q^*$, which is obtained from (3). Permit allocations to these firms, a_A , are equal to the difference between their unrestricted emissions and the target \bar{q} such that (α is the fraction of affected firms)

$$\int_0^\alpha a_A^i di = \alpha \int_{\underline{u}}^{\bar{u}} u dF - \bar{q} = \alpha u_0 - q^* \quad (5)$$

where the ‘allocation function’, a_A^i , can be chosen arbitrarily. In the absence of transaction costs and uncertainty on trade approval, the initial allocation to affected firms is irrelevant from an efficiency standpoint.¹⁶ Summarizing:

Proposition 1. *In a world of perfect information, the regulator allocates permits to opt-in firms equal to their unrestricted emissions. Aggregate permits to affected firms are set equal to the difference between their aggregate unrestricted emissions and the first-best reduction target q^* . (Note that in the absence of distributional concerns and income effects the regulator can also achieve the social optimum by allocating permits equal to $a_{OP} > u$ for opt-in firms and proportionally lower for affected firms such that the target remains at the first-best level).*

Fig. 2 illustrates the first-best result more generally. $C'_{ANA}(\cdot)$ is the marginal control costs from affected and non-affected firms, and because all low-cost units opt in, it is also the marginal cost for affected and opt-in firms combined, $C'_{AOP}(\cdot)$. First, the regulator optimally sets \bar{q} by issuing permits to affected firms. Then, s/he sets the voluntary opt-in allocation rule $a_{OP} = u$. With that allocation rule, all

¹⁵ Recall firms can reduce u units of emissions at a constant marginal cost of c .

¹⁶ See Stavins (1995) and Montero (1998).

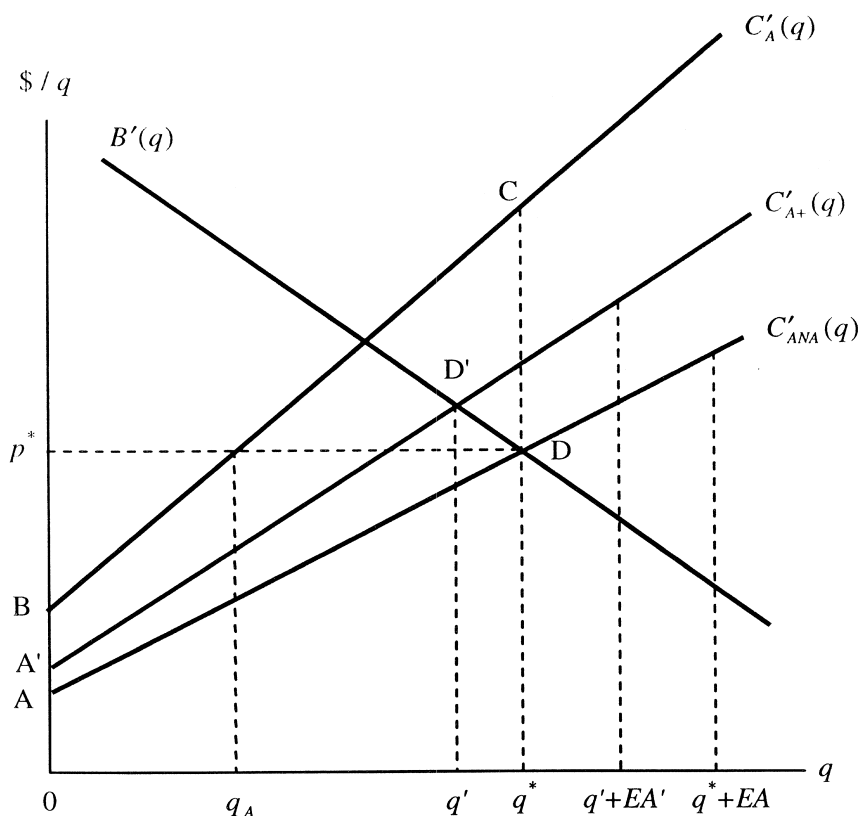


Fig. 2. Optimal allocations for affected and opt-in firms.

non-affected firms opt in, and since there are no excess permits, $EA=0$, the additional benefits from the voluntary program are equal to $A(ABCD)$. Thus, the regulator achieves the social optimum (maximum net benefits). At the social optimum, the market permits price is p^* , so affected units control at q_A rather than at their original target \bar{q} . The difference, $\bar{q} - q_A$, are emission reductions from opt-in firms.

4. Optimal design under incomplete information and unlimited transfers

Consider now incomplete information on period 1 unrestricted emissions u and control costs c . The regulator cannot anticipate u from both affected and opt-in firms. At the aggregate level, however, the regulator knows that unrestricted emissions are equal to period 0 aggregate emissions. While imperfect information

regarding affected firms does not matter from an efficiency standpoint, since all firms are affected, it does matter regarding non-affected firms, since firms reducing emissions independent of compliance are more likely to receive excess permits and to opt in.

The regulator knows the aggregate marginal cost curves $C'_A(q)$ and $C'_{NA}(q)$,¹⁷ but s/he has imperfect information on individual cost values c . Note that observing c and not u does not solve the adverse selection problem entirely, as observing only u would. If the regulator knows c , s/he can distribute permits only to firms with $c < p$. But because of participation constraint (4), part of the trade-off between efficiency and information rents still persists.¹⁸

The regulator's problem, again, is to find the permit allocations to affected and opt-in firms that maximizes the value of (1). Since the regulator has two instruments (allocations to affected and opt-in firms) and two objectives (minimization of control costs and extraction of information rents), it remains to show that it is feasible to achieve the first-best.

For a given reduction target upon affected firms \bar{q} (or allocation function a_A) and an allocation rule a_{OP} , there will be a final equilibrium price $p = p(\bar{q}, a_{OP})$,¹⁹ which the regulator can deduce, even though he cannot observe individual marginal costs. Given p and a_{OP} , the likelihood of a non-affected firm opting in is illustrated in Fig. 3. The horizontal axis depicts the range of possible marginal costs c while the vertical axis depicts the range of possible unrestricted emissions u . A non-affected firm represented by the pair (c, u) will opt in as long as it falls in area A_1 , A_2 or A_3 , that is where $\pi \geq 0$. A firm falls in area A_1 if it has unrestricted emissions below its permit allocation ($u \leq a_{OP}$) and is making no reduction because $c \geq p$. It falls in A_2 if $u \leq a_{OP}$ and is making reduction of u because $c \leq p$. Finally, it falls in A_3 if, having $u \geq a_{OP}$ it still makes a reduction of u because $\pi \geq 0$, where $c(u) = pa_{OP}/u$ as indicated by Eq. (4).

Thus, the total emissions reduction from opt-in firms (q_{OP}), total control costs (C_{OP}), and total excess allocation of permits (EA) would be given by

$$q_{OP} = q_{OP}(a_{OP}, p(\bar{q}, a_{OP})) = (1 - \alpha) \iint_{A_2 A_3} u dF dG \quad (6)$$

$$C_{OP} = C_{OP}(a_{OP}, p(\bar{q}, a_{OP})) = (1 - \alpha) \iint_{A_2 A_3} c u dF dG \quad (7)$$

¹⁷In Section 5 I introduce uncertainty in the knowledge of these curves. Part of that uncertainty may come from not knowing u_0 in period 1.

¹⁸Consider the marginal firm with $c = p$. To make sure this firm opts in, the regulator will need to set $a_{OP} = \bar{u}$.

¹⁹For an interior solution, I assume $\underline{c} < p < \bar{c}$.

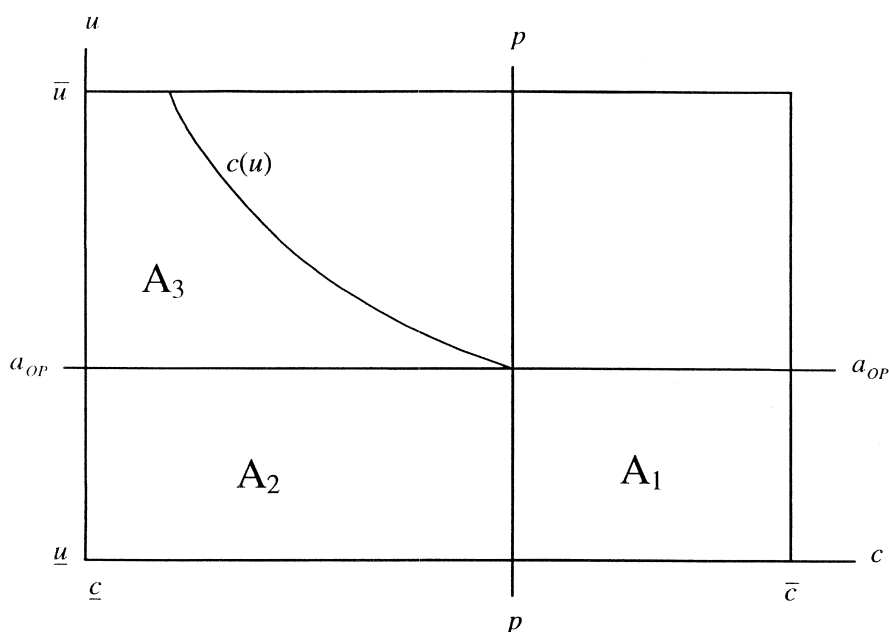


Fig. 3. Likelihood of opting-in for a non-affected firm.

and

$$EA = EA(a_{OP}, p(\bar{q}, a_{OP})) = (1 - \alpha) \iint_{A_1 A_2 A_3} (a_{OP} - u) dF dG, \quad (8)$$

respectively.

If the regulator imposes a reduction \bar{q} on affected firms by issuing permits a_A , and setting a_{OP} , the actual total reduction turns out to be $\bar{q} - EA$, and the reduction from affected units $q_A = \bar{q} - EA - q_{OP}$. Therefore, the objective of our risk-neutral regulator is to find a mechanism (\bar{q}, a_{OP}) that can implement the first-best outcome (q^*, p^*) by solving

$$\max_{\bar{q}, a_{OP}} W = B(\bar{q} - EA) - C_A(\bar{q} - EA - q_{OP}) - C_{OP}, \quad (9)$$

subject to (6), (7) and (8). From the envelope theorem, derivatives of W with respect to \bar{q} and a_{OP} take into account only the direct effect of \bar{q} and a_{OP} , and not the indirect effect stemming from adjustments in price p . Thus, the solution must satisfy the two first-order conditions

$$\frac{\partial W}{\partial \bar{q}} = B'(\cdot) \cdot 1 - C'_A(\cdot) \cdot 1 = 0 \quad (10)$$

$$\frac{\partial W}{\partial a_{OP}} = -B'(\cdot) \frac{\partial EA}{\partial a_{OP}} + C'_A(\cdot) \frac{\partial EA}{\partial a_{OP}} + C'_A(\cdot) \frac{\partial q_{OP}}{\partial a_{OP}} - \frac{\partial C_{OP}}{\partial a_{OP}} = 0, \quad (11)$$

where $C'_A(\cdot) = p$, by definition of a perfectly functioning permits market.

First-order condition (10) indicates that at the optimum marginal benefits and marginal costs are equal, that is $b(\bar{q}, a_{OP}) = p(\bar{q}, a_{OP})$, where $b(\cdot) \equiv B'(\cdot)$. Condition (11), on the other hand, indicates that at the optimum, marginal gains from voluntary participation are equal to marginal losses. The first two terms on the right-hand side represent marginal losses and gains from excess permits, which cancel out at the optimum since $b = p$. The final two terms represent marginal gains from cheaper reductions from opt-in firms. Using (6) and (7), first-order condition (11) can be rewritten as

$$\frac{\partial}{\partial a_{OP}} \left(\iint_{A_2 A_3} (p - c) u dF dG \right) = 0. \quad (12)$$

Eq. (12) indicates that the optimal permit allocation a_{OP} must be such that no additional gains from cheap reductions from non-affected firms are possible if the allocation is increased a bit. Since $p \geq c$, for all firms making a reduction (i.e. in either area A_2 or A_3), Eq. (12) holds in two situations. The first situation is when a_{OP} is sufficiently lower than \bar{u} that no firm opts in, because a small increase in a_{OP} does not change things; obviously, this is not optimal. The second case is when $a_{OP} \geq \bar{u}$. When $a_{OP} < \bar{u}$, the regulator can always increase a_{OP} for a given p and obtain additional gains from cheaper reductions ($A_2 + A_3$ increases with a_{OP}). As before, the regulator sets $a_{OP} = \bar{u}$ so that all firms just opt in. (Note that she may still choose an allocation $a_{OP} > \bar{u}$ but the ‘permits transfer’ from affected to opt-in firms would be larger).

Now, with $a_{OP} = \bar{u}$, we can obtain EA and hence the optimal reduction imposed upon affected firms \bar{q} (or allocation function a_A). Since the fraction of $1 - \alpha$ of non-affected firms opt in, we have that $EA = (1 - \alpha)(\bar{u} - u_0)$ and total reduction is $\bar{q} - EA$. To achieve the first-best reduction q^* , the regulator must increase the reduction target upon affected firms, \bar{q} , from q^* to $q^* + (1 - \alpha)(\bar{u} - u_0)$. Thus, total and arbitrarily distributed permits to affected firms are given by

$$\int_0^\alpha a_A^i di = \alpha \int_{\bar{u}}^{\bar{u}} u dF - \bar{q} = u_0 - \bar{u}(1 - \alpha) - q^*. \quad (13)$$

Note that if α is small and/or $(\bar{u} - u_0)$ large such that $u_0 < \bar{u}(1 - \alpha)$, the permit transfer of $(1 - \alpha)(\bar{u} - u_0)$ from affected to opt-in firms may become so large that affected firms receive negative permits. We can now summarize our findings.

Proposition 2. *Despite information asymmetries, the regulator can achieve the first-best outcome when distributional concerns are not important. The regulator*

sets the permit allocation of opt-in firms high enough so that all non-affected firms opt in. Affected firms receive fewer permits than otherwise in an amount equal to total (expected) excess permits from opt-in firms.

With the aid of Fig. 2, this result can be explained more generally. To achieve the first-best, affected firms are required to reduce $q^* + EA$ rather than q^* . If the regulator sets $a_{op} < \bar{u}$, some low-cost units in the upper left corner of Fig. 3 would not opt in. Then, $C'_{ANA}(q)$ would no longer be the total marginal cost curve, but $C'_A + (q)$, which is a combination of marginal costs from affected and opt-in firms. In that case, the best the regulator can do is to set the reduction target for affected firms equal to $q' + EA'$ such that the final equilibrium is D', instead of the first-best D. The welfare loss is $A(AA'D'D)$. Therefore, $a_{op} < \bar{u}$ cannot be optimal.²⁰

The above result is similar to those of Loeb and Magat (1979) and Spulber (1988), for the case of monopoly and environmental regulation, respectively, in that the information asymmetries may have no deleterious welfare effects. Given that the regulator has two instruments in this case, she can optimize for both control cost minimization and information rent extraction. Intuitively, all non-affected firms (the entirety of all four quadrants in Fig. 3) become opt-in firms. Excess permits become the 'social cost' of getting all cost-effective abatement possibilities, but that can be completely offset by reducing permits to originally affected firms.

In practice, however, first-best outcomes may not be implemented either because of significant distributional effects, regulator's inability to make transfer permits from one group of firms to the other, or simply because affected firms cannot receive 'negative' permits (α small and/or $\bar{u} - u_0$ large). If that is the case and we constrain a_A to be some non-negative number, for example, we are in front of a second-best problem. Finally, it is worth noting that imperfect information on individual cost did not affect the design. That changes in a second-best design, as we shall see in the next section.

5. Optimal design under incomplete information and limited transfers

If the process of allocating permits to affected firms is carried out independently of the design of any opt-in program, the regulator has only one instrument — the allocation rule of opt-in firms — to deal with the adverse selection problem if the opt-in program is actually implemented. As in the SO₂ emissions trading program, the regulator (in that case, the EPA) cannot reduce the permit allocation to affected firms in order to make transfers to opt-in firms.

²⁰If $p^* > \bar{c}$, we may have a corner solution. A high price may not prevent any firm from opting in, even if $a_{op} < \bar{u}$.

To derive the optimal design, I will start by assuming that affected firms are required to reduce a predetermined amount of emissions \bar{q} , so the aggregate number of permits issued to these firms is fixed. Thus, to derive the second-best allocation rule a_{OP} of opt-in firms we solve Eq. (11), which can be rewritten as

$$\frac{\partial}{\partial a_{OP}} \left(\iint_{A_2 A_3} (p - c) u dF dG \right) = (b - p) \frac{\partial EA}{\partial a_{OP}}. \quad (14)$$

As explained before, for a given p , the term of the left-hand side is non-negative and $\partial EA / \partial a_{OP} > 0$, by construction. For Eq. (14) to hold, at the second-best optimum we must have $b(\bar{q}, a_{OP}) \geq p(\bar{q}, a_{OP})$. Two cases are possible, depending on whether the reduction target of affected firms \bar{q} was pre-fixed above or below the optimal target when there is incomplete information and unlimited transfers, which is $q^* + (1 - \alpha)(\bar{u} - u_0)$. If $\bar{q} \geq q^* + (1 - \alpha)(\bar{u} - u_0)$ we return to the first-best case by making $a_{OP} \geq \bar{u}$ to the point where $b = p = p^*$. Note that to be in this case the reduction imposed upon affected firms must be sufficiently large.

In what follows, I focus on the (more likely) second case, which is when $\bar{q} < q^* + (1 - \alpha)(\bar{u} - u_0)$. Here, $b > p$, and the right-hand side of (14) is positive, so $a_{OP} < \bar{u}$, in order for a_{OP} to solve (14). The second-best opt-in rule $a_{OP} < \bar{u}$ implies that the regulator must give up some cost efficiency by preventing low-cost non-affected firms from opting in to extract some information rents or excess permits. At the second-best a_{OP} , both effects exactly offset each other. Total excess permits will be given by

$$EA = (1 - \alpha) \iint_{A_1 A_2 A_3} (a_{OP} - u) dF dG \quad (15)$$

and total reduction is $q_A + q_{OP} = \bar{q} - EA < q^*$. We then can establish:

Proposition 3. *In the presence of incomplete information and limited transfers, the regulator implements the second-best outcome by issuing permits to opt-in firms equal to $a_{OP} < \bar{u}$. The regulator lowers the first-best opt-in allocation to the point where cost efficiency losses exactly offset gains in information rent extraction. (In the rare case where the permit allocation (reduction target) to affected firms was set too low (high), it may be possible to implement the first-best with an opt-in allocation $a_{OP} \geq \bar{u}$).*

In the remainder of this section I illustrate some comparative statics and see whether an allocation such as u_0 can be second-best optimal.²¹ For tractability, we require some simplifying assumptions; otherwise we would need to rely on

²¹Possibly an allocation rule a_{OP} close to u_0 , such as in the SO₂ trading program, generates less resistance from a political point of view.

numerical solutions. First, let u and c be independently, uniformly distributed in their respective intervals so that $f(u) = 1/\Delta u$ and $g(c) = 1/\Delta c$, where $\Delta u = \bar{u} - \underline{u}$ and $\Delta c = \bar{c} - \underline{c}$.²² And without loss of generality, I assume that firms reduce one unit of emissions (instead of u) at a marginal cost c .²³ By incorporating (6), (7) and (8) into (11), including the appropriate limits of integration, and rearranging terms, we can reduce first-order condition (11) to

$$\frac{\partial}{\partial a_{OP}} \left(\int_{a_{OP}}^{\bar{u}} \int_{\underline{c}}^{c(u)} (p - c) dG dF + \int_{\underline{u}}^{a_{OP}} \int_{\underline{c}}^p (p - c) dG dF - \int_{a_{OP}}^{\bar{u}} \int_{\underline{c}}^{c(u)} (b - p)(a_{OP} - u) dG dF - \int_{\underline{u}}^{a_{OP}} \int_{\underline{c}}^{\bar{c}} (b - p)(a_{OP} - u) dG dF \right) = 0 \quad (16)$$

where $c(u) = (a - u + 1)p$, is the indifference opt-in curve in A_3 of Fig. 3 that makes $\pi = 0$. The first two terms in the bracket represent cost savings due to lower control cost reductions from opt-in firms; the third and fourth terms are control costs savings and social benefit losses from excess permits.

Substituting $dF = du/\Delta u$ and $dG = dc/\Delta c$, and applying Leibnitz's rule twice, we obtain for the first-order condition the quadratics

$$\frac{3p^2 - 2bp}{2} x^2 + (b - p)(p + \Delta c - \underline{c})x - (b - p)\Delta c \Delta u = 0 \quad (17)$$

where $x \equiv \bar{u} - a_{OP}$ is the solution to (17), which is obtained together with p and b through an iterative process. We are interested only in the positive-root solution.²⁴ It is not difficult to show that when $b > p$, $x > 0$ or, equivalently, $a_{OP} < \bar{u}$. Note that if $b = p$, $x = 0$ as before. But as $b - p$ increases the regulator tightens the allocation a_{OP} (x increases) because losses from information rents becomes more important than cost efficiency gains from low-cost opt-in firms.

Simple comparative statics can be done for the case where the second-best outcome leads to $p = 2b/3$, in which case $x = \Delta c \Delta u / (p + \Delta c - \underline{c})$. In fact, if p is slightly below \bar{c} , so that most non-affected firms have low control costs, we have that $x \approx \Delta u/2$ or that $a_{OP} \approx u_0$. In other words, the optimal allocation rule is very close to historic emissions. In contrast, if p is slightly above \underline{c} , so there are few cost-effective reduction possibilities beyond affected firms, the regulator will probably set a_{OP} only slightly above \underline{u} , so very few units will opt in.

²²If one assumes that u and c are correlated, I would think that a negative correlation is more likely because of economies of scale in emissions reduction. If u and c are negatively correlated A_1 increases relative to A_2 and the adverse selection problem becomes more severe. So the optimal a_{OP} should be lower than if u and c are correlated positively or not at all.

²³Same qualitative results were obtained from numerical solutions.

²⁴The negative-root solution is out of the relevant range.

The optimal choice of a_{OP} also depends on the extent to which unrestricted emissions can depart from historic emissions (i.e. variance of u). For example, if $p=2b/3$ is still the result from the second-best design, $\partial x/\partial \Delta u = \Delta c/(p + \Delta c - \underline{c})$, and provided that $\underline{c} < p < \bar{c}$, we have that $1/2 < \partial x/\partial \Delta u < 1$. Thus, for a mean preserving spread of u , x increases more than proportionally (a_{OP} decreases), despite the fact that u_0 has not changed. An important implication would be that as the historic year used to establish opt-in allocations (period 0) is moved further from the compliance year (period 1), the variance of u is likely to increase, and the optimal allocation rule a_{OP} would be tightened.

The intuition of the above result can be explained with Fig. 3. Keeping a_{OP} fixed at its second-best level, a ‘very small’ mean preserving spread of u affects in different ways the amount of excess permits and reductions from areas A_1 , A_2 and A_3 (p and b do not change at the margin by the envelope theorem). The number of firms located in A_1 and A_2 do not change, which results in the same reductions and (marginally) more excess permits. The number of firms located in A_3 drops a bit because few of those firms with very high u will no longer opt-in, which results in fewer reductions. Despite few firms opt-out there will be fewer excess permits coming from A_3 because of the (marginally) higher u ; unless $c(\bar{u})$ is too close to or smaller than \underline{c} .

While less reduction would suggest increasing a_{OP} , higher excess permits would suggest doing the opposite. Looking at the size of the different areas A_1 , A_2 and A_3 , the latter suggestion dominates the smaller p is relative to \bar{c} [or the higher the difference $\bar{c} - c(\bar{u})$]. Further, the latter suggestion also dominates the smaller p is compared to b , because cheaper reductions (control cost minimization) become relatively less important than leaving excess permits (information rents extraction).²⁵

6. Benefit and cost uncertainty

In this section, I incorporate aggregate uncertainty concerning the (marginal) benefit and the (marginal) control cost functions. The marginal benefit value for a given reduction is imperfectly known at present (period 0), which is when the regulator establishes the opt-in allocation rule.²⁶ As in Weitzman (1974) and Baumol and Oates (1988), I model marginal benefit uncertainty as an additive stochastic error term, that is $B'(q, \theta) = B'(q) + \theta$, or in our simplified notation $b(q, \theta) = b(q) + \theta$, where $E[\theta] = 0$, $E[\theta^2] > 0$ and $E[\cdot]$ is the expected value operator.

In addition, the regulator is uncertain about the marginal cost curves at the time

²⁵The first suggestion would apply for cases where p is close to b and to \bar{c} .

²⁶In a dynamic context is important to consider whether or not part of the uncertainty is resolved ex-post.

s/he establishes the opt-in allocation rule. Again, I model marginal cost uncertainty as an additive and uniform stochastic error term across firms such that $C'_A(q, \eta) = C'_A(q) + \eta$ and $C'_{NA}(q, \eta) = C'_{NA}(q) + \eta$, where $E[\eta] = 0$, $E[\eta^2] > 0$ and $E[\theta\eta]$ does not need be zero. Since $C'(q) = c$ (see footnote 11), this specification of uncertainty implies that $c(\eta) = c + \eta$. In addition this specification yields that $p(\bar{q}, a_{OP}, \eta) = p(\bar{q}, a_{OP}) + \eta$.

The regulator's problem is to find the permit allocations to affected and opt-in firms that maximizes the expected value of (1), which is

$$E[W] = E[B(q, \theta) - C_A(q_A, \eta) - C_{NA}(q_{NA}, \eta)]. \quad (18)$$

The solution $q^\#$ must satisfy the first order condition

$$E[b(\cdot)] = E[C'_A(\cdot)] = E[C'_{NA}(\cdot)] = E[p(\cdot)] \quad (19)$$

which yields $q^\# = q^*$, $q_A^\# = q_A^*$, and $q_{NA}^\# = q_{NA}^*$. If the regulator has complete information or two instruments, he can implement the ex-ante first-best by setting permit allocations according to Proposition 1 or Proposition 2, respectively.

If the regulator, however, has incomplete information and cannot make permit transfers, uncertainty plays a role. It is immediately apparent from Eq. (14) that, since $\partial EA / \partial a_{OP}$ is a function of p and not b , there will be an additional stochastic term as a function of η , and of θ if b is correlated with p . To illustrate this further, I use the specific example described in the previous section and let the regulator maximize expected welfare. Placing the expected value operator in front of Eq. (16) and setting the derivative with respect to a_{OP} equal zero, we have

$$E \left[\frac{3p^2 - 2bp}{2} x^2 + (b - p)(p + \Delta c - \underline{c})x - (b - p)\Delta c \Delta u \right] = 0. \quad (20)$$

Substituting $b(\cdot, \theta) = b(\cdot) + \theta$, $p(\cdot, \eta) = p(\cdot) + \eta$, $\bar{c} = \bar{c} + \eta$, and $\underline{c} = \underline{c} + \eta$, and taking expectations, we obtain

$$\begin{aligned} & \frac{3p^2 - 2bp}{2} x^2 + (b - p)(p + \Delta c - \underline{c})x - (b - p)\Delta c \Delta u + \frac{3E[\eta^2] - 2E[\eta\theta]}{2} x^2 \\ & = 0. \end{aligned} \quad (21)$$

The new solution of x will be lower (a_{OP} higher) compared to the 'certain' second-best as long as $3E[\eta^2] > 2E[\eta\theta]$, regardless of whether $3p > 2b$ or not. Because cost curves are convex ($C'(\cdot)$, $C''(\cdot) > 0$), savings from opt-in firms are convex in p . As insurance against the high-cost event ($\eta > 0$), the regulator slightly increases the allocation a_{OP} to allow some additional low cost units to opt-in and also some additional excess permits. However, the cost of such insurance (higher emissions) may completely offset its benefits if marginal cost and marginal benefit are positively correlated ($E[\eta\theta] > 0$). The rationale is that for any high marginal cost event, there is likely to be a high marginal benefit event, so the regulator may not be willing to pay the price of more excess permits. If benefit and cost are

correlated negatively or not at all, it always pays off for the regulator to increase a_{OP} around the ‘certain’ second-best.²⁷ We can summarize this as follows:

Proposition 4. *Marginal cost and marginal benefit uncertainty are relevant only for second-best instrument design. If benefit and cost uncertainties are correlated negatively or not at all, it always pays off for the regulator to set the optimal rule a_{OP} slightly above the ‘certain’ second-best rule.*

7. Conclusions and policy implications

For either political or practical reasons, phase-in emissions trading programs that include opt-in provisions for non-affected firms are receiving significant attention. I have presented a theoretical analysis of the welfare implications and implications for instrument design when the phase-in trading program is implemented under conditions of imperfect information regarding individual unrestricted emissions (i.e. emissions that would have been observed in the absence of the regulation) and control costs, distributional concerns, and cost and benefit uncertainty.

I have shown that the regulator faces a trade-off between production efficiency (control cost minimization) and information rent extraction (reduction of excess permits for opt-in firms). A regulator having two instruments — the permit allocation to originally affected firms and to voluntary opt-in firms — can, in the absence of income effects and distributional concerns, implement the first-best outcome. If the regulator cannot make permit transfers from affected to opt-in firms, so that she has only one instrument — the permit allocation to opt-in firms — she implements the second-best allocation to opt-in firms, which is lower than the first-best allocation to the point where gains from information rent extraction are just offset by the productive efficiency losses of leaving low-cost non-affected firms outside the program. Finally, I showed that the second-best result is sensitive to uncertainty in aggregate control costs and benefits. If benefit and cost uncertainties are correlated negatively or not at all, it always pays off for the regulator to set the new optimum allocation slightly above the ‘certain’ second-best allocation.

The results of this paper can have important policy implications for the design of an emissions trading scheme to prevent global warming. Current proposals call for early carbon dioxide restrictions on OECD and few other countries with voluntarily participation possibilities from less developed countries. In deciding about the total number of permits (a_{OP}) to be credited to an ‘opt-in project’, the results of this paper indicate that the imperfectly informed regulator would face the

²⁷See Weitzman (1974) and Stavins (1996) for a similar finding regarding optimal instrument choice.

same trade-off between production efficiency and information rent extraction. I leave for future research the development of a dynamic setting to study this particular application in more detail.

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