Environmental Regulation in a Dynamic Model with Uncertainty and Investment

March 2006

Nori Tarui

The Earth Institute, Columbia University

(Email: nt2135@columbia.edu)

Stephen Polasky

Department of Applied Economics, University of Minnesota

(Email: polasky@umn.edu)

Abstract

This paper studies dynamic environmental regulation with endogenous choice of emissions abatement technology by regulated firms and exogenous learning about environmental damages from emissions by a regulator. Investments in abatement technology by one firm that lower abatement costs for the firm, may also lower abatement costs of other firms (technology spillovers). There are two issues facing environmental regulators: i) setting regulation to achieve optimal abatement given available information, and ii) setting regulations to achieve optimal investment given possible strategic investment and technology spillovers. We compare taxes, standards and marketable permits, under flexibility, in which policy is updated upon learning new information, versus under commitment, in which policy is not updated. Flexible policy allows regulation to reflect the most up to date information. However, under flexible policy firms can invest strategically to influence future regulation. We find that an optimal solution for both investment and abatement decisions can be achieved under a flexible marketable permit scheme in which the permit allocation to a firm is increasing in the firm's investment. No other policy scheme, taxes, auctioned permits, or standards, under either flexibility or commitment, will guarantee achieving an optimal solution. These results run counter to prior literature that find price-based mechanisms are superior to quantity-based mechanisms, or that such comparisons depend on conditions.

1 Introduction

Much of the environmental economics literature concerns optimal regulation of externalities using a static model. But many environmental regulatory issues have important dynamic elements. Stock pollutants, such as greenhouse gases, PCBs, and nuclear waste have persistent environmental effects that can last for decades, or millennia in the case of nuclear wastes. Even in the case of flow pollutants, where the biophysical effect of emissions in the environment dissipates quickly, there are important temporal dimensions to many decisions. Investment in capital, including abatement equipment, is typically long-lived. Environmental regulations themselves typically are adjusted only periodically to reflect new realities.

In addition to dynamics, environmental issues also often are subject to considerable uncertainty. How damaging are emissions? How costly will it be to reduce emissions? Scientific advances over time change our understanding of the severity of various environmental threats. For example, it was not known until the 1970s that chlorofluorocarbons (CFCs) posed a threat the earth's ozone layer that shields living organisms from harmful ultraviolet radiation. In other cases, environmental threats have faded with further scientific understanding. On the cost side, investments by firms in R&D and abatement technology change the costs associated with emissions reductions. DuPont's success in finding substitutes for CFCs made phasing out CFC production under the Montreal Protocol a relatively inexpensive proposition.

The acquisition of new information about either benefits or costs of environmental improvement would seem to call for flexible environmental policy that can be updating to reflect new information. Flexible policy, though, opens the door for possible strategic behavior by firms. In making an investment decision, a rational firm would take account of the direct investment cost and the direct benefit from reduction in abatement cost, and in addition, would take account of indirect effects on costs through impacts on investment choices of other firms and impacts on future regulatory policy. Of course, to have any impact on other firms or the regulator, a firm must be of sufficient size relative to the market. Here we are thinking of firms such as large automobile manufacturers (e.g., Ford, GM, Toyota), chemical companies (e.g. DuPont), or oil companies (e.g., ExxonMobil, Chevron) that are major players in the environmental arena as well as in their respective markets. Such firms have government relations staffs and clearly think about how their actions will play in the market and in policy arenas.

Each firm's investment may influence future regulations not only directly but also indirectly through the influence on the other firms' investment and emission choice via strategic interactions and technology spillovers. Technology change in one firm not only reduces its own abatement costs but may reduce other firms' abatement costs through technology spillovers. Such technology spillovers are observed in environmental and energy R&D (Margolis and Kammen 1999, Popp 2005) as well as in other areas (Jaffe 1986, Bloom et al. 2005). Competition among firms in environmental R&D can take several different forms. On the one hand, firms may invest in abatement technology to get tougher environmental rules in an attempt to raise rivals' costs (Salop and Scheffman 1983). After ARCO discovered a way to produce cleaner reformulated gasoline, the California Air

Resources Board mandated that all oil companies sell gasoline causing fewer emissions.[1] Because ARCO had an advantage in producing such gasoline, the regulatory shift gave ARCO a competitive advantage. DuPont's discovery of substitutes for CFCs was major factor in strengthening the Montreal Protocol from a 50% reduction in CFC production by 1999 to a complete production ban. DuPont profited by shifting demand from CFCs to substitutes where DuPont held patents (Lyons and Maxwell 2004). On the other hand, firms sometimes collaborate in environmental R&D. The California Fuel Cell Partnership, a collaborative of auto makers and energy companies to develop hybrid cars, is one such example.

In setting regulatory policy, the regulator should also think strategically. Not only will regulation affect abatement choices by firms but will also affect investment decisions. Over the long-run, the effect on investment choices may be of far greater significance than short-run abatement decisions (Jaffe et al. 2003). The regulator faces a difficult challenge in trying to set optimal dynamic environmental regulation. A regulator whose goal is to maximize social welfare will need to set regulatory policy with an eye on how policy affects abatement decisions as well as investment decisions. Ideally, the regulator would like to equate expected marginal benefits and marginal costs of abatement given current technology and information about damages as well as provide proper incentives for investment in new abatement technology. Finding an optimal regulatory scheme is complicated by the fact that: i) the regulator will gain information about the degree to which emissions cause environmental damages through time so that environmental targets may change, ii) firms may act strategically vis-à-vis the regulator, and iii) there are technology spillovers between firms from investment in abatement technology.

In this paper, we analyze a dynamic model of environmental regulation with endogenous choice of emissions abatement technology by regulated firms and exogenous learning about environmental damages from emissions by a regulator. We compare the efficacy of various regulatory policy mechanisms. We consider "flexible policy" in which the regulator can adjust policy to reflect new conditions, and "commitment policy" in which the regulator fixes policy and does not change it. For both flexible and commitment policies, we compare outcomes with taxes, standards, tradable permits that are auctioned, and tradable permits that are distributed at no charge to firms. In general, it is difficult to find optimal solutions to the dynamic regulatory problem because correct incentives need to be provided for both emissions abatement and investment decisions. Optimal solutions typically require at least as many policy instruments and problems to be addressed. We show that taxes, standards, and auctioned tradable permits will not achieve an optimal solution (except by chance). These policies fail to achieve an optimal solution because they are single instruments addressing two problems. However, a flexible tradable permit scheme where the total number of permits allocated is set to the point where marginal benefits of abatement equals marginal cost given conditions, and where permits are allocated to firms based on their investment, can guarantee achieving an optimal solution. Decisions on the total number of permits and the allocation of permits among firms gives the regulator two instruments by which to address both

[1] Cited from http://www.aqmd.gov/monthly/aprilcov.html.

investment and abatement decisions. The result that freely distributing tradable permits yields an efficient outcome while auctioning permits contrasts with previous studies that find that auctioning permits is preferable or the same as free distribution (Milliman and Prince 1989, Jung, et al. 1996) or that price mechanisms (taxes) are preferable to quantity mechanisms (Tarui and Polasky 2005).

When uncertainty about environmental damages from emissions is relatively small, there is little loss from the regulator committing to policy. In this case, commitment policy is preferred to flexible policy because avoiding distorting investment incentives is more important than adjusting policy in light of new information. We also find that commitment is preferable to flexibility under damage uncertainty if the slope of marginal abatement costs is large and if the marginal contribution of investment to lowering marginal abatement costs is large relative to the slope of marginal damages. In such cases, correcting investment incentives by choosing fixed targets will generate smaller welfare losses than flexible policies, which induce ex post optimal emissions but distort investments.

Under commitment policy, taxes and standards yield exactly the same outcome. The regulator sets regulation such that expected marginal benefits of abatement equal expected marginal costs (post investment). Freely distributed tradable permits also yield the same outcome as a tax or a standard as long as the regulator chooses firms' initial endowment of permits such that no permit trading occurs in equilibrium. When permits are auctioned, however, each firm has an incentive to over-invest in abatement technology in order to lower abatement costs, which results in a lower equilibrium permit price. When technology spillovers are large, auctioning permits is preferred to the other commitment policy instruments because firms choose larger investments.

With flexible policies, taxes and auctioned permits generate the same outcome but this outcome differs from the outcome with standards or freely distributed tradable permits. Knowing that regulations will be changed to reflect future conditions, regulated firms can invest strategically to change future regulation.[2] With flexible standards, each firm has a strategic incentive to reduce investment in order to get looser emissions standards. With flexible taxes or auctioned permits, each firm has a strategic incentive to increase investment in order to get a lower tax rate or permit price. Whether freely distributed permit trading is preferred to auctioned permit trading depends on the regulator's rule for distributing permits.

Our results also illustrate the possibility that firms may have an incentive to lower rivals' abatement costs under environmental regulation. With auctioned permits under commitment and auctioned permits and taxes under flexibility, a firm gains by lowering rivals' costs. In the presence of technology spillovers, letting other firms use better technology lowers their abatement cost curves, which in turn leads to a lower tax rate or permit price. Though spillovers imply that each firm may free ride on the other firms' investments, we find that the equilibrium investment can be increasing in the degree of technology spillovers. The result that firms may wish to lower rival's costs runs counter to the incentive to raise rival's cost that often operates in strategic competition models

[2] This point about strategic investment is analyzed in Biglaiser et al. (1995), Kennedy and Laplante (1999), Karp and Zhang (2001), Moledina et al. (2003), Requate (2005b), and Tarui and Polasky (2005).

(Salop and Scheffman 1983).

Prior literature on dynamic environmental regulation (see Jaffe et al. 2003 and Requate 2005a for recent surveys) has analyzed incentives to adopt new technology assuming that regulation is fixed, as in our paper with commitment (e.g., Downing and White 1986, Milliman and Prince 1989), and assuming that regulation changes with technology adoption, as in our paper with flexibility (e.g., Kennedy and Laplante 1999). Biglaiser et al. (1995) and Requate (2005b) consider both commitment and flexibility in analyzing incentives for technology adoption. Other recent studies characterize optimal policy with learning and irreversibility (Kolstad 1996, Ulph and Ulph 1997, Kelly and Kolstad 1999, Pindyck 2000 and Saphores 2002). The most closely related papers to the current paper analyze equilibrium in a game where the regulator learns about the damage function or the cost function through time (Benford 1998, Hoel and Karp 2002, Karp and Zhang 2001, 2002, Kennedy 1999, Moledina et al. 2003, Newell and Pizer 2003, Tarui and Polasky 2005). Most prior literature has found that taxes are superior to standards. Karp and Zhang (2002) find that the relative efficiency of taxes over standards increases as the regulator has more opportunities for learning in a model with a stock pollutant and non-strategic firms. Tarui and Polasky (2005) find that taxes are preferred to standards with quadratic costs and damages in a game with a single regulated firm. This paper extends their analysis by considering a game of a regulator and multiple firms in the presence of technology spillovers across firms. The extension to multiple firms allows us to analyze tradable permits as well as taxes and standards.

Section 2 describes the game with investment in R&D, technology spillovers and learning about the damage function. We compare equilibrium outcomes under taxes, standards, auctioned tradable permits and freely distributed tradable permits. Section 3 considers these policy instruments under commitment while section 4 compares these policies under flexibility. Section 5 compares commitment versus flexibility. Section 6 concludes the paper with comments on potential future research.

2 A game with investment, learning and technology spillovers

This section introduces a game by a regulator and $N \geq 2$ firms. The firms generate emissions which cause environmental damages. Let k_i be firm i's investment for R&D where the outcome of innovation is deterministic. Given investment profile $k = (k_1, \ldots, k_N)$, firm i's cost of choosing emission $x_i \geq 0$ is given by $C_i(x_i, z_i(k))$ where

$$z_i(k) = k_i + \lambda \sum_{j \neq i} k_j$$

represents the effective emission abatement capital available to firm i. Parameter λ measures the degree of technology spillovers across firms. This specification of spillovers follows the standard models of technology innovation in industrial organization (e.g. Spence 1984). Function C_i is convex with derivatives $C_{ix}, C_{iz} < 0$, $C_{ixx}, C_{izz} > 0$ and $C_{ixz} > 0$ for all i. Under the last assumption, the marginal abatement cost is decreasing in abatement capital z_i. Firm i's cost of investing k_i is given by $G_i(k_i)$ where $G_i' > 0$ and $G_i'' \geq 0$. Total emissions $X = \sum_i x_i$ cause environmental damages $D(X;\delta)$ given unknown damage parameter δ where $D_x > 0$ and $D_{xx} > 0$. At the outset of the game, the regulator knows the distribution of δ.

We assume the following sequence of moves by the players.

1. The regulator chooses regulatory regime: quantity regulations (standards or tradable permits) or price regulation (tax); commitment or flexibility.
2. Firms simultaneously choose investment k.
3. Uncertainty about damage function is resolved, and the regulator learns the realization of δ.
4. Given (k, δ), the regulator sets flexible policy (if flexibility was chosen in the first stage).
5. Firms choose emissions.
6. Players receive their payoffs.

The number of firms N is fixed and there is no entry or exit of firms. The regulator has complete information about the firms' technology, investment and emissions.

The first-best investment and emissions plan minimizes the expected cost of investment, abatement and damages:

$$\min_{k,x} \sum_i \left[G_i(k_i) + E\left\{C_i(x_i(\delta), z_i(k))\right\}\right] + ED(X(\delta);\delta)$$

An interior solution equates the marginal abatement cost of each firm with the marginal damages:

$$-C_{ix}(x_i^*(\delta), z_i(k^*)) = D_x(X^*(\delta);\delta)$$

for all i and δ where $X^*(\delta) \equiv \sum_i x_i^*(\delta)$. The solution also satisfies

$$G_i'(k_i^*) + E\left[C_{iz}(x_i^*(\delta), z_i(k^*)) + \textstyle\sum_{j\neq i}\lambda C_{jz}(x_j^*(\delta), z_j(k^*))\right] = 0 \quad (1)$$

for all i. The marginal cost of investment by firm i, $G_i'(k_i^*)$, equals the marginal benefit of investment which is the sum of the marginal benefit of reducing firm i's abatement cost $-C_{iz}$ and the spillover effects $-\sum_{j\neq i}\lambda C_{jz}$.

We solve for the subgame perfect equilibrium of the subgames corresponding to different regulatory choice by the regulator, and compare the equilibrium outcomes with the first best outcome. First we compare policies under commitment.

3 Policies under commitment

3.1 Committed standards

The regulator sets emissions standards $q = (q_1, \ldots, q_N)$ at the outset of the game. Given standards q, firm i chooses emission and investment to solve

$$\min_{x_i, k_i \geq 0} G_i(k_i) + C_i(x_i, z_i(k))$$

subject to $x_i \leq q_i$. The cost-minimizing emission is $x_i = q_i$. The cost-minimizing investment profile $k(q) = \{k_i(q)\}$ satisfies

$$G_i'(k_i(q)) + C_{iz}(q_i, z_i(k(q))) = 0. \tag{2}$$

for all i. In the first stage, the regulator chooses standards to minimize the social cost:

$$\min_{q \geq 0} \sum_i [G_i(k_i(q)) + C_i(q_i, z_i(k(q)))] + ED(Q; \delta)$$

where $Q = \sum_i q_i$. The first order condition is

$$\textstyle\sum_j G_j'(k_j) \frac{\partial k_j}{\partial q_i} + C_{ix} + \sum_j C_{jz} \left[\frac{\partial k_j}{\partial q_i} + \sum_{l \neq j} \lambda \frac{\partial k_l}{\partial q_i} \right] + ED_x(Q; \delta) = 0$$

for all i. Using equation (2), we have

$$C_{ix} + \textstyle\sum_j C_{jz} \sum_{l \neq j} \lambda \frac{\partial k_l}{\partial q_i} + ED_x(Q; \delta) = 0 \tag{3}$$

for all i. Under committed standards, the expected marginal damage does not equal the marginal abatement cost of each firm. It equals the sum of the marginal abatement cost and the marginal spillover effects induced by a change in investment which is caused by a change in the standards for each firm.

3.2 Committed tax

The regulator sets an emission tax rate τ at the outset of the game. Given τ and k_{-i}, firm i chooses emission and investment to solve

$$\min_{x_i, k_i \geq 0} G_i(k_i) + C_i(x_i, z_i(k)) + \tau x_i.$$

The first order condition is

$$C_{ix}(x_i, z_i(k)) + \tau = 0, \tag{4}$$

$$G_i'(k_i) + C_{iz}(x_i, z_i(k)) = 0 \tag{5}$$

for all i. Let $\{x_i(\tau), k_i(\tau)\}$ be the Nash equilibrium given tax τ. The regulator chooses τ to minimize the social cost:

$$\min_{\tau \geq 0} \sum_i [G_i(k_i(\tau)) + C_i(x_i(\tau), z_i(k(\tau)))] + ED(X(\tau); \delta)$$

where $X(\tau) \equiv \sum_i x_i(\tau)$. The first order condition is

$$\sum_i \left[G_i'(k_i) k_i'(\tau) + C_{ix} x_i'(\tau) + C_{iz} \left[k_i'(\tau) + \textstyle\sum_{j \neq i} \lambda k_j'(\tau) \right] \right] + E \left[\textstyle\sum_i D_x(X; \delta) x_i'(\tau) \right] = 0.$$

Using equation (5), we have

$$\sum_i \left[C_{ix} x_i'(\tau) + C_{iz} \lambda \textstyle\sum_{j \neq i} k_j'(\tau) \right] + E \left[\textstyle\sum_i D_x(X; \delta) x_i'(\tau) \right] = 0 \tag{6}$$

as the condition for a subgame perfect equilibrium of a committed-tax subgame.

Under commitment, tax and standard are equivalent.

Proposition 1 *Under commitment, the equilibrium standards and taxes achieve the same outcome.*

See the appendix for the proof. Tarui and Polasky (2005) showed this result with $N = 1$ (a single firm). Because the regulator has committed to a policy (tax or standard), the firm faces no uncertainty when it makes its choice of investment and emissions level. Further, note that the firms' investments will satisfy $G_i'(k_i) + C_{iz}(x_i, z_i(k)) = 0$ for all i under both the tax and the standard. As long as the emissions level is equal under tax and standard, the investment will be equal. As in conditions (3) and (6), the regulator sets the tax or the standard such that the expected marginal damage equals the sum of the marginal abatement cost and the marginal spillover effects. Therefore, the regulator can induce the firms to choose the same levels of investment and emissions via either a standard or a tax. Note that this outcome is not ex post optimal because in fact the firms' emissions choice should reflect the true state of damages rather than expected damages and the firms' investment choice should reflect the spillover effects of investments. In the presence of spillovers, the equilibrium tax rate exceeds the expected marginal damage.

Corollary 1 *If $\lambda > 0$, the equilibrium committed tax rate exceeds the expected marginal damage.*

This result is analogous to the findings in Requate (2005b) where the optimal tax rate exceeds the marginal damages in the presence of a monopolistic innovator. The optimal committed tax exceeds the expected marginal damage in order to mitigate investment disincentives due to spillover effects.

3.3 Committed permit auction

Under auctioned permits, the regulator sets the total amount of allowed emissions at the outset of the game prior to the firms' investment decisions. We assume that the equilibrium price equates the marginal abatement costs of N firms.[3] Let $\{x_i(Q, k)\}$ and $p(Q, k)$ be the emissions outcome and the permit price upon Nash bargaining given total permit Q and investment profile k. They satisfy $\sum_{i=1}^{N} x_i(Q, k) = Q$ and

$$C_{ix}(x_i(Q, k), z_i(k)) + p(Q, k) = 0 \tag{7}$$

for all i. In the investment stage, firm i chooses investment to minimize the cost of abatement:

$$G_i(k_i) + C_i(x_i(Q, k), z_i(k)) + p(Q, k)x_i(Q, k).$$

The first order condition is

$$G'(k_i) + C_{ix}\frac{\partial x_i}{\partial k_i} + C_{iz} + p(Q, k)\frac{\partial x_i}{\partial k_i} + \frac{\partial p}{\partial k_i}x_i(Q, k) = 0$$

which reduces to

$$G_i(k_i) + C_{iz} + \frac{\partial p}{\partial k_i}x_i(Q, k) = 0 \tag{8}$$

[3]Montero (2002) used the same assumption for an analysis of permit trading with investments in abatement technology.

because of condition (7). In the above condition, the third term on the left-hand side implies that each firm chooses investment taking into account how its investment influences the equilibrium permit price. Let $\{k_i(Q)\}$ be the equilibrium investment profile given permits Q. The regulator chooses the total permits Q to minimize the social cost:

$$\min_{Q\geq 0}\sum_i\left[G_i(k_i(Q))+C_i\Big(x_i(Q,k(Q)),z_i(k(Q))\Big)\right]+ED(Q;\delta).$$

The first order condition is

$$\sum_i\left[G_i'(k_i)k_i'(Q)+C_{ix}\left\{\frac{\partial x_i}{\partial Q}+\sum_j\frac{\partial x_i}{\partial k_j}k_j'(Q)\right\}+C_{iz}\left[k_i'(Q)+\textstyle\sum_{j\neq i}\lambda k_j'(Q)\right]\right]+ED_x(Q;\delta)=0.$$

3.4 Committed free permit trading

Under committed free permit trading, the regulator sets the total permits Q and distributes them to the firms. Suppose that the rule of distributing Q is given: firm i's allocation is $q_i=\alpha_i Q$ for some $0\leq\alpha\leq 1$ where $\sum\alpha_i=1$. In the investment stage, firm i chooses investment to minimize the cost of abatement

$$G_i(k_i)+C_i(x_i(Q,k),z_i(k))+p(Q,k)[x_i(Q,k)-q_i].$$

The first order condition is

$$G_i'(k_i)+C_{ix}\frac{\partial x_i}{\partial k_i}+C_{iz}+P(Q,z)\frac{\partial x_i}{\partial k_i}+\frac{\partial p}{\partial k_i}[x_i(Q,k)-q_i]=0$$

which reduces to

$$G_i(k_i)+C_{iz}+\frac{\partial p}{\partial k_i}[x_i(Q,k)-q_i]=0 \tag{9}$$

because of condition (7). Given the firms' best investment response functions $k(Q)$, the regulator chooses the distribution of permits to minimize the expected social cost of emission reduction.

$$\min_{Q\geq 0}\sum_i\left[G_i(k_i(Q))+C_i\Big(x_i(Q,k(Q)),z_i(k(Q))\Big)\right]+ED(Q;\delta).$$

The first order condition is

$$\textstyle\sum_j G_j'(k_j)\frac{dk_j}{dQ}+\sum_j C_{jx}\frac{dx_j}{dQ}+\sum_j C_{jz}\left[\frac{dk_j}{dQ}+\sum_{l\neq j}\lambda\frac{dk_l}{dQ}\right]+ED_x(Q;\delta)=0 \tag{10}$$

for all i.

With a correctly specified permit allocation, free permit trading induces the same equilibrium outcome as tax and standard under commitment.

Proposition 2 *Suppose $q_i=x_i(Q,k(Q))$ for all i. Then the equilibrium outcomes under committed standards and committed free permit trading are equivalent.*

This result holds because condition (9) for free permit trading is equivalent to conditions (3) for standards and (6) for tax when no permit trading occurs in equilibrium. In the absence of technology spillovers and damage uncertainty, these three policy instruments induce the first-best outcome.

Proposition 3 *If $\lambda = Var(\delta) = 0$, then the equilibrium outcomes under committed tax, subsidy and free permit trading are efficient while committed auctioned permit trading does not yield an efficient outcome.*

If a firm is a buyer of permits, then the firm prefers a lower permit price. Given $D_{xx} > 0$, the permit price is lower when any firm's marginal abatement cost is lower. In the presence of technology spillovers, investment by firm i not only reduces i's marginal abatement costs but also the other firms' marginal abatement cost. Hence, investment results in lowering rivals' costs, which in turn benefits the investing firm. While all firms are buyers of permits under permit auction, not all firms are under free permits. Hence, each firm's incentive to lower rivals' costs is larger under auctioned permits than the other committed policies.

Proposition 4 *Given the same total emissions target, the firms' investments under auctioned permits are larger than the investments under free permits.*

Hence, auctioned permits may be more preferred to the other policy instruments when the degree of technology spillovers is large.

3.5 Example

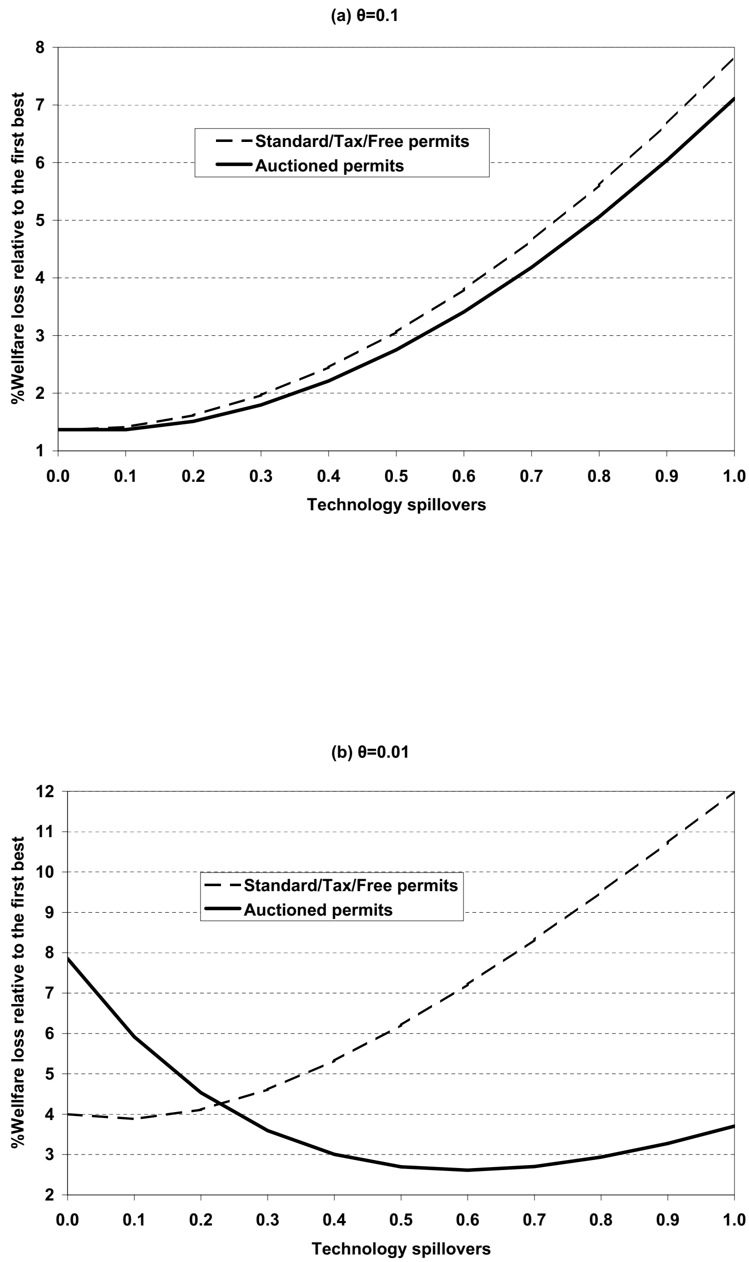
With tax or standard, there is no room for the firms' strategic moves. With permit trading, however, the firms' investment may influence the equilibrium permit price. To compare different policy instruments under commitment, consider the following example. Suppose

$$G_i(k) = \frac{r}{2}k^2, \quad C_i(x_i, z_i) = \frac{(\bar{e}_i - x_i - az_i)^2}{2\theta}, \quad i = 1, \ldots, N. \tag{11}$$

Parameter $\bar{e}_i > 0$ represents firm i's emission under no regulation on emissions. A larger value of θ implies a lower marginal abatement cost. The damage function is given by

$$D(X; \delta) = \frac{\delta X^2}{2}. \tag{12}$$

Based on this example, Figure 1 describes the equilibrium welfare loss under alternative schemes under commitment. As in Propositions 1 and 2, committed tax, standards and free permit trading are equivalent. Permit auction tends to be preferred to the other instruments when the degree of technology spillovers is large. Over-investment incentives to lower rivals' costs reduce the gap between the first-best investment level and the equilibrium investment level. Such effects are present under permit auction while they are not under other policy instruments.



Note: $a = 10, P(\delta = 150) = P(\delta = 50) = 1/2, N = 2, \bar{e}_1 = \bar{e}_2 = 5000, r = 10,000.$

Figure 1: Policies under commitment.

Table 1: Policy instruments under commitment.

	Auctioned permits (AP)	Free permits (FP)	Taxes (T)	Standards (S)
No spillovers				
No damage uncertainty	Inefficient	FP ⇔ T ⇔ S, efficient		
Damage uncertain	FP ⇔ T ⇔ S, preferred to AP			
Positive spillovers		FP ⇔ T ⇔ S		
	AP preferred to others if λ is large and marginal abatement costs are large.			

3.6 Commitment: summary

Table 1 summarizes the findings regarding commitment policies.

Under commitment, there are two sources of distortions: one due to policies not incorporating learning by the regulator, and the other due to spillover effects of investments. Under auctioned permits, there is another distortion due to strategic investments by the firms. Figure 1 demonstrates that the third effect may reduce the negative spillover effects and hence auctioned permits may be preferred to the other instruments when λ is large. The third effect disappears as the number of firms increases, and all commitment policies remain inefficient when N becomes larger. When auctioned permit outperforms the other instruments under a small λ, the advantage of auctioned permits disappears for a large N.

4 Policies under flexibility

4.1 Flexible permit auction

Under flexible auctioned permits, the regulator determines the total amount of emission permits based on technology chosen by firms and learning about damages. In the permit trading stage, firm i minimizes the cost of abatement plus the cost of purchasing permits given investment k, $C_i(x_i, k_i) + px_i$, where p is the price of permit. The equilibrium price p satisfies

$$C_{ix}(x_i, z_i(k)) + p = 0 \tag{13}$$

for all i given k. Let $Q(z(k), \delta)$ be the regulator's equilibrium choice of total permits given k and state δ, which satisfies

$$C_{ix}(q_i(z(k), \delta), z_i) + D_x(Q(z(k), \delta); \delta) = 0$$

for all i, z and all δ. The following lemma proves useful for the succeeding analysis.

Lemma 1 *Let $Q(z(k), \delta)$ be the optimal total emission given $z(k)$ and δ. Let $p(z(k), \delta)$ be the equilibrium permit price given $z(k)$ and δ. Then $\frac{\partial X(z(k),\delta)}{\partial k_i} < 0$ for all k, s and all i given any $\lambda \geq 0$ and $\frac{\partial p(z(k),\delta)}{\partial k_i} < 0$ for all i.*

Hence, both the total permits and the permit price are decreasing in firms' investment. This fact implies firms' strategic incentives for investment under flexibility.

Proposition 5 *With flexible auctioned permits, suppose* $\lambda = 0$*. Then the equilibrium results in over-investment.*

The logic of this result is described in Kennedy and Laplante (1999) and Moledina et al. (2001). Because the equilibrium permit price is lower if higher investment is observed, each firm will have an incentive to increase investment in order to manipulate the regulator into setting a lower emissions target which in turns implies lower permit price.

With auctioned permits and $\lambda > 0$, both under-investments and over-investments are possible because of spillover effects. In the quadratic example, we can find a threshold value of λ below which auctioned permits induce over-investment.

Proposition 6 *Suppose the functions* $\{G_i, C_i\}, D$ *are given by equations (11) and (12). With auctioned permits, the total equilibrium investment* K^{DAP} *satisfies the following.*

1. $K^{DAP}(\lambda) > K^*$ *for any* $\lambda \in [0, \hat{\lambda})$ *where* $\hat{\lambda}$ *satisfies*

$$\hat{\lambda} \equiv \frac{B}{(NA - B)(N-1)}$$

where $A \equiv E\left[\frac{\delta}{1+N\theta\delta}\right]$ *and* $B \equiv E\left[\frac{\delta}{(1+N\theta\delta)^2}\right]$*;*

2. $K^{DAP}(\lambda) < K^*$ *for any* $\lambda > \hat{\lambda}$*;*
3. $K^{DAP}(\lambda) = K^*$ *if* $\lambda = \hat{\lambda}$*.*

Hence, larger spillovers cause each firm to choose lower investment in R&D, and this effect overcomes the firms' incentive to over-invest if spillovers are large enough. Under a deterministic case ($E\delta = d$ and $\sigma^2 = 0$), we have

$$\hat{\lambda} \equiv \frac{1}{N(N-2) + N^2\theta d(N-1) + 1}.$$

The threshold $\hat{\lambda}$ is decreasing in the number of firms N, productivity of emission abatement θ and the slope of the marginal damage function d. If the firms are identical and $\lambda = \hat{\lambda}$, then flexible auctioned permits support the first best outcome.

4.2 Flexible free permit trading

Given investment and a realization of δ, the regulator sets the total permits $Q(k, \delta)$ in the same way as under permit auction. The regulator also specifies distribution of permits to the firms $\{q_i(k, \delta)\}$ where $\sum_i q_i(k, \delta) = Q(k, \delta)$ for all (k, δ). Given q_i, expectation of permit price P and other firm's investment k_{-i}, firm i solves

$$\min_{k_i \geq 0} G_i(k_i) + E[C_i(x_i(k, \delta), z_i(k)) + P(z, \delta)(x_i(k, \delta) - q_i(k, \delta))].$$

After applying the envelope theorem, we have the following first order condition for all i:

$$G_i'(k_i) + E\left[C_{iz}(x_i(k,\delta), z_i(k)) + \frac{\partial P(z,\delta)}{\partial k_i}[x_i(k,\delta) - q_i(k,\delta)] - P(z,\delta)\left(\frac{\partial q_i(k,\delta)}{\partial k_i}\right)\right] = 0.$$

The term $\frac{\partial P(z,\delta)}{\partial k_i}[x_i(k,\delta) - q_i(k,\delta)]$ represents the emissions payment effect (Fischer et al. 2003). Note that $\partial P/\partial k_i < 0$ for all i by Lemma 1. The sign of the emissions payment effect depends on whether firm i is a seller or a buyer of permits. A seller (a buyer) has an incentive to invest less (more) so that permit price stays high (low). (Under permit auction, all firms are buyers of permits.) The last term $-P\frac{\partial q_i}{\partial k_i}$ represents the permit allocation effect: firms consider how their investments influence the permit allocation. To evaluate the total investment, consider the following assumption on functions $\{C_i\}$.

$$\text{If } C_{ix} = C_{jx} \text{ for all } i,j, \text{ then } \quad \textstyle\sum_j C_{ix}(x_j, z_j(k)) = C_{ix}(\sum_j x_j, \sum_j z_j(k)) \quad \text{for all } i. \tag{14}$$

The example with equation (11) satisfies this condition. Under condition (14), we have $\partial P/\partial k_i = \partial P/\partial k_j$ for all i, j. Hence, summation of both sides of individual firms' first order conditions yields

$$\textstyle\sum_i G_i'(k_i) + E\left[C_{iz}(X(k,\delta), \sum_j z_j(k)) + \frac{\partial P(z,\delta)}{\partial k_i}\sum_j [x_j(k,\delta) - q_j(k,\delta)] - P(z,\delta)\left(\sum_j \frac{\partial q_j(k,\delta)}{\partial k_j}\right)\right] = 0.$$

Note that $\sum_j [x_j(k,\delta) - q_j(k,\delta)] = X(K,\delta) - Q(K,\delta) = 0$: at the industry level, the emissions payment effect disappears. Hence, whether there is over-investment at the industry level depends on the sign of the permit allocation effect $\sum_i \frac{\partial q_i(k)}{\partial k_i}$.

We now present the main result of this paper. Unlike other policies, flexible free permit trading may support the first best outcome under technology spillovers and damage uncertainty.

Proposition 7 *Let $\{k^*, x^*(\cdot)\}$ be the first best investment and emission plan. Flexible free permit trading supports the first best outcome under a permit distribution rule $q^* \equiv \{q_i^*(k,\delta)\}$ which satisfies*

$$\frac{\partial q_i^*(k^*;\delta)}{\partial k_i} = \frac{\lambda \sum_{j\neq i} \left|C_{jz}(x_j^*(\delta), z_j(k^*))\right|}{D_x(X^*(\delta);\delta)}, \tag{15}$$

$$\sum_i q_i^*(k;\delta) = \sum_i x_i(k;\delta) \quad \textit{and} \quad q_i^*(k^*;\delta) = x_i^*(\delta) \tag{16}$$

for all i, k. δ.

Proof. Under the specified permit allocation rule, the first best plan $\{k^*, x^*(\cdot)\}$ satisfies the necessary and sufficient condition of each firm's payoff maximization:

$$C_{ix}(x_i(\delta), z_i(k^*) = p(z(k^*), \delta),$$

$$G_i'(k_i^*) + E\left[C_{iz}(x_i^*(\delta), z_i(k^*)) - p(z(k^*),\delta)\frac{\lambda \sum_{j\neq i} \left|C_{jz}(x_j^*(\delta), z_j(k^*))\right|}{D_x(X^*;\delta)}\right] = 0 \quad \text{for all } i,$$

where $p(z(k^*),\delta) = D_x(X^*(\delta);\delta)$. ■

Under the permit distribution rule (15) and (16), the regulator sets the total emission cap at the ex-post optimal level given the firms' investment and exogenous learning. Permit distribution to each firm is increasing in its own investment and decreasing in investment by the other firms—the regulator rewards a firm conducting a larger investment for the contribution to reduce the other firms' abatement costs. Given q^*, the emissions payment effect is zero for all firms if the firms choose k^*. The formula for the permit allocation rule (15) specifies that the marginal increase in the permit allocation for firm i equals the marginal contribution of firm i's investment on the decreases in the other firms' marginal abatement costs through technology spillovers discounted by the marginal damages of emissions. If $\lambda = 0$, then firm i's permit allocation should be independent of firm i's investment. If $\lambda > 0$, then the allocation should be increasing in the firm's investment. The above permit allocation rule solves the discrepancy between private and social returns of investment. In contrast, flexible permit auction or taxes do not solve this discrepancy (unless $\lambda = \hat{\lambda}$ by chance). Flexible standards exacerbates this discrepancy even further.

For the quadratic example (equations 11 and 12), the first best permit allocation rule q^* is given by

$$q_i^*(k;\delta) = \alpha_i(\delta) + \beta k_i - \gamma(\delta) \sum_{j \neq i} k_j$$

where

$$\alpha_i(\delta) = \frac{\bar{e}_i + N\theta\delta\left(\bar{e}_i - \frac{\bar{E}}{N}\right)}{1 + N\theta\delta}, \quad \beta = \lambda a(N-1), \quad \gamma(\delta) = \frac{1}{N-1}\left(\beta + \frac{af(\lambda)}{1+N\theta\delta}\right).$$

In the above specification, β satisfies condition (15) and induce the firms to choose the first best investments. Specification of α_i's ensures that the total distribution $\sum_i q_i^*(k,\delta)$ equals that the optimal total emissions $X(k,\delta)$ for all (k,δ) and that q_i^*'s satisfy condition (16).

There are many other ways for the regulator to determine permit distribution.[4] The following proposition describes the effects of alternative permit distribution rules on the equilibrium investment.

Proposition 8 *Suppose the functions $\{G_i, C_i\}, D$ are given by equations (11) and (12). Let $q_i(k)$ be the permits distributed to firm i given investment profile k.*

1. *Suppose $\frac{\partial q_i(k)}{\partial k_i} = 0$ for all i (that is, each firm's permit endowment is independent of its own investment decision). If $\lambda > 0$, then the equilibrium total investment is lower than the first best level.*
2. *Alternatively, suppose permits distributed to each firm is a function of total investment K. Then flexible permit trading results in under-investment given any $\lambda \geq 0$.*

The permit allocation rules specified in Proposition 8 do not provide the correct investment incentives to firms. Grandfathering of permits practiced in the US Acid Rain Program and EU Emissions Trading Scheme corresponds to the first rule in the proposition. If the rule specified in Proposition 7 is not feasible, then flexible taxes and permit auction may be preferred to free permit trading.

[4]Ellerman et al. 2000 discuss that the initial distribution of permits for the SO2 market was influenced by interest group politics (though not significantly according to their statistical analysis and though allocation was based on past levels of emissions).

4.3 Flexible taxes

The equilibrium permit prices under auctioned permits and the equilibrium flexible taxes depend on the firms' investment profile in the same way. Because they are equivalent from the firms' point of view, the equilibria under the two policy instruments support the same outcome.

Proposition 9 *Under flexibility, the equilibrium under taxes and auctioned permits are equivalent.*

Each firms' incentive to free-ride on other firms' investments increases when spillovers are larger. However, the equilibrium investment may be increasing in the degree of technology spillovers λ under some circumstances.

Proposition 10 *Suppose the functions $\{G_i, C_i\}, D$ are given by equations (11) and (12). Under flexible taxes and auctioned permits, the equilibrium investment of each firm is increasing in λ when r is large and when a and all realizations of δ are small.*

The above proposition shows that each firm's investment is increasing in λ if the marginal investment cost is large, the marginal contribution of investment on reducing abatement costs is small, and the slope of the marginal damages is small. Under oligopolistic competition or monopoly with threats of entry, incumbents conduct investment to raise the rivals' costs (Salop and Scheffman 1983, Lyon and Maxwell 2004). In the context of environmental regulation with flexible policy update, however, lowering the other firms' costs may result in less stringent regulation. Because the tax rate and the equilibrium price of auctioned permits are decreasing in every firm's marginal abatement cost, it may be of each firm's interest to choose a larger investment level when spillovers are larger.

4.4 Flexible standards

Under emissions standards, the regulator sets the upper limit of emissions for each firm. The regulator can choose the distribution of total emissions across firms in many ways. For example, under uniform concentration standards (uniform standards on emission per outputs or inputs), $q_i(k;\delta)$ is equal to $\bar{e}_i \cdot \frac{Q(k;\delta)}{\bar{E}}$ if $\bar{e}_i$ is proportional to firm i's outputs/inputs for all i. Alternatively, the regulator can set firm i's standard at $\alpha_i Q(k;\delta)$ for some given share α_i where $\alpha_i \geq 0$ and $\sum_i \alpha_i = 1$.[5] We consider standards where firm i's emissions standard is the optimal emissions given (k, δ). Let $Q(k;\delta)$ be the optimal total emissions given investment profile k. Let $q(k;\delta) = (q_1(k;\delta), q_2(k;\delta), \ldots, q_N(k;\delta))$ be the standard for the firms such that $\sum_i q_i(k) = Q(k)$.

Lemma 2 *If the firms are identical or if $\{G_i, C_i\}$ and D are quadratic as in equations (11) and (12), then the equilibrium total investment under flexible emissions taxes is larger than the equilibrium total investment under flexible emissions standards.*

[5] Montero (2002) compares permit trading with concentration standards where regulated firms compete in output markets.

The logic behind this result is explained in Kennedy and Laplante (1999) and Tarui and Polasky (2005). The regulator sets larger emissions standards given lower investments. Hence, each firm has an incentive to choose lower investment in order to induce the regulator to choose less stringent standards. With a quadratic example, the flexible taxes are preferred to flexible standards regardless of the degree of technology spillovers.

Proposition 11 *Suppose the functions $\{G_i, C_i\}, D$ are given by equations (11) and (12). Under a flexible policy regime, the expected social costs are lower in equilibrium with emissions taxes than in equilibrium with emissions standards.*

This result extends the finding in Tarui and Polasky (2005) to the case of multiple firms. Let K^*, K^T, K^S be the total investment under the first best, flexible taxes and standards. We have $K^T > K^* > K^S$ when technology spillovers are small. With a quadratic example, distortions due to over-investment under taxes are smaller than distortions due to under-investment under standards. For larger spillovers, we have $K^S < K^T < K^*$ and distortions due to under-investment are larger under standards.

4.5 Flexibility: summary

Table 2 summarizes the findings regarding flexible policies. Flexible auctioned permits and flexible taxes generate the same equilibrium outcome and may result in over-investment when technology spillovers are small. With free permits, the permit allocation rule matters. In particular, the equilibrium supports the first best outcome if the permit allocation for a firm is increasing in the firm's investment.

Under flexibility, there are two sources of distortions: one due to strategic investments by the firms and the other due to spillover effects of investments. In the absence of spillovers ($\lambda = 0$), the former effect disappears as the number of firms increases. Hence, any flexible policy can achieve the first-best outcome if $\lambda = 0$ and N tends to infinity. When $\lambda > 0$, the spillover effect does not disappear even if N is large. Given λ, the cost-reducing effect of firm i's investment on the other firms' costs diminishes as N increases. Hence, each firm cannot strategically lower rivals' costs under flexible taxes or standards with a large number of firms. Using the permit allocation rule in proposition 7, the regulator can achieve the first best outcome with free permit trading regardless of the number of firms.

5 Commitment versus flexibility

We compare the equilibrium total costs under commitment policies and flexible policies. Figures 2-4 compare the percentage excess social costs under each policy instrument under different degrees of technology spillovers λ using the example with equations (11) and (12). As in Proposition 11, flexible taxes are always preferred to flexible standards. Figure 2 implies that commitment is preferred to flexibility even under damage uncertainty when the marginal cost of investment is relatively smaller. The figure also implies that the ranking of commitment versus flexibility may

Table 2: Policy instruments under flexibility.

	Auctioned permits (AP)	Free permits (FP)	Taxes (T)	Standards (S)
No spillovers				
Total investment	$K^{AP} > K^*$	$K^{FP} \leq K^*$	$K^{AP} > K^*$	$K^S < K^*$
Total emission	$X^{AP} < X^*$	$X^{FP} \geq X^*$	$X^{AP} < X^*$	$X^S > X^*$
Welfare				
Positive spillovers				
Total investment	$K^{AP} < (>) K^*$ for large (small) spillovers	$K^{FP} \leq K^*$	$K^T < (>) K^*$ for large (small) spillovers	$K^S < K^*$
Total emission	$X^{AP} > (<) X^*$ for large (small) spillovers	$X^{FP} \geq X^*$	$X^T > (<) X^*$ for large (small) spillovers	$X^S > X^*$
Welfare	AP $\Leftrightarrow$ T	First best possible	T preferred to S	

Note: K and X denote the equilibrium total investment and emissions. Superscript $*$ denotes the first best level.

differ depending on the degree of technology spillovers. In Figure 3(a), committed free permits outperform the other instruments when spillovers are small, but are less preferred when spillovers are large.[6] For a smaller slope of marginal abatement costs (i.e. large θ), flexible taxes and committed auctioned permits are the most preferred instruments (Figure 3b). When the marginal abatement costs are relatively larger, it becomes more important for the regulator to correct the firms' investment incentives than to update policy stringency based on learning about damage.

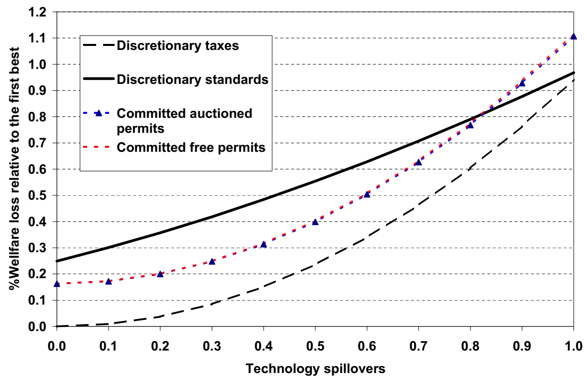
Figure 4 illustrates that committed policies are less preferred when θ is larger , i.e. when the slope of the marginal abatement cost is smaller. For a sufficiently small θ, committed auctioned permits are more preferred to flexible standards even under damage uncertainty. Figure 4 assumes $N = 10$; the figure implies that distortions due to strategic investments can be large even when the number of firms is large.

6 Discussion

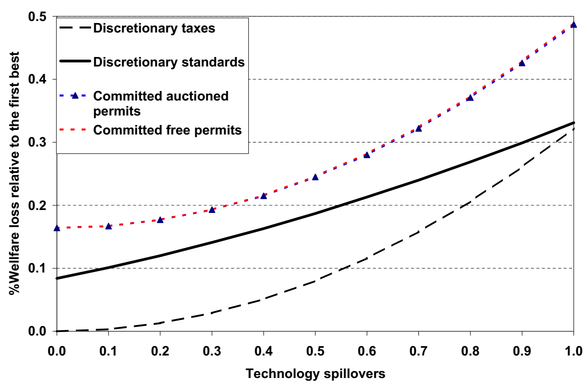
In this paper we studied environmental regulation given exogenous learning about environmental damages from emissions by a regulator, endogenous choice of emissions abatement technology by regulated firms, and technology spillovers across firms. We compared emissions control policies and under flexibility, in which policy is updated upon learning new information, versus under commitment, in which policy is not updated. In order to achieve the first best outcome, the regulator needs to provide firms with correct incentives for investments and emissions abatement. Our main finding is that a flexible permit trading with freely distributed permits works to solve

[6] In Figure 3(a) the percentage welfare loss under flexible standards exceeds 10% at any level of λ and is not shown in the figure.

(a) r=1

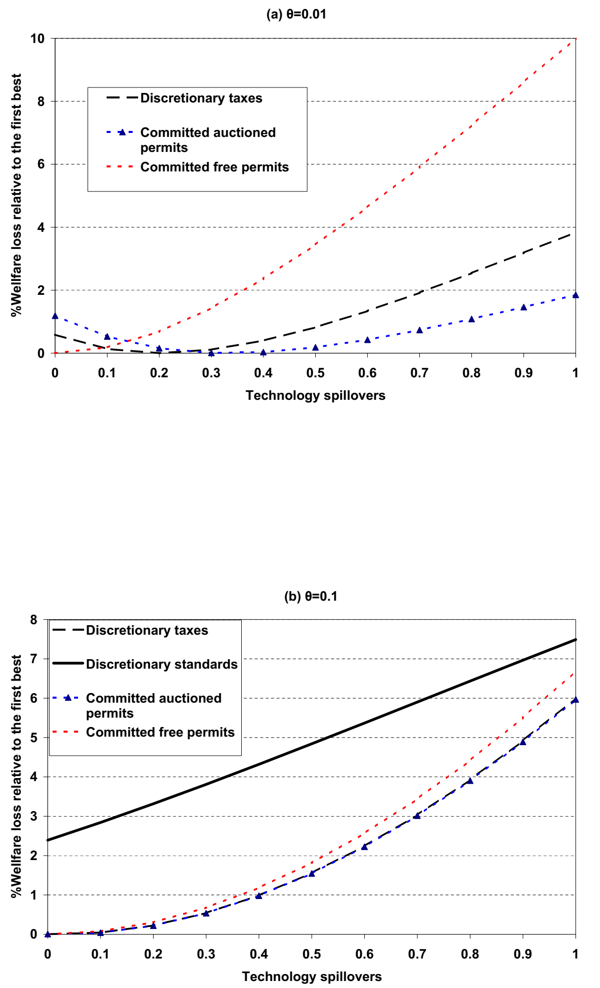


(b) r=3



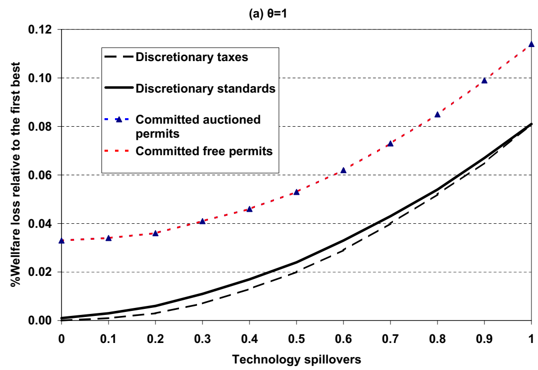
Note: $a = 0.1, \theta = 1, P(\delta = 150) = P(\delta = 50) = 1/2, N = 2, \bar{e}_1 = \bar{e}_2 = 500.$

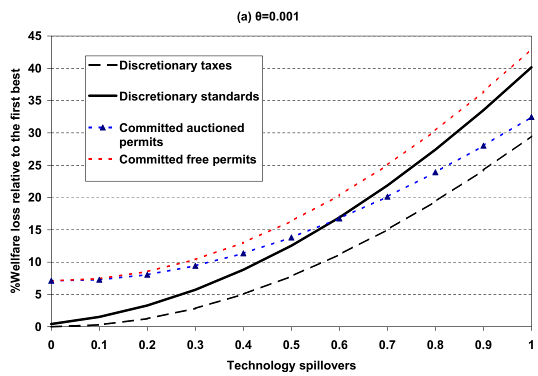
Figure 2: Commitment versus flexibility (1)

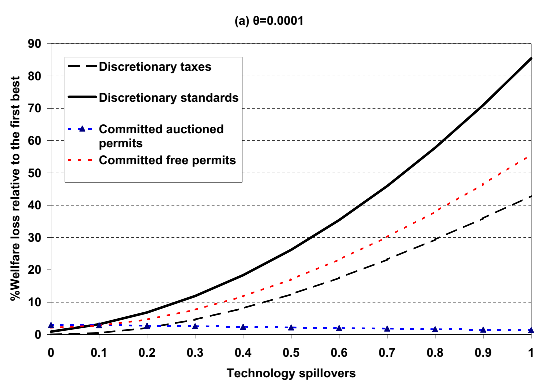


Note: $a = 10, r = 10,000, P(\delta = 150) = P(\delta = 50) = 1/2, N = 2, \bar{e}_1 = \bar{e}_2 = 5000$.

Figure 3: Commitment versus flexibility (2)







Note: $a = 0.1, r = 100,000, P(\delta = 150) = P(\delta = 50) = 1/2, N = 10, \bar{e}_1 = \bar{e}_2 = 500.$

Figure 4: Commitment versus flexibility (3)

both of these incentive problems. Flexibility allows the regulator to set the total emission cap at the ex-post optimal level upon learning. With a correctly specified permit distribution rule, the regulator rewards a firm which generates more advanced abatement technology with a larger amount of emission permits. This extra reward of permits for R&D internalizes the externality due to technology spillovers.

We also found that no other policy scheme—taxes, auctioned permits, or standards, under either flexibility or commitment—will guarantee achieving an optimal solution. Comparing suboptimal policies, whether flexibility is preferred to commitment depends on the relative magnitudes of the marginal cost of investment, marginal abatement costs, and marginal damages as well as the degree of damage uncertainty (and hence the value of learning). Under commitment, taxes and standards are equivalent. Free permit trading is also equivalent to taxes and standards if the permit distribution is specified so that no permit trading occurs in equilibrium. Committed auctioned permits tend to be preferred to the other commitment policies when the degree of technology spillovers and the slope of the marginal abatement costs are larger. With flexible policy and quadratic benefits and costs, this paper finds that taxes are always superior to standards. This result contrasts with other findings in the literature where the superiority of price or quantity mechanisms depends upon circumstances, such as the cost of innovation, the slope and level of marginal benefits of abatement (Fischer et al. 2003) or the slopes of marginal benefit and marginal cost (Weitzman 1974).

Strategic investments under other flexible policies occur only when the number of firms is small. In the presence of technology spillovers, flexible free permit trading can achieve the first best outcome regardless of the number of firms while the other policies do not when the number of firms is large.

The inefficiency of environmental policy under both commitment and flexibility is caused by the fact that investment occurs prior to the resolution of uncertainty. If it were possible to reverse the order so that all uncertainty were resolved prior to investment, the regulator could make policy dependent on actual conditions but not dependent upon investment. This would avoid distorting investment incentives while still allowing regulation to reflect actual conditions. This order is not likely to be reversed in practice because investments for technology adoption tend to be long-lived while new information is learned on a fairly frequent basis. Further, spillover effects will not be externalized even with the reversed timing of learning and investment.

The result that free permit trading can support the first best outcome is appealing. Unlike flexible taxes, standards and permit auction, free permit trading with a specific permit distribution rule induces the firms to choose the socially optimal investments without additional environmental technology policies (unlike flexible taxes and standards). The specific permit distribution rule requires the regulator to reward the firm with larger technology improvement with larger permit distributions. However, existing permit distribution rules do not have such characteristics. For example, SO_2 allowances under the US Acid Rain Program were distributed mostly according to historical emissions of electric utilities, and hence independent of investments or technologies adopted by the utilities (Ellerman et al. 2000). Our analysis demonstrated that the welfare loss under flexible free permit trading may be larger than those under other flexible policies if the first-best permit distribution rule is not available.

The analysis did not consider the possibility of oligopoly competition in output markets (see Fischer et al. 2003 and Montero 2002 for analysis of these issues). The effects of emissions regulation on innovation may differ depending on whether innovation reduces the marginal cost of output or it only reduces the emission per output.

We considered a model in which the firm chooses a technology from a menu of available existing technologies. In the model, larger investment leads to lower abatement costs with certainty. In practice, the return to investment on technology is stochastic. Firms choose expenditures on research and development for technology innovation, where greater investment results in a larger probability of finding a new technology with lower abatement costs. Stochastic returns to investment in R&D add another source of uncertainty to the model and make flexibility preferable to commitment.[7]

In this model we focused on symmetric uncertainty about damages in the model. An alternative formulation of the model would be to assume that the results of technology adoption or innovation are private information to the firm, which would then make the model one of regulation under asymmetric information. In addition to firms' private information about costs, the regulator's type may be another source of asymmetric information. For example, perhaps commitment is somewhat less than categorical. The firm may be uncertain whether a regulator really can or cannot commit to the initially announced regulatory stringency. The firm will form a belief on the regulator's type (the ability of the regulator to commit) and the firm's response will depend on such beliefs. We leave analysis of asymmetric information models for future research.

Appendix

First best outcome

The first-best investment emission and allocation (k^*, x^*) minimizes the expected social cost of emissions $C(k,x)$ where $C(k,x) \equiv \sum_i [G_i(k_i) + EC_i(x_i(\delta), z_i(k))] + ED(X(\delta))$. With G_i, $\{C_i\}$ and D given by equations (11) and (12), the first order condition is

$$\frac{\partial C(k,x)}{\partial k_i} = rk_i - E\left[\frac{a(\bar{e}_i - a(k_i + \lambda \sum_{j\neq i} k_j) - x_i(\delta))}{\theta} + \frac{a\lambda}{\theta}\sum_{j\neq i}\left\{\bar{e}_j - a\left(k_j + \lambda \sum_{l\neq j} k_l\right) - x_j(\delta)\right\}\right] = 0, \tag{17}$$

$$\frac{\partial C(k,x)}{\partial x_i(\delta)} = -\frac{\bar{e}_i - x_i(\delta) - az_i(k)}{\theta} + \delta X(\delta) = 0 \tag{18}$$

for all i and all s. Summing up condition (17) for all i, we have

$$\begin{aligned} & r\theta K - E\left[a(\bar{E} - X(\delta) - a(K + \lambda(N-1)K)) + a\lambda \sum_i \sum_{j\neq i}\left\{\bar{e}_j - a\left(k_j + \lambda \sum_{l\neq j} k_l\right) - x_j(\delta)\right\}\right] \\ = \; & r\theta K - E\left[a(\bar{E} - X(\delta) - a(K + \lambda(N-1)K)) + a\lambda((N-1)\bar{E} - (N-1)X(\delta))\right] \end{aligned}$$

[7] Requate (2005b) analyzes such cases assuming a single innovator, competitive technology adopters and deterministic damages.

$$
\begin{aligned}
& -a\lambda[(N-1)K + \lambda \textstyle\sum_i [(N-1)k_i + (N-2)\sum_{j\neq i} k_j]] \\
= \; & r\theta K - E\left[a(\bar{E} - X(\delta) - a(K + \lambda(N-1)K)) - a\lambda((N-1)\bar{E} - (N-1)X(\delta))\right] \\
& -a\lambda[(N-1)K + \lambda[(N-1)K + (N-2)(N-1)K]]
\end{aligned}
$$

where $\bar{E} \equiv \sum_i \bar{e}_i$ and $K \equiv \sum_i k_i$.[8] Hence,

$$r\theta K = Ea(1 + \lambda(N-1))(\bar{E} - X(\delta) - a(1 + \lambda(N-1))K). \tag{19}$$

Similarly, from condition (18) we have

$$\bar{E} - X(\delta) - aK(1 + \lambda(N-1)) = N\theta\delta X(\delta). \tag{20}$$

From (20) we have

$$X(\delta) = \frac{\bar{E} - af(\lambda)K}{1 + N\theta\delta}$$

where $f(\lambda) \equiv 1 + \lambda(N-1)$. Substitute it into (19) and we have

$$rK = Aaf(\lambda)N(\bar{E} - af(\lambda)K)$$

where $A \equiv E\frac{\delta}{1+N\theta\delta}$. Hence,

$$K^* = \frac{ANaf(\lambda)\bar{E}}{r + AN(af(\lambda))^2} \quad \text{and} \quad X^*(\delta) = \frac{r\bar{E}}{(1 + N\theta\delta)[r + AN(af(\lambda))^2]}.$$

To compute individual firms' equilibrium choice, note from (18) that $\bar{e}_i - x_i(\delta) - az_i(k) = \theta\delta X^*(\delta)$ for all i. It then follows from (17) that

$$\theta rk_i - E[a\theta\delta X^*(\delta) + a\lambda(N-1)\theta\delta X^*(\delta)] = 0$$

and hence

$$k_i^* = \frac{Aaf(\lambda)\bar{E}}{r + AN(af(\lambda))^2}$$

for all i. (So $k_i^* = K^*/N$ for all i.) Substitute this into (18) and we obtain $x_i^*(\delta) = \bar{e}_i - az_i(k^*) - \theta\delta X^*(\delta)$ for all i.

Proof of Proposition 1

Multiply condition (3) by $x_i'(\tau)$ and sum up the resulting expression over all i to obtain

$$\textstyle\sum_i \left[C_{ix}x_i'(\tau) + \sum_j C_{jz}\sum_{l\neq j}\lambda\frac{\partial k_l}{\partial q_i}x_i'(\tau)\right] + \sum_i ED_x(Q;\delta)x_i'(\tau) = 0$$

where

$$\sum_i\sum_j C_{jz}\sum_{l\neq j}\lambda\frac{\partial k_l}{\partial q_i}x_i'(\tau) = \sum_j C_{jz}\lambda\sum_{l\neq j}\sum_i\frac{\partial k_l}{\partial q_i}x_i'(\tau) = \sum_i C_{iz}\lambda\sum_{j\neq i}\sum_l\frac{\partial k_j}{\partial q_l}e_l'(\tau)$$

[8] Note that $\sum_{i=1}^N (k_i + \lambda\sum_{j\neq i} k_j) = \sum_{i=1}^N k_i + \lambda\sum_{i=1}^N\sum_{j\neq i} k_j = K + \lambda\sum_{j=1}^N (N-1)k_j = (1 + \lambda(N-1))K$.

We will show that the same emission and investment plan (e, k) satisfies both the above condition and the condition (6). We can solve N conditions (5) for $k_1, \ldots, k_N$ as functions of emissions x. Then substitute these functions $\{k_i(x)\}$ into N conditions (4) and solve x as functions of τ. Because (2) and (5) are identical when $q_i = x_i(\tau)$ and $k_i(q) = k_i(\tau)$, we have

$$k_j'(\tau) = \sum_l \frac{\partial k_j}{\partial q_l} e_l'(\tau)$$

for all j. Hence, the same investment and emissions plan satisfies the conditions for both the standards and the tax. ∎

Proof of Corollary 1

It follows from conditions (4) and (6) that

$$\tau = ED_x(X, \delta) + \lambda \frac{\sum_i C_{iz} \sum_{j \neq i} k_j'(\tau)}{\sum_i x_i'(\tau)} < ED_x(X, \delta) \quad \text{if } \lambda > 0.$$

∎

Proof of Proposition 2

In condition (10) we have $C_{jx}(x_j(Q, k(q)), z_j(k)) = C_{ix}(x_i(Q, k(q)), z_i(k))$ for all i, j because the marginal abatement costs are equalized under permit trading. Hence,

$$\sum_j C_{jx} \frac{dx_j}{dQ} = C_{lx} \sum_j \frac{dx_j}{dQ} = C_{lx} \frac{d \sum_j q_j}{dQ} = C_{lx}$$

for all i, j, l. Under the condition $q_i = x_i(Q, k(Q))$, condition (9) implies

$$C_{ix} + \textstyle\sum_j C_{jz} \sum_{l \neq j} \lambda \frac{dk_l}{dQ} + ED_x(Q; \delta) = 0$$

for all i, which is identical to the condition for the equilibrium under committed tax (3). ∎

Proof of Proposition 3

When $\lambda = 0$, the necessary and sufficient conditions of the first best outcome and the equilibrium outcomes under committed tax, standards and free permit trading are equivalent. ∎

Proof of Proposition 4

Condition (8) for auctioned permits and condition (9) with $x_i(Q, k) = q_i$ for free permits imply that each firm chooses a larger investment given the same total emissions Q. ∎

Proof of Lemma 1

Suppose not. Suppose k and k' differ only in the ith element where $k_i < k'_i$. Let $z = (z_1(k), \dots, z_N(k))$ and $z' = (z_1(k'), \dots, z_N(k'))$. Note that $z_j(k) \le z_j(k')$ for all j. Suppose $X(z, \delta) \le X(z', \delta)$. Because D_x is increasing in emissions, we have

$$D_x(X(z, \delta); \delta) \le D_x(X(z', \delta); \delta). \tag{21}$$

By the definition of $x_i(\cdot, \cdot)$ and $X(\cdot, \cdot)$, we have

$$C_{ix}(x_i(z, \delta), z_i(k)) + D_x(X(z, \delta); \delta) = 0 \text{ and } C_{ix}(x_i(z', \delta), z_i(k')) + D_x(X(z', \delta); \delta) = 0. \tag{22}$$

(21) and (22) implies

$$C_{ix}(x_i(z, \delta), z_i(k)) \ge C_{ix}(x_i(z', \delta), z_i(k')).$$

Because C_{ix} is increasing in investment, we also have

$$C_{ix}(x_i(z, \delta), z_i(k)) < C_{ix}(x_i(z, \delta), z_i(k')).$$

The last two inequalities imply $C_{ix}(x_i(z', \delta), z_i(k')) < C_{ix}(x_i(z, \delta), z_i(k'))$, i.e. $x_i(z', \delta) < x_i(z, \delta)$ because $C_{ixx} > 0$. So $x_j(z', \delta) > x_j(z, \delta)$ must hold for some $j \ne i$ in order for $X(z, \delta) \le X(z', \delta)$ to hold. Hence,

$$C_{jx}(x_j(z, \delta), z_j(k)) < C_{jx}(x_j(z', \delta), z_j(k)) \le C_{jx}(x_j(z', \delta), z_j(k'))$$

where the last inequality follows from $C_{jez} > 0$. However, this implies

$$0 = C_{jx}(x_j(z, \delta), z_j(k)) + D_x(X(z, \delta); \delta) < C_{jx}(x_j(z', \delta), z_j(k')) + D_x(X(z', \delta); \delta) = 0,$$

a contradiction. Hence, $\frac{\partial X(k,\delta)}{\partial k_i} < 0$ for all k, s and all i. Because p satisfies $p(z, \delta) = D_x(X(z, \delta); \delta)$, we have $\frac{\partial p}{\partial z_i} = D_{xx} \cdot \frac{\partial X(z,\delta)}{\partial k_i} < 0$. for all k, δ, i. ■

Proof of Proposition 5

Equilibrium emissions profile given $z(k), \delta$ satisfies $C_{ix}(x_i(z, \delta), z_i(k)) + D_x(Q(z, \delta); \delta) = 0$ for all i where $\sum_i x_i(z, \delta) = Q(z, \delta)$. In the investment stage, firm i solves

$$\min_{k_i} G_i(k_i) + E[C_i(x_i(z, \delta), z_i(k)) + p(z, \delta)x_i(z, \delta)].$$

The first order condition is

$$G'_i(k_i) + E\left[C_{ix}\left\{\frac{\partial x_i}{\partial z_i} + \lambda \sum_{j \ne i} \frac{\partial x_i}{\partial z_j}\right\} + C_{iz} + p(z,\delta)\left\{\frac{\partial x_i}{\partial z_i} + \lambda \sum_{j \ne i} \frac{\partial x_i}{\partial z_j}\right\} + \left\{\frac{\partial p}{\partial z_i} + \lambda \sum_{j \ne i} \frac{\partial p}{\partial z_j}\right\} x_i(z,\delta)\right] = 0.$$

By equation (13) we have

$$G'_i(k_i) + E\left[C_{iz} + \left\{\frac{\partial p}{\partial z_i} + \lambda \sum_{j \ne i} \frac{\partial p}{\partial z_j}\right\} x_i(z, \delta)\right] = 0.$$

With $\lambda = 0$, the first best investments k^* satisfy

$$G_i'(k_i^*) + EC_{iz}(x_i^*(z(k^*), \delta), z_i(k^*)) = 0$$

for all i and the equilibrium investments $\widetilde{k}$ satisfy

$$G_i'(\widetilde{k}_i) + E\left[C_{iz}(x_i^*(z(\widetilde{k}), \delta), z_i(\widetilde{k})) + \frac{\partial p}{\partial z_i} x_i^*(z(\widetilde{k}), \delta)\right] = 0.$$

for all i where $\frac{\partial p}{\partial z_i}$ is negative by Lemma 1. Hence, the equilibrium investment is larger than the first best level. ■

Proof of Proposition 6

The regulator's choice of total permits given k and a realization of δ satisfies

$$Q(K, \delta) = \frac{\bar{E} - af(\lambda)K}{1 + N\theta\delta}.$$

where $\bar{E} \equiv \sum_i \bar{e}_i$. The equilibrium price of permits P satisfies

$$P(K, \delta) = \frac{\delta(\bar{E} - af(\lambda)K)}{1 + N\theta\delta}.$$

Firm i's emission is given by

$$x_i(k, \delta) = \bar{e}_i - az_i(k) - \frac{\theta\delta(\bar{E} - af(\lambda)K)}{1 + N\theta\delta}.$$

Given k_{-i} and function $P(\cdot)$, firm i chooses investment to minimize the total cost of emission reduction:

$$\min_{k_i} G_i(k_i) + E[C_i(x_i(k, \delta), z_i(k)) + P(K, \delta)x_i(k, \delta)].$$

Using the envelope theorem, the first order condition is given by

$$rk_i - E\left[\frac{a(\bar{e}_i - x_i(k, \delta) - az_i(k))}{\theta}\right] + E\left[\frac{\partial P(K, \delta)}{\partial k_i} x_i(k, \delta)\right] = 0.$$

Sum this up for all firms and have

$$rK - ANa(\bar{E} - af(\lambda)K) - Baf(\lambda)[\bar{E} - af(\lambda)K] = 0.$$

where $A \equiv E\left[\frac{\delta}{1+N\theta\delta}\right]$ and $B \equiv E\left[\frac{\delta}{(1+N\theta\delta)^2}\right]$. Rearrange the terms and we have

$$K^{DAP}(\lambda) = \frac{ANa\bar{E} + Baf(\lambda)\bar{E}}{r + ANa^2 f(\lambda) + B(af(\lambda))^2}.$$

We know from the previous example that $K^{DAP}(\lambda) > K^*$ if $\lambda = 0$. With this example, we have $K^{DAP}(\lambda) > K^*$ when λ is small and $K^{DAP}(\lambda) < K^*$ when λ is large. The difference between K^{DAP} and K^* is given by

$$\Delta \equiv K^{DAP} - K^* = \frac{r\bar{E}[ANa^2 f(\lambda)(1 - f(\lambda)) + B(af(\lambda))^2]]}{af(\lambda)(r + AN(af(\lambda))^2 + B(af(\lambda))^2)(r + AN(af(\lambda))^2))}.$$

It follows that $\partial\Delta/\partial\lambda < 0$ and $\Delta < (>)0$ if $\lambda > (<)\hat{\lambda}$. ■

Proof of Proposition 8

1. If $\frac{\partial q_i(k)}{\partial k_i} = 0$ for all k and all i, we have

$$K^{DFP} = \frac{ANa\bar{E}}{r + ANa^2 f(\lambda)} = \frac{ANaf(\lambda)\bar{E}}{f(\lambda)r + AN(af(\lambda))^2} < \frac{ANaf(\lambda)\bar{E}}{r + AN(af(\lambda))^2} = K^*$$

   if $\lambda > 0$. We have $K^{DFP} = K^*$ if $\lambda = 0$. Hence, we have under-investment at the industry level.

2. If $q_i(k) = q_i(K)$ for all k and all i, then we have further under-investment. In this case, investment K satisfies

$$rK - E\left[\frac{a}{\theta}(\bar{E} - af(\lambda)K - X(K,\delta)) - \frac{\delta(\bar{E} - af(\lambda)K)}{1 + N\theta\delta}\frac{af(\lambda)}{1 + N\theta\delta}\right] = 0.$$

   K satisfying the above equation is given by

$$K^{DFP'} = \frac{ANa\bar{E} - Baf(\lambda)\bar{E}}{r + ANa^2 f(\lambda) - B(af(\lambda))^2},$$

   which is smaller than K^{DFP} in case 1. Both spillovers and the permit allocation effect work to lower the equilibrium industry investment compared to the first-best level.

■

Proof of Proposition 9

Under flexible auctioned permits, the total permits given (z, δ) satisfies

$$C_{ix}(x_i(z,\delta), z_i(k)) + D_x(Q(z,\delta);\delta) = 0$$

for all i where $\sum_i x_i(z,\delta) = Q(z,\delta)$ and the equilibrium permit price $p(z,\delta)$ satisfies

$$p(z,\delta) = D_x(Q(z,\delta);\delta).$$

In the investment stage, firm i solves

$$\min_{k_i} G(k_i) + E[C_i(x_i(z,\delta), z_i(k)) + p(z,\delta)x_i(z,\delta)].$$

The first order condition is

$$G_i'(k_i) + E\left[C_{iz} + \left\{\frac{\partial p}{\partial z_i} + \lambda\sum_{j\neq i}\frac{\partial p}{\partial z_j}\right\}x_i(z,\delta)\right] = 0. \tag{23}$$

Under flexible taxes, the tax rate (z, δ) satisfies

$$\tau(z,\delta) = D_x(Q(z,\delta);\delta) = 0.$$

In the investment stage, firm i solves

$$\min_{k_i} G_i(k_i) + E[C_i(x_i(z,\delta), z_i(k)) + \tau(z,\delta)x_i(z,\delta)].$$

$$G_i'(k_i) + E\left[C_{iz} + \left\{\frac{\partial \tau}{\partial z_i} + \lambda \sum_{j \neq i} \frac{\partial \tau}{\partial z_j}\right\} x_i(z,\delta)\right] = 0. \tag{24}$$

Because $\tau(z,\delta) = p(z,\delta)$ for all (z,δ), conditions (23) and (24) are equivalent. Therefore, the equilibrium outcomes under flexible auctioned permits and taxes are the same. ■

Proof of Lemma 10

The derivative of the equilibrium investment with respect to λ is proportional to

$$E\left[\frac{r(1+N\theta\delta)^2 - \delta a^2 \{f(\lambda) + N(1+N\theta\delta)\}^2}{\delta(1+N\theta\delta)^4}\right].$$

This expression is positive if r is large and if a and the realizations of δ are small enough. ■

Proof of Lemma 2

Suppose the firms are identical and $G_i = G$, $C_i = C$ for all i. Under flexible taxes, the equilibrium investment k^D satisfies

$$G'(k^D) + E\left[C_z + \frac{\partial \tau(k^D,\delta)}{\partial k} x(k^D,\delta)\right] = 0.$$

The equilibrium investment k^S under standards satisfies

$$G'(k^S) + E\left[C_z + C_x \frac{\partial x(k^S,\delta)}{\partial k}\right] = 0.$$

Because $\frac{\partial \tau}{\partial k} x(k,\delta) < 0 < C_x \frac{\partial x(k,\delta)}{\partial k}$ for all k and δ, we have $k^T > k^S$.

With a quadratic example, the equilibrium total investment is given by

$$K^T = \frac{ANa\bar{E} + Baf(\lambda)\bar{E}}{r + ANa^2 f(\lambda) + B(af(\lambda))^2}$$

under flexible taxes where $A \equiv E\left[\frac{\delta}{1+N\theta\delta}\right]$ and $B \equiv E\left[\frac{\delta}{(1+N\theta\delta)^2}\right]$. Under flexible standards, the equilibrium total investment is given by

$$K^S = \frac{CNaf(\lambda)\theta\bar{E}}{r + CN\theta(af(\lambda))^2}$$

where $C \equiv E\left[\frac{\delta^2}{(1+N\theta\delta)^2}\right]$. We have

$$K^S - K^T = \frac{E\left[\frac{N\theta\delta^2[f(\lambda)-N] - N\delta - f(\lambda)\delta}{(1+N\theta\delta)^2}\right] ra\bar{E}}{(r + CN\theta(af(\lambda))^2)(r + ANa^2 f(\lambda) + B(af(\lambda))^2)} < 0.$$

■

Proof of Proposition 11

We solve for the equilibrium total investments under taxes and standards (K^T and K^S), express the equilibrium social costs under both instruments as functions of K^T and K^S, and show that the equilibrium social cost is larger under standards.

Under either policy instrument, the equilibrium social cost as a function of equilibrium investment is given by

$$TC = \sum_i \frac{r}{2} k_i^2 + E \sum_i \frac{1}{2\theta} \left(\bar{e}_i - x_i(k;\delta) - a z_i(k)\right)^2 + E \frac{\delta}{2} \left(\frac{\bar{E} - af(\lambda)K}{1 + N\theta\delta} \right)^2.$$

The equilibrium emissions and investments equate the firms' marginal abatement costs and the marginal damages under each state:

$$\frac{\bar{e}_i - x_i(z;\delta) - a z_i(k)}{\theta} = \delta X(K;\delta)$$

for all i, K, δ where $X(K)$ is the equilibrium total emissions given $(K;\delta)$. Hence,

$$\begin{aligned} TC &= \frac{Nr}{2} \left(\frac{K}{N}\right)^2 + \frac{N}{2\theta} E \left(\theta\delta \frac{\bar{E} - af(\lambda)K}{1 + N\theta\delta} \right)^2 + E \frac{\delta}{2} \left(\frac{\bar{E} - af(\lambda)K}{1 + N\theta\delta} \right)^2 \\ &= \frac{r}{2N} K^2 + \frac{N\theta}{2} C \left(\bar{E} - af(\lambda)K\right)^2 + \frac{B}{2} \left(\bar{E} - af(\lambda)K\right)^2 \\ &= \frac{r}{2N} K^2 + \frac{N\theta C + B}{2} \left(\bar{E} - af(\lambda)K\right)^2 = \frac{r}{2N} K^2 + \frac{A}{2} \left(\bar{E} - af(\lambda)K\right)^2 \end{aligned}$$

where the last equality follows from

$$N\theta C + B = E \frac{N\theta\delta^2 + \delta}{(1 + N\theta\delta)^2} = E \frac{\delta(1 + N\theta\delta)}{(1 + N\theta\delta)^2} = E \frac{\delta}{1 + N\theta\delta} \equiv A.$$

Hence, the difference between the total costs under flexible taxes and standards is

$$\begin{aligned} TC^S - TC^T &= \frac{r}{2N} \left((K^S)^2 - (K^T)^2\right) + \frac{A}{2} \left[\left(\bar{E} - af(\lambda)K^S\right)^2 - \left(\bar{E} - af(\lambda)K^T\right)^2 \right] \\ &= \frac{r}{2N} \left(K^S + K^T\right)\left(K^S - K^T\right) + \frac{A}{2} \left[-2\bar{E} a f(\lambda)(K^S - K^T) + (af(\lambda))^2 \left(K^S + K^T\right)\left(K^S - K^T\right) \right] \\ &= \frac{a\bar{E}(K^S - K^T)}{2N} \underbrace{\left[\left(r + NA(af(\lambda))^2\right) \left(\frac{K^S + K^T}{a\bar{E}} \right) - 2NAf(\lambda) \right]}_{(*)}. \end{aligned}$$

Because $K^S < K^T$, it remains to show that the expression inside the square brackets $(*)$ is negative for $TC^S - TC^T > 0$. It follows that

$$(*) = \frac{(r + NA(af(\lambda))^2)(2AN^2\theta C(af(\lambda))^2 + 2BNf(\lambda)\theta C(af(\lambda))^2 + rA(N + f(\lambda))) - 2NAf(\lambda)}{(r + CN\theta(af(\lambda))^2)(r + ANa^2 f(\lambda) + B(af(\lambda))^2)}$$

and the numerator is equal to

$$\begin{aligned} &r^2 A(N + f(\lambda) - 2Nf(\lambda)) + 2rAN^2\theta C(af(\lambda))^2(1 - f(\lambda)) \\ &+ rNA^2(af(\lambda))^2(f(\lambda) - N) + 2rf(\lambda)BN(af(\lambda))^2 E \left(\frac{-1 + (1 - N)\theta\delta^2}{(1 + N\theta\delta)^2} \right) < 0. \end{aligned}$$

Therefore, $TC^S - TC^T > 0$. ■

References

[1] Benford, F. A. 1998. On the dynamics of the regulation of pollution: incentive compatible regulation of a persistent pollutant. *Journal of Environmental Economics and Management,* 36: 1-25.

[2] Biglaiser, G., J. K. Horowitz, and J. Quiggin. 1995. Dynamic pollution regulation. *Journal of Regulatory Economics,* 8: 33-44.

[3] Bloom, N., M. Schankerman, and J. V. Reenen. 2005. Identifying Technology Spillovers and Product Market Rivalry. Centre for Economic Performance Discussion Paper No 675, London School of Economics and Political Science.

[4] Downing, P. B and L. J. White. 1986. Innovation in pollution control. *Journal of Environmental Economics and Management,* 13: 18-29.

[5] Ellerman, D. A., P. L. Joskow, R. Schmalensee, J.-P. Montero, and E. M. Bailey. 2000. *Markets for clean air: the U.S. acid rain program.* Cambridge: Cambridge University Press.

[6] Fischer, C., I. W. H. Parry, and W. A. Pizer. 2003. Instrument choice for environmental protection when technological innovation is endogenous. *Journal of Environmental Economics and Management,* 45: 523-545.

[7] Hackett, S. C. 1995. Pollution-controlling innovation in oligopolistic industries: some comparisons between patent races and research joint ventures. *Journal of Environmental Economics and Management,* 29: 339-356.

[8] Hahn, R. W. 1984. Market power and transferable property rights. *Quarterly Journal of Economics,* 99: 753-765.

[9] M. Hoel and L. Karp. 2002. Taxes versus quotas for a stock pollutant. *Resource and Energy Economics,* 24: 367-384.

[10] Jaffe, A. 1986. Technological Opportunity and Spillovers of R&D: Evidence from Firms Patents, Profits and Market Value. *American Economic Review,* 76: 984-1001.

[11] Jaffe, A. B., R. G. Newell, and R. N. Stavins. 2003. Technology change and the environment, in *Handbook of Environmental Economics.* (K. G. Mäler and J. Vincent, Eds.), Amsterdam: North Holland/Elsevier Science.

[12] Jung, C., K. Krutilla, and R. Boyd. 1996. Incentives for advanced pollution abatement technology at the industry level: an evaluation of policy alternatives. *Journal of Environmental Economics and Management,* 30: 95111.

[13] Karp, L.and J. Zhang. 2001. Controlling a stock pollutant with endogenous investment and asymmetric information. Working Paper, Department of Agricultural and Resource Economics, University of California, Berkeley, CA.

[14] Kelly, D. L. and C. D. Kolstad. 1999. Bayesian learning, growth, and pollution. *Journal of Economic Dynamics and Control,* 23: 491-518.

[15] Kennedy, P. W. 1999. Learning about environmental damage: implications for emissions trading. *Canadian Journal of Economics,* 32: 1313-1327

[16] Kennedy, P. W. and B. Laplante. 1999. Environmental policy and time consistency: emission taxes and emissions trading, in *Environmental Regulation and Market Power.* (E. Petrakis, E. S. Sartzetakis and A. Xepapadeas, Eds.), Cheltenham: Edward Elgar, 116-144.

[17] Kolstad, C. D. 1996. Learning and stock effects in environmental regulation: the case of greenhouse gas emissions. *Journal of Environmental Economics and Management,* 31: 1-18.

[18] Leone, R. A. 1998. Technology-forcing public policies in the automobile, in J.A. Gomez-Ibanez, W.B. Tye, C. Winston (Eds.), *Essays in Transportation Economics and Policy,* Washington, DC: Brookings Institution Press, 291-324.

[19] Lyon, T. P. and J. W. Maxwell. 2004. *Corporate Environmentalism and Public Policy,* Cambridge: Cambridge University Press.

[20] Margolis, R. M., D. M. Kammen, 1999. Evidence of under-investment in energy R&D in the United States and the impact of Federal policy. *Energy Policy,* 27: 575-584.

[21] Milliman, S. R. and R. Prince, 1989. Firm incentives to promote technological change in pollution. *Journal of Environmental Economics and Management,* 17: 292-296.

[22] Moledina, A. A., J. S. Coggins, S. Polasky, and C. Costello. 2003. Dynamic environmental policy with strategic firms: prices versus quantities. *Journal of Environmental Economics and Management,* 45: 356-376.

[23] Montero, J-P. 2002. Permits, standards, and technology innovation. *Journal of Environmental Economics and Management,* 44: 23-44.

[24] Popp, D. 2005. International innovation and diffusion of air pollution control technologies: the effects of NOX and SO2 regulation in the US, Japan, and Germany. *Journal of Environmental Economics and Management,* in press, available online August 1, 2005.

[25] Pindyck, R. S. 2000. Irreversibility and the timing of environmental policy. *Resource and Energy Economics,* 22: 233-259.

[26] Requate, T. 2005a. Dynamic incentives by environmental policy. *Ecological Economics,* 54: 175-195.

[27] Requate, T. 2005b. Timing and Commitment of Environmental Policy, Adoption of New Technology, and Repercussions on R&D. *Environmental and Resource Economics,* 31: 175-199.

[28] Requate, T. and W. Unold. 2003. Environmental policy incentives to adopt advanced abatement technology: Will the true ranking please stand up? *European Economic Review,* 47: 125-146.

[29] Salop, S. C. and D. T. Scheffman. 1983. Raising rivals' costs. *American Economic Review Papers and Proceedings,* 73: 267-271.

[30] Saphores, J. M. 2002. Environmental uncertainty and the timing of environmental policy. Working Paper 01-02-06, Department of Economics, University of California, Irvine, CA.

[31] Spence, M. 1984. Cost reduction, competition, and industry performance. *Econometrica,* 52: 101-122.

[32] Tarui, N. and S. Polasky. 2005. Environmental regulation with technology adoption, learning and strategic behavior. *Journal of Environmental Economics and Management,* 50: 447-467.

[33] Ulph, A. and D. Ulph. 1997. Global warming, irreversibility and learning. *Economic Journal,* 107: 636-650.

[34] Weitzman, M.L. 1974. Prices vs. quantities. *Review of Economic Studies,* 41: 477-491.