Commitment and Timing of Environmental Policy, Adoption of New Technology and Repercussions on R&D

by Till Requate

C | A | U
Christian-Albrechts-Universität Kiel
Department of Economics

Economics Working Paper
No 2003-07

Commitment and Timing of Environmental Policy, Adoption of New Technology, and Repercussions on R&D *

by

Till Requate

Department of Economics

Kiel University

Olshausenstrasse 40

24098 Kiel

Germany

Phone: (++49) 431 – 8804424,

Email: REQUATE@economics.uni-kiel.de

March 2003

*I am greatful to Paul Mensink, Pablo Montero, Ville Mälkonen, and Richard Newell for very helpful comments.

Abstract

We investigate the interplay between environmental policy, incentives to adopt new technology, and repercussions on R&D. We study a model where a monopolistic upstream firm engages in R&D and sells advanced abatement technology to polluting downstream firms which are subject to regulation. We consider four different timing and commitment regimes of environmental tax and permit policies: ex post taxation (or issuing permits), ex interim commitment to a tax rate (a quota of permits) after observing R&D success but before adoption, and two types of ex ante commitment before R&D activity. We study the second best tax and permit rules and rank the policies with respect to welfare.

1 Introduction

Important criteria to evaluate environmental policy instruments are effectiveness and efficiency. As Kneese and Schulze [1975] have pointed out early, however, the long term incentives provided by environmental policy to *adopt* and to *develop* new, less polluting technology are as least as important as static efficiency. In this paper we investigate those long term incentives, in particular the interplay between pricing and adoption of new technology, and the incentives to engage in R&D to develop a new, less polluting technology. We do not only address the question of instrument choice, we also ask how the timing of environmental policy and the ability of commitment to particular tax rates or permit quantities affects both the R&D effort to develop new, less polluting technology and the incentive to adopt such technology.

In contrast to most of the literature which either assumes ex ante commitment to a certain policy level, or ex post optimal, time-consistent policy reaction, we study four different timing and commitment regimes: first, *ex post* optimal setting of the tax rate or a quota of permits, respectively; secondly, *ex interim commitment* to a particular tax rate or quota of permits after knowing whether or not R&D has been successful but before pricing and adoption of the new technology. Thirdly, we study *ex ante commitment* to a fixed tax rate (or permit quantity, respectively) *before* R&D effort and before R&D success is guaranteed. Finally we study *ex ante commitment* to a *menu* of tax rates (or permit quantities, respectively) contingent on R&D success but before R&D is undertaken.[1] The last regime is reminiscent of principal agent theory where a principal makes a commitment to a whole menu of rewards to an agent contingent on different outcomes. In the classical regulation theory the commitment to a menu of policy levels has been considered less often.

In our set-up we distinguish between the regulated polluting industry which *employs* abatement technology and the R&D industry which *develops* new abatement

[1] I am greatful to Paul Mensink who suggested to consider this regime.

technology. Empirical results by Lanjouw and Mody (1995) support this distinction. Those authors found that only 5% of air and 8% of water pollution abatement technology, respectively, developed by the machinery sector is used by the same industry itself. The remaining 95% and 92% of innovations, respectively, are developed for other industries.

For simplicity we consider the case of a monopolistic R&D industry for the most part of the paper. In section 8 we briefly sketch how to extend the analysis to R&D oligopoly.

Our policies and their commitment structures can be ranked as follows: ex ante commitment to a menu of tax rates contingent on R&D success dominates all other policies including ex ante commitment to a menu of permit quotas. Ex interim taxation dominates all ex post optimal policies. Taxation dominates permit trading under both ex ante commitment contingent on R&D success and ex interim commitment. The reason for this is that the R&D monopolist can manipulate the price for emission allowances by his price or output policy which he is not able to do if the regulator makes a commitment to a particular tax policy. An unambiguous ranking is neither possible between ex interim and ex ante commitment (either taxes or permits) independent of R&D success, nor between the tax and permit policies under ex ante commitment independent of R&D success.

Moreover, we can show that the second best optimal tax rate always *exceeds* marginal damage under ex interim regulation and can exceed marginal damage under ex ante commitment. This result seems to be surprizing in the light of Parry's (1995) findings and many results on taxation of imperfectly competing firms. The reason for our result, however, is that the monopolistic R&D firm prices too high and thus sells too few units of the new technology to the polluting sector. To compensate for this distortion the regulator raises the polluting firms' willingness to pay for the new technology by enhancing the tax rate above marginal damage. Little can be said in general concerning a comparison of the optimal tax rates (or permit prices) for the different timings. Tax rates can be higher or lower under ex post ex post regulation compared to ex interim regulation. The same holds true for a comparison between ex ante and ex interim regulation.

Finally, we would like to know whether decentralized policy induces too much or too little R&D. However, no definite answer can be given to this question. The (expected) private value of innovation to the monopolist may exceed or fall short of the (expected) social value of innovation. This contrasts from Arrow's (1962) result, popularized e.g. by Tirole (1988), according to which in a world without externalities a monopolist's value of innovation always falls short of the social value.

So far we have discussed environmental policy only. In an additional section we show that the regulator can restore first best outcomes by the choice of three policy instruments: Emission taxes or permits to regulate pollution, a subsidy for the R&D monopolist per unit of equipment sold to the polluting industry to adjust for too little output, and finally a profit tax or subsidy in order to equalize private and social values of innovation. However, neither individual profit taxes nor output subsidies (or subsidies for adoption of certain technology) are always feasible. Just recently the EU commission argued that a new German law which allows to subsidize the use of renewable resources violates the competition rules of the European Treaty. Hence, it is important to study the impact of pure pollution control policies on R&D and their (second best) optimal design as is done for the most part of this paper.

The article builds on two strands of literature. The oldest one deals with the incentives to *adopt* new technology, given that the new technology is already available. In a series of papers Downing and White (1987), Milliman and Prince (1989), Jung et al. (1997), Requate and Unold (2001, 2002) have investigated those incentives. Especially Requate and Unold demonstrated that emission taxes lead to over-investment if the regulator has made an ex ante commitment to the optimal tax rate before a new, less polluting technology was available. In contrast, a similar commitment to auctioned or free permit quotas leads to under-investment. Those authors have also demonstrated that under competitive conditions the regulator can achieve first best outcomes by optimally responding to diffusion of the new technology.

In all those models it was assumed that the new technology was already available. More recent developments deal with the simultaneous incentives for adoption and R&D of new technology. With respect to environmental R&D, the papers by Biglaiser and Horowitz (1995), Parry (1995), and Denicolo (1999) are closest to the spirit of this paper. Biglaiser and Horowitz consider a model where the regulated polluting firms can engage in R&D themselves. As in our model this technology can be sold to other firms. Those authors consider ex post regulation only. They also restrict their analysis to linear damage functions and thus neglect important features of policy adjustment, commitment and timing. By contrast, Parry studies ex ante commitment to one tax rate only, independently of R&D success. Parry finds that the second best optimal tax rate falls short of marginal damage, whereas in my model the tax rate may exceed marginal damage. Denicolo considers a deterministic model with endogenous technology and compares ex post regulation and commitment. His kind of commitment corresponds to our regime of ex ante commitment with only one tax rate (or quota of permits). Denicolo also finds that taxes and permits are equivalent under ex post regulation but different under commitment. Moreover, he finds that taxes are superior to permits under commitment. In contrast to my model, however, Denicolo always finds under-investment under commitment, whereas in my model over-investment can also happen. Zhao (2001) studies a general equilibrium model with exogenous uncertainty. He finds that permits give higher incentives to invest in cleaner technology than taxes.

This paper is organized as follows. The next section sets up the model. In section 3 we characterize the social optimum. In section 4 we describe the possible timings of regulation in the decentralized settings. In section 5.1 we characterize both the polluting "downstream" firms' and the "upstream" monopolist's behavior under tax and permit policies. In section 6 we characterize the second best optimal rules for environmental policies and for the different timing and commitment regimes, and we make a comparison of those policies. In section 7 we show how to restore first best outcomes by a combining three policy instruments. In section 8 we briefly discuss how to generalize the model for the case of upstream duopoly. Most of the proofs are given in the appendix. The final section summarizes the results, presents some policy conclusions, and gives some directions for further research.

2 The Model

We consider a model with two industries, a competitive, polluting downstream industry which is subject to environmental regulation and a non-competitive upstream industry which engages in R&D to develop a new, environmentally more friendly technology and sells it to the polluting downstream firms. For the most part of the paper we assume the R&D industry to be monopolistic.

2.1 Abatement and Investment Cost of Downstream Firms

There is a continuum of downstream firms $x \in [0,1]$ which, prior to innovation, are represented by their identical abatement cost functions[2] $C^0(e)$ which satisfies $-C^0_e(e) := dC^0(e)/de > 0$ and $C^0_{ee}(e) := d^2C^0(e)/(de)^2 > 0$ for $e \leq e^0_{\max}$, i.e. we have positive and decreasing marginal abatement costs as long as emissions fall short of the maximal, or laisser-faire emission level $e^0_{\max}$.

An upstream monopolist engages in R&D. With a certain probability y, contingent on R&D effort, the upstream firm develops a new, exogenously given technology which leads to both, lower abatement cost $C^A(e,x) < C^0(e)$ and lower marginal abatement costs, $-C^A_e(e,x) < -C^0_e(e)$ for all $e \leq e^0_{\max}$ and all x, which is a firm specific parameter of downstream firm $x \in [0,1]$. The cost functions $C^A(e,x)$ satisfy the same

[2] Since the downstream industry is perfectly competitive, it is not necessary to explicitly model the output market of those firms since the output adjustment upon environmental regulation is already implied in the abatement cost function.

properties as $C^0(e)$, i.e. $-C_e^A(e,x) > 0$ and $C_{ee}^A > 0$ for $e < e_{\max}^x$. The new technology, however, is of different value for the downstream firms. The crucial assumption is $C_x^A \geq 0$ and $-C_{ex}^A \geq 0$, which means that the closer the firm specific parameter x is to 0, the more suitable is the technology for that downstream firm. For technical reasons we assume convexity, implying $C_{ee}^A C_{xx}^A - [C_{ex}^A]^2 > 0$. The cost function $C^A(\cdot,\cdot)$ may also contain fixed set-up costs which need not be considered explicitely.[3]

In the decentralized situations, to be treated below, the downstream firms will also have to pay a price p to the upstream monopolist.

2.2 R&D and Production Costs of Upstream Firms

The upstream R&D firm faces a cost $R(y)$ in order to be to be successful in R&D with probability y. We assume $R(0) = 0$, $R' > 0$, $R'' > 0$, and $\lim_{y \to 1} R(y) = \infty$. Besides the R&D costs the upstream firm has constant marginal production cost c in order to produce one unit of the new technology. Let π^M denote the upstream firm's gross monopoly profit after R&D success, i.e. without the R&D costs. Hence, the ex ante expected profit is given by

$$\widetilde{\Pi}(y) = y\pi^M - R(y)$$

2.3 Social Costs and Efficient Allocation

Total emissions are given by

$$E = \int_0^x e^{\tilde{x}} d\tilde{x} + (1-x)e^0 \tag{1}$$

and are evaluated by a convex damage function $D(\cdot)$ which depends on total emissions only. In order to define total social costs we first define $SC^I = SC^I(x, e_0, \{e^{\tilde{x}}\}_{\tilde{x} \in [0,x]})$ as the social cost of pollution in case that the upstream firm has been successful in

[3]Introducing heterogeneity of non-investing firms is possible but does not change the results.

R&D. Thus:

$$SC^I = \int_0^x [C^A(e^{\tilde{x}}, \tilde{x}) + c]d\tilde{x} + (1-x)C^0(e^0) + D(E) \tag{2}$$

In this case those downstream firms represented by the interval $[0, x]$ adopt the new technology, facing total costs represented by the integral.[4] The remaining share of downstream firms $(1-x)$ does not adopt the new technology and hence faces abatement cost $C^0(e^0)$ borne from the conventional technology.

In case of no R&D success, the social cost is simply given by[5]

$$SC^0(e^0) = C(e^0) + D(e^0).$$

Including cost and probability of R&D success we obtain the ex ante expected total social cost as

$$TSC(y, x, e_0, \{e^{\tilde{x}}\}_{\tilde{x}\in[0,x]}) = ySC^I + (1-y)SC^0 + R(y) \tag{3}$$

3 Socially Optimal Allocations

A social planner proceeds as follows. First he chooses the level of R&D. Then given success or failure of the upstream firm, he chooses the share x of firms to adopt the new technology. Finally he chooses emission levels e^0, and $\{e^{\tilde{x}}\}_{\tilde{x}\in[0,x]}$, respectively.

To solve the problem of minimizing total social costs, we start backwards. Independently of R&D success, emissions must satisfy the rule

$$-C_e^0(e^0) = D'(E) \tag{4}$$

and

$$-C_e^A(e^x, x) = D'(E) \text{ for all } x, \tag{5}$$

[4]Since $\partial C/\partial x > 0$, it is efficient that firm $\widetilde{x} < x$ adopts the new technology, if x should adopt it.

[5]Note that in this case $E_0 = 1 \cdot e_0$ since the total of firms has measure 1.

i.e. marginal abatement costs of each firm must be equal to marginal social damage.[6]

The *optimal share* x of firms to *adopt* the new technology given that the upstream firm was successful is given by the first order condition

$$C^A(e^x, x) + c - C_0(e^0) = D'(E)[e^0 - e^x] \tag{6}$$

Finally, the optimal level of R&D is simply determined by the first order condition:[7]

$$SC^0 - SC^I = R'(y) \quad . \tag{7}$$

4 Timing of Regulatory Policies:

In sections 5.1 and 6 we will study the impact of downstream regulation on both upstream R&D effort and pricing of the new technology. Since timing and commitment of regulation will turn out to be crucial, we will first of all define the different games between the regulator and the firms. For this purpose look at figure 1. Irresepective of regulation, the industry moves in the following order: first, the R&D firm decides on the amount of its R&D effort. In case of R&D success, it fixes a price for the new technology. Thirdly, the downstream firms decide whether or not to adopt the new technology. Finally, the downstream firms decide on how much to abate by setting their marginal abatement costs equal to the tax rate, or the permit price, respectively. On top of this structure, the regulator as different options to choose the point of time where to inact policy. Let us start backwards: with timing **D** (ex post regulation) the regulator moves after having observed both R&D success and the rate of adoption. Under timing **D'** the regulator observes both, R&D success and the price for the new technology and inacts policy before adoption of the new technology. Although this timing does not seem to be very realistic, it can be shown (see Requate and Unold 2001

[6] Note that (4) yields different values of e^0, contingent on R&D success.

[7] Employing the envelope theorem we can neglect the indirect effect on x and e^0, $\{e^{\tilde{x}}\}_{\tilde{x}\in[0,x]}$.

and 2003) that this timing is equivalent to timing **D**. Hence we will not further consider it here. With timing **C** (ex interim regulation) the regulator makes a commitment to the level of his policy instrument after observing whether or not the R&D sector has been successful. With timings **A** and **B** (ex ante commitments) the regulator makes commitments to the level of his instruments even before the R&D sector engages in R&D effort. The difference between policy regime **A** and **B** is that with regime **B** the regulator decides only for a single tax rate, or a single quantity of permits, respectively, irrespective of whether R&D has been successful or not. With regime **B** the regulator makes a commitment to a whole menu of instruments. The latter form of policy is well known from principal agent theory where the principal moves first by choosing a whole menu of rewards to pay the agent contingent on different outcomes.

Figure 1 about here.

In the following sections we first analyze the behavior of the downstream firms, secondly the behavior of the upstream firms, and finally we study second best optimal tax and permit policies. This procedure is more efficient than analyzing the four different regimes one by one since the downstream firms' behavior is always the same and the upstream firms' behavior is almost identical for the regimes A, B, and C.

5 The Firms' Behavior

5.1 Behavior of Polluting Downstream Firms

Irrespective of the timing, in the last stage of all games the downstream firms set their marginal abatement costs equal to the tax rate τ or permit price σ, respectively (we treat the case of taxes here, the case of permits works the same), i.e.

$$
\begin{aligned}
-C_e^0(e) &= \tau &(8)\\
-C_e^A(e,x) &= \tau &(9)
\end{aligned}
$$

The solutions in e are denoted by $e^0(\tau)$ and $e^x(\tau)$, respectively. At this place an additional assumption is in order:

Aassumption 1 $d[e^0(\tau) - e^x(\tau)]/d\tau \leq 0$.

The assumption says that the difference between emissions of the old and the new technology decreases if the tax rate rises or if both firms reduce emissions keeping marginal abatement costs equal.[8]

Next consider the downstream firm's decision whether of not to adopt the new technology. Recall that p denotes the price of the advanced technology charged by the upstream firm. Then a downstream firm decides to invest if and only if

$$C^A(e^x, x) + \tau e^x + p \leq C^0(e^0) + \tau e^0 \tag{10}$$

If (10) holds with equality, the firm is indifferent between investing or not. Observe that if it pays for firm x to adopt the new technology, it also pays for any firm $\tilde{x} < x$ since the abatement costs with the new technology are lower for firm $\tilde{x}$ then for firm x. Thus, if (10) holds with equality, it implicitly defines the demand for new technology as a function of the tax rate, or equivalently, (10) defines the downstream firms' inverse demand or willingness to pay function $p(x, \tau)$ which is downward sloping with respect to quantity and will be shifted upwards if the tax rate (or permit price) goes up:

Lemma 1 $p_x < 0$, *and,* $p_\tau > 0$.

For proof see the appendix.

[8] This assumption is consistent with physical evidence according to which by the entropy law the marginal abatement costs go to infinity if emissions go to zero. Note that this assumption allows also for a parallel shift of the marginal abatement cost curve, in which case the derivative is zero.

5.2 Behavior of R&D Firm

Finally we study the R&D sector, starting with the output decision once R&D was successful.

5.2.1 Output and Pricing

For the output and pricing decision the regime of regulation does matter. Under the timings A, B, and C, the monopolist takes the tax rate as given, whereas in timing D he can manipulate the tax rate, or the permit price, respectively. However, the monopolist can also manipulate the permit price under the timings A, B, and C.

Tax regime under ex ante or ex interim regulation (timings A - C): Given R&D success and facing the tax rate τ, the monopolistic firm maximizes its monopoly profit $\pi(x,\tau) = [p(x,\tau) - c]\,x$. The first order condition for monopoly output is as usual:

$$\pi_x(x,\tau) = p_x + p(x,\tau) - c = 0 \tag{11}$$

However, the **comparative statics effect** of the monopoly output x as a reaction on τ is ambiguous in general. But we obtain:

Lemma 2 *If the tax increases, the upstream monopolist produces more output, if and only if*

$$(e^0 - e^x)C^A_{ee} + C^A_{xe}x > 0 \tag{12}$$

The reason why $x_\tau := \partial x/\partial\tau$ cannot be signed unambiguously is that, on the one hand, the inverse demand curve shifts upwards since $p_\tau > 0$. This would allow the monopolist to charge a higher price. On the other hand, the inverse demand curve becomes also more elastic (steeper) since $p_{x\tau} < 0$, leading - other things being equal - to lower monopoly output. If C^A_{xe} is sufficiently small, which e.g. holds for parallel shifts of the marginal abatement costs curve through x, we obtain $x_\tau > 0$.

Tax regime under ex post regulation (timing D): Since the R&D firm can manipulate the tax rate, or permit price respectively, in regime D, we briefly have to look at the regulator's behavior. He clearly sets the tax rate equal to marginal damage:

$$\tau_D = D'(E) \tag{13}$$

Since aggregate emissions E depend on x and since the regulator is the last to move, the tax rate τ depends on x, too. To see the impact of x on τ we differentiate (13) with respect to x, obtaining

$$\frac{d\tau}{dx} = D''(E) \cdot \left\{ [e_x - e_0] + \frac{d\tau}{dx}\frac{\partial E}{\partial \tau} \right\} \tag{14}$$

where

$$\frac{\partial E}{\partial \tau} = \int_0^x \frac{\partial e(\tilde{x}, \tau)}{\partial \tau} d\widetilde{x} + (1-x)\frac{de_0}{d\tau} < 0$$

is the partial effect of a tax increase on emissions if the share of adopting firms is kept constant. Note that both $\frac{\partial e(\tilde{x},\tau)}{\partial \tau}$ and $\frac{de_0}{d\tau}$ are negative. Solving (14) for $d\tau/dx$ yields

$$\frac{d\tau}{dx} = -\frac{D''(E)[e^0 - e^x]}{1 - D''(E)\frac{\partial E}{\partial \tau}} < 0 \tag{15}$$

Since with this timing the tax rate depends on x, the upstream firm's profit can be written as

$$\pi(x) = [p(x, \tau(x)) - c]x$$

The first order condition for profit maximum is now given by

$$\pi'(x) = [p_x + p_\tau]x + p - c = 0 \tag{16}$$

Since $p_x + p_\tau(d\tau/dx) < p_x$ the monopolist's effective inverse demand function is steeper in the case where he can influence the tax rate than in the case where the firm has to take it as given (as is the case in the timings A through C). See Figure 2.

Permit regime under ex ante or ex interim regulation (timing A through C): We now study regulation by issuing permits. The total supply of permits is written as L. The downstream firms take the price for permits σ as given and thus choose their emissions according to $-C_e^0(e) = \sigma$ and $-C_e^A(e, x) = \sigma$, respectively. The last equation again defines $e^x(\sigma)$. The permit market clears according to

$$\int_0^x e^{\widetilde{x}}(\sigma) d\widetilde{x} + (1 - x)e^0(\sigma) = L \tag{17}$$

Note that the permit price is a function of both L and x. In the appendix we show the following result.

Lemma 3 *i)* $\frac{\partial\sigma}{\partial L} = \frac{1}{E_\sigma} < 0.$

ii) $\frac{\partial\sigma}{\partial x} = \frac{e^0 - e^x}{E_\sigma} < 0.$

iii) If (12) holds then $\frac{dx}{dL} < 0.$

i) is the usual result that the price for permits falls if the supply of permits rises. ii) says that the monopolistic upstream firm can depress the permit price by selling more units of her new technology. iii) represents the total reaction of the upstream monopolist's output on increasing supply of permits. The latter effect can be ambiguous in general, but it is negative as intuitively expected under some mild additional assumption, i.e. (12). Note that in contrast to the case of taxes, (12) is a coarse sufficient but no necessary condition for iii) to hold. The monopolist's profit can now be written as

$$\pi(x) = [p(x, \sigma(x, L)) - c]x$$

The first order condition for profit maximization then given by

$$[p_x + p_\sigma \sigma_x]x + p - c = 0 \tag{18}$$

This equation looks similar to (16). But since under a permit regime in scenarios A through C total emissions remain constant whereas they can be manipulated by the monopolist in timing D, the terms σ_x and τ_x are different. Hence (16) and (18) are not equivalent.

Permit regime under ex post regulation (timing D): Here is no difference to regulation by taxes since if the regulator is the last to move, the share of adopting firms x is already fixed. Thus we are in the ordinary case of regulation under perfect competition and perfect information. We know that in this case taxes and permits are equivalent. Note, however, that the inverse demand function, faced by the monopolist is more elastic under the permit regimes than under the tax regimes. The reason is that if the monopolist increases output, the permit price falls since the adopting firms have a lower demand for permits. But the decreasing permit price lowers the downstream firms' willingness to pay for the new technology.

5.2.2 R&D Effort

For the R&D decision of the upstream firm the final profit is crucial. Hence let Π_j^M denote the monopoly profit under timing $j = A, ..., D$. Then the expected profit net R&D costs is given by

$$\widetilde{\Pi}(y) := y\Pi_j^M - R(y)$$

The first order condition simply reads

$$R'(y) = \Pi_j^M \tag{19}$$

It is interesting to study the impact of a tax increase on the success probability and R&D effort in the timings A through C (under timing D this question does not make sense since for the monopolist the tax rate is not an exogenous variable). By employing the envelope theorem we obtain

$$\frac{dy}{d\tau} = \frac{(e^0 - e^x)x}{R''(y)} > 0 \tag{20}$$

For permits we obtain $dy/dL = (e^0 - e^x)x\sigma_L/R''(y) < 0$, i.e. *reducing (!)* the quota of permits also enhances the upstream monopolist's R&D effort.

6 The Regulator's Problem

We are now ready to study the regulator's problem under the different regimes. Clearly in Scenario D the regulator sets the tax rate equal to marginal damage or issues the corresponding number of permits, respectively. We have already made use of this rule when studying the pricing rule of the upstream monopolist in section 5.1. In the next section we study second best policies under timings $A - C$:

6.1 Second Best Tax and Permit Rules for Timing C

6.1.1 Tax Regime

Given R&D success the regulator minimizes the social cost under the constraints (8), (9), and (11). Thus the objective function is given by (2) where x, e^x, and e^0 are all functions of the tax rate. It is then straightforward to calculate the second best tax rate:

$$\tau_C = D'(E) - \frac{(p-c)x_\tau}{dE/d\tau} = D'(E) + \frac{p_x(x,\tau)x \cdot x_\tau}{dE/d\tau} \tag{21}$$

where the total derivative of E with respect to τ is given by $\frac{dE}{d\tau} = (e_A - e_0)x_\tau + E_\tau$. The partial derivative $E_\tau = \frac{\partial}{\partial\tau}\left[\int_0^x e(\tau,\widetilde{x})d\widetilde{x} + (1-x)e_0(\tau)\right] < 0$ is the reaction of the downstream firms on the tax rate given the share of adopting firms x. Formula (21) is proved in the appendix. We can derive the following result:

Proposition 4 *Under timing C, with R&D success*

i) the second best tax rate τ_C is **higher than marginal damage** *if and only if (12) holds.*

ii) If in timing C the regulator charges τ_D, the second best tax rate from scenario D, the monopolist sells more units of the new technology than in timing D, formally $x_C(\tau_D) > x_D$, where x_C (x_D) is the share of adopting firms under optimal taxation in timing C (D).

iii) The second best share of adopting firms x_C is less than socially optimal but greater than x_D.

iv) The social value of innovation, and thus also the ex ante expected social value of innovation, is greater under timing C than under timing D.

v) The second best tax rate τ_C may exceed or fall short of τ_D.

The most important of the above results is certainly iv). It says that some commitment is good if the regulator cannot directly enhance output of the monopolistic innovator. Observe further the apparent contradiction between i) and v) since τ_c exceeds marginal damage whereas τ_D is always equal to marginal damage. However, emissions and thus the marginal damage are different in the two regimes. Since the monopolist produces fewer units under ex post regulation (timing D) as compared to the ex interim case, emissions and thus marginal damage are higher in timing D than in timing C.

Proof: i) follows immediately from the signs $x_\tau > 0$ and $E_\tau < 0$. For ii) observe that, on the one hand, the monopolist's inverse demand function under timing C is less elastic if the tax rate is given as fixed. On the other hand, the two inverse demand functions $p(x, \tau_D)$ for timing C and $p(x, \tau(x))$ for timing D cross at $x = x_C$ (see Figure 2). Hence the optimal point for the monopolist under timing C must be on the right hand side of x_D. iii) follows from ii) and is proven in the appendix (see also Figure 3). iv) Follows from the slopes of the reaction functions and Figure 3. Since $x_\tau > 0$ and $\tau'(x) < 0$, the regulator is clearly better off when moving first. In Figure 3 τ_D is smaller than τ_C. It is obvious that τ_D can also be greater than τ_C.[9] Qed.

Figures 2 and 3 about here.

[9]Numerical examples where τ_D is smaller or greater than τ_C can be obtained by the auhor on request.

6.1.2 Second Best Permit Rule for Timing C

We now study regulation by issuing an amount L of permits. The regulator minimizes the social cost given by

$$SC(L) = \int_0^x [C^A(e^{\widetilde{x}}, \widetilde{x}) + c]d\widetilde{x} + (1-x)C^0(e^0) + D(L)$$

Using $(dE/d\sigma)\sigma_L = 1$, we can write $dx/dL = x_\sigma \sigma_L = x_\sigma \sigma_L/((dE/d\sigma)\sigma_L) = x_\sigma/(dE/d\sigma)$. The first order condition for the second best number of permits can then be written as

$$\begin{aligned} \sigma &= D'(L) - \frac{(p-c)x_\sigma}{dE/d\sigma} && (22) \\ &= D'(L) - \frac{[p_x + p_\sigma \sigma_x]x x_\sigma}{dE/d\sigma} && (23) \end{aligned}$$

Now we are ready to compare the performance of taxes versus permits under timing C.

Proposition 5 *i) If the regulator issues the number of permits corresponding to the resulting emissions of any tax rate τ, i.e. $L = E(\tau)$, then the resulting permit price exceeds the tax rate, i.e. $\sigma(x, L) > \tau$, and the resulting share of adopting firms under permits, denoted by x_C^P, is smaller than the resulting share of adopting firms under taxes $x(\tau_C)$.*

ii) The second best optimal permit regime yields lower welfare than the second best optimal tax regime.

iii) The second best optimal number of permits can be higher or lower than the second best optimal emission level under taxes.

The result, proved in the appendix, seems to be surprising at first glance. If the regulator issues permits and some firms adopt the new technology, the price should be expected to fall. However, the monopolistic producer of new technology anticipates this. Since his inverse demand function is steeper under permits than under taxes at the point of his monopoly price for taxes, he charges a higher price under permits than under taxes. The higher permit price is a direct consequence of the monopolist lowering output. Thus for any emission target, be it achieved by issuing permits L or by charging the corresponding tax with resulting emissions $E(\tau) = L$, there is less supply and thus less adoption of new technology under permits than under taxes. Since the monopolist supplies less units of the new technology under the second best optimal permit policy compared to the second best optimal tax policy and since there is too little supply even under taxes, welfare must be lower under permits compared to taxes.

6.2 Second Best Optimal Tax and Permit Rules for Timing B

Under this timing the regulator makes a commitment to a tax policy before the firms engage in R&D. However, the regulator sets two different tax rates τ_B^0 and τ_B^I contingent on R&D success. Thus the regulator's problem is now

$$\min_{\tau_0, \tau_I} \left\{ ySC^I(\tau_B^I) + (1-y)SC^0(\tau_B^0) + R(y) \right\}$$

taking the behavior of up- and downstream firms as given through the equations (8), (9), (11) and (19). Note that the monopolist's behavior is as in timing C. Since he does not make a profit in case of R&D failure, we obtain $\partial y / \partial \tau_0 = 0$. Thus following a similar procedure as in the last section we obtain the solution for the two second best optimal tax rules

$$\tau_B^0 = D'(E_0) \tag{24}$$

$$\tau_B^I = D'(E_I) - \frac{(p-c)x_\tau}{\frac{dE_I}{d\tau_I}} + \frac{\frac{\partial y}{\partial \tau_I}}{y\frac{dE_I}{d\tau_I}} \left[SC_I(\tau_I) - SC_0(\tau_0) + R'(y) \right] \tag{25}$$

If there is no R&D success, there is no further market imperfection and the regulator should set the tax equal to marginal damage. Looking at τ_B^I, we see that the first two terms are the same as for the second best optimal tax rule for timing B, given by (21). In addition there is a term which in a first best allocation is equal to zero due to (7). I was not able sign $SC_I(\tau_B^I) - SC_0(\tau_B^0) + R'(y)$ for this second best scenario. However, since $\partial y/\partial\tau$ is positive, and $dE_I/d\tau$ is negative, the last term is positive if and only if there is too little R&D effort. The same applies to formula (24). We see also that, by contrast to timing C, where the regulator moves after R&D success, in which case there is no way to influence R&D effort, the regulator is now able to correct for too little or too much R&D effort. Hence welfare must be higher under this timing compared to timing C, where we have also two tax rates contingent on R&D success.

The case of permits is similar. The regulator now commits to two different quantities L_B^0 and L_B^I satisfying the following rules:

$$\sigma_B^0 = D'(L_B^0) \tag{26}$$

$$\sigma_B^I = D'(L_B^I) - (p-c)x_L + \frac{\frac{\partial y}{\partial\sigma}\frac{\partial\sigma}{\partial L}}{y}\left[SC^I(L_B^I) - SC^0(L_B^0) + R'(y)\right] \tag{27}$$

However, the distortion is larger under permits since the innovating monopolist's inverse demand function is more elastic by the same reason as in timing C. Hence expected welfare must be larger under taxes than under permits.

6.3 Second Best Optimal Tax and Permit Rules for Timing A.

Finally we consider the case where the regulator commits to a tax policy *before* the upstream firm starts R&D, but he is not able to commit to a menu of different tax rates contingent on R&D success. In other words, the tax rate remains the same irrespective of whether or not the upstream firm is successful. In this case the regulator minimizes (3) with respect to one tax rate, again taking as given the behavior of up- and downstream firms. Some tedious but straightforward calculations yield the second best optimal tax formula:

$$\begin{aligned}\tau_A = {} & \frac{1}{y\frac{dE^I}{d\tau} + (1-y)\frac{dE^0}{d\tau}}[y \cdot \left(D'(E^I)\frac{dE^I}{d\tau} - p_x(x,\tau)\frac{dx}{d\tau}\right) \\ & +(1-y)D'(e^0)\frac{de^0}{d\tau} + (SC^A - SC^0 + R'(y))\frac{dy}{d\tau}]\end{aligned} \tag{28}$$

where E^I are total emissions after successful innovation, and e^0 is the emission level in case of no R&D success. The formula takes into account the reaction of R&D firm with respect to its R&D effort. It also takes into account that with a certain probability there is no R&D success which in turn results in high emissions. Note that the tax formula boils down to (21) if $y = 1$, which in equilibrium, of course, cannot be the case by the assumption that R&D costs go to infinity as y goes to 1.

The **second best optimal permit rule** is similar as the second best optimal tax rule. In this case, however, the price of permits is subject to uncertainty whereas emissions and thus the marginal damage is under the control of the regulator. Similar calculations as in the tax case lead to the following rule:

$$\overline{\sigma} = D'(L) + y \cdot [p_x + p_\sigma \sigma_x] x_L + [SC^I - SC^0 + R'(y)] y_L \tag{29}$$

where $\overline{\sigma} = y\sigma^I + (1-y)\sigma^0$ is the expected permit price, σ^I is the permit price after R&D success, and σ^0 is the permit price in the absence of success.

6.4 Comparison

We are now ready to summarize our results from this section and rank the policies as far as possible. It is clear that ex ante commitment to a menu of tax rates (timing B) beats all other policy regimes. It beats taxation with timing A since it can always mimick timing A by choosing $\tau_B^I = \tau_B^0 = \tau_A$. Taxation with timing B also beats taxation with timing C because through ex ante commiting to a particular tax level the regulator can take influence on the R&D effort, which he is not able to do with timing C. (Note that with timing B the regulator can also always mimick the result of timing C since in both cases he can use two tax rates.) It it also clear from our arguments put forward above that each tax regime under timing B and C beats the corresponding permit regime. The reason is that with permits the inverse demand function faced by the R&D firm is more elastic, and the distortion under permits is thus more severe than under taxes. We summerize this as follows:

Proposition 6 *i) Ex ante tax policy contingent on R&D success (taxation with timing B) dominates all other regimes (including permit policy with timing B).*

ii) Each tax regime beats the corresponding permit regime under timing A, B, and C.

iii) Ex interim tax policy (timing C) dominates ex post (tax or permit) policy (timing D).

Under ex ante commitment with only a single tax rate (timing A), no unique ranking between the tax and the permit policy is possible. One can show, however, that for relatively flat damage functions taxes dominate permits whereas for relatively steep damage function the opposite holds true. This is consistent with Weitzman's (1976) results. The situation here is similar to Weitzman's scenario since in our model there is uncertainty on the abatement costs due to random R&D success. Since timing A is dominated by timing B anyway, this result is not so important and we do not give a proof.

Comparison between the tax or permit regimes under timing A to those of timing C are also ambigous. Little can also be said in general about a ranking of the second best optimal tax rates (or permit prices) under the different regimes. Furthermore, we would like to know whether decentralized policy induces too much or too little R&D! Even here no definite answer can be given. The (expected) private value of innovation to the monopolist can exceed or fall short of the (expected) social value of innovation.[10] This stands in contrast to ARROW's [1962] early result according to which a monopolist's value of a process innovation always falls short of the social value of innovation. In Arrow's model, however, there are no externalities and no regulation. The reason why we may arrive at a different result is that our second best tax rates may exceed the marginal damage, and thus the marginal cost incurred by the firms

[10] Numerical examples can be obtained by the author on request.

may exceed the total social marginal costs. If this is so, the private value of innovation may also exceed the social value of innovation.

7 First Best Regulation

In the last section it was assumed that the regulator could use environmental policy only although in the long term there are three market imperfections: pollution, too high prices for new technology due to monopoly power, and insufficient R&D effort since the social and the private values of innovation may differ. In this section we show that the regulator can restore first best allocations by the choice of three instruments: an emissions tax, a subsidy on the purchase of the advanced abatement technology, and a profit tax for the R&D monopolist. It is well known from conventional monopoly theory that a regulator can induce a monopolist to produce the socially optimal output by paying a suitable subsidy. This also works here. However, the timing and the choice of the environmental policy instrument do still matter for the size of the subsidy. If the regulator decides ex post on the size of the tax rate etc., he makes himself a slave to the regulator who can take influence on the tax rate by holding down or enhancing output. Even under the ex interim permit policy (timing C) the monopolist is in a better position than under ex interim taxation. The permits regime requires a higher subsidy than in case of a tax policy. Finally an output tax is necessary to guarantee that the monopoly profit after R&D success is equal to the social value of innovation. To see this more clearly consider first ex interim taxation.

7.1 Ex interim taxation

The regulator commits to an emission tax τ, he pays a subsidy σ per unit of output of the advanced abatement technology, and he charges a tax t on gross profits after R&D success, i.e. R&D expenditures are not deductible from the tax bill. The tax t may be negative, i.e. resulting in a further subsidy. This, however, is unlikely since the output subsidy shifts the inverse demand function outwards, thus leading to huge gross profits anyway. Thus the gross profit of the R&D firm is given by

$$\Pi(x;t,\tau,\sigma) = t \cdot y \cdot [p(x,\tau) + \sigma - c]x - R(y)$$

After R&D success the upstream monopolist sets

$$p_x x + p + \sigma - c = 0 \tag{30}$$

As usual the regulator has to set

$$\sigma^* = -p_x(x^*,\tau^*)x^* \tag{31}$$

where x^* denotes the socially optimal share of adoption (=output) of the new technology, and

$$\tau^* = S'(E_I^*) \tag{32}$$

is the optimal tax rate equal to marginal damage.

Since the output price is given by

$$p = C^0(e^0) - C^A(e^x,x) + \tau[e^0 - e^x] \tag{33}$$

(see 10), plugging (33), (32), and (31) into (30) yields the corresponding first order condition for the socially optimal share of adoption (6).

Let $\widetilde{\Pi}^* = [p(x^*,\tau^*) + \sigma^* - c]x^*$ denote the resulting gross profit. Then the optimal profit tax has to be set according to:

$$t^* = (SC^{0*} - SC^{I*})/\widetilde{\Pi}^*$$

7.2 Ex interim permit policy and ex post regulation

Let us now consider the choice of the three instruments under *ex interim* commitment to permits. Clearly, in order to obtain first best the regulator must set $L^* = E_I^*$.

However, the profit after R&D is now given by $\pi(x) = [p(x, \sigma(x, L)) + \sigma - c]x$, and the first order condition becomes $[p_x + p_\sigma \sigma_x]x + p + \sigma - c = 0$. From this we see immediately that the optimal subsidy is now given by

$$\sigma^{**} = -p_x(x^*, \sigma(x^*, L^*)x^* - p_\sigma(x^*, \sigma(x^*, L^*) \cdot \sigma_x(x^*, L^*) > \sigma^* \tag{34}$$

I.e. in case of a permit policy, the subsidy rate to be paid to the monopolist exceeds the subsidy rate which corresponds to the tax regime. Hence also the corresponding profit tax t^{**} must be greater than t^*.

A similar argument holds if the regulator fixes the tax rate (or the number of permits) *ex post*. Under a tax policy the profit writes $\pi(x) = [p(x, \tau(x) + \sigma - c]x$, leading to a subsidy $\sigma^{***} = -p_x x^* - p_\tau \tau'(x^*) > \sigma^*$.

If gross profit taxes are possible, ex ante commitment does not provide further advantages towards ex interim regulation since the regulator can use the profit tax to equalize private and social benefits from innovation and thus can stir the R&D effort.

Often individual profit taxes are not feasible though. The lesson to be drawn from our analysis then is that, if subsidizing advanced abatement technology is still possible and an individual profit tax is not, the regulator is clearly better off by making an ex interim commitment to the tax policy because in this case he needs to pay less subsidies to the monopolist compared to the case of ex interim commitment to permits and compared to ex post regulation with either taxes or permits.

8 Extensions to R&D Duopoly

In this section we briefly sketch how to extend the model to R&D duopoly. The easiest way is to assume two symmetric upstream R&D firms $j = A, B$ which develop a new, exogenously given technology with abatement cost $C^A(e, x)$ or $C^B(e, x)$, respectively, where x is a firm specific parameter of the downstream firm $x \in [0, 1]$. The abatement cost function of firm B satisfies the same properties as that of firm A, with the only difference that for B now $C_x^B \leq 0$ and $-C_{ex}^B \leq 0$ holds whereas for firms A we have $C_x^A \geq 0$ and $C_{ex}^A \geq 0$ as assumed above. This means that the closer to 0 the firm specific parameter x, the more suitable is technology A for that firm. The closer to 1 the parameter x, the less suitable is technology A and the more suitable is technology B. Thus we have a Hotelling kind of model of product differentiation. In this case in a social optimum, there is either a gap of firms in the middle of the interval [0,1] which should not adopt the new technology, or all the firms should adopt one of the two technologies. The first case boils down to two "local" natural monopolies. If we assume in the latter case that the market is covered in the decentralized situation, there will be no difference between ex post and ex interim regulation, in case that both upstream firms have been successful. If the market is covered, there is no distortion by the upstream firms. If, however, only one firm is successful, we are in the same situation as in the monopoly case with ex interim and ex post regulation.

One can show that the R&D effort by a single firm is lower than in the monopoly case. Since both firms engage in R&D, the total probability that at least one firm is successful can be higher or lower than in the case of pure monopoly. Hence it is also difficult to compare the ex ante optimal tax rates of the duopoly case to the monopoly case.

Full market coverage by a duopoly may be considered as little plausible. One can avoid this by extending the one dimensional parameter space $[0, 1]$ to higher dimension. In such a model, some firms may be indifferent between the technology of upstream firm A and upstream firm B, but prefer both technologies to the conventional one, whereas another set of firms does not like, say, technology B but is indifferent between the technology A and the old technology. In that case, lowering the price by upstream firm A not only steels demand from firm B, but also sells more units to firms which otherwise would not buy new technology at all. The main effects, discovered from our monopoly model carry over to this case: There is too little output by the duopoly.

The second best optimal tax rate exceeds marginal damage under timing C. In this case, too, the regulator can restore first best by using three instruments. The subsidy is of course lower for duopoly than for monopoly.

Thus with the monopoly model we have worked out basic insights which would also hold if there are more than only one R&D firm.

9 Conclusions

In this paper we investigated the interplay of environmental policy, incentives to adopt new technology, and the repercussions on R&D. We have studied an industry structure consisting of many competitive, but heterogenous polluting firms and a monopolistic R&D sector. We investigated different forms of timings and commitment: Ex post regulation, ex interim regulation after observing R&D success but before adoption of new technology, and finally ex ante regulation with both different tax rates contingent on R&D success and with a single tax rate independently of R&D success. We found that ex ante commitment with different tax rates dominates all other regimes. Ex interim regulation dominates ex post regulation, and tax regimes dominate permit regimes for the timings B and C. For the most part of the paper the regulator was assumed to have only one instrument. We have seen that the regulator can restore the first best outcome by a combining three policy instruments: emission taxes, subsidies on adoption of the advanced abatement technology, and a profit tax on the R&D firms. Nevertheless even with these three instruments the timing turned out to be crucial since it has an impact on the size of the subsidy.

What policy conclusions can be drawn from our results? First of all, if only environmental policy is feasible, early commitment before R&D activity is socially beneficial since then environmental policy has a stronger impact on R&D effort. However, the commitment should include a flexible menu of tax rates (permit quantities) contingent on R&D success. Secondly, taxes are unambiguously superior to permits since the R&D firm's inverse demand function under permits is more elastic and hence leads to higher distortions. However, the more competition in the upstream sector the less severe these distortions will be.

It is once again interesting to compare our results to those obtained by PARRY (1995). Since his model is fully symmetric, and there are no fixed cost of technology adoption, all the firms always adopt the new technology. PARRY also allows for free entry. As a consequence in his model, a tax increase induces a *move along* the demand curve, whereas it shifts up the inverse demand curve in my model. Whereas in PARRY's model "*reducing* the tax rate drives down the licence fee, and hence *increases* diffusion", the opposite is true here: *enhancing* the tax rate makes the new technology more attractive to polluting firms and thus *increases their willingness to pay* for the new technology. This effect will be exploited by the monopolist who can charge a higher licence fee if the tax rate increases. Thus PARRY obtains a tax rate falling short of marginal damage whereas in my model the tax rate may exceed marginal damage. It would be desirable to bring together features of PARRY's free entry model and features of firm heterogeneity. Unfortunately this seems to be impossible since free entry is (almost) inconsistent with heterogeneity of firms.

In the model considered here, the number of R&D firms was assumed to be exogenous. It would be worthwhile to endogenize this number through a model of market entry and monopolistic competition. It would also be interesting to take advantage of these results for endogenous growth models with technological progress induced by environmental policy.

10 Appendix

Proof of Lemma 1: Rewriting (10) we get:

$$p^A(x,\tau) = C^0(e^0) - C^A(e^x, x) + \tau(e^0 - e^x) \tag{35}$$

Differentiating w.r.t. x and τ yields:

$$p_x^A(x,\tau) = -C_x^A(e^x,x) < 0 \tag{36}$$

$$p_\tau^A(x,\tau) = e^0 - e^x > 0 \tag{37}$$

Qed.

Proof of Lemma 2: First observe that $e_x^x := de^x/dx = -C_{ex}^A/C_{ee}^A > 0$, i.e. the higher the firm specific parameter x, the less advantageous the new technology, i.e. the higher the emissions e^x. Next we differentiate (36) w.r.t. x to obtain:

$$p_{xx}^A(x,\tau) = -C_{xx}^A(e^x,x) - C_{xe}^A e_x^x \tag{38}$$

$$= -\frac{C_{xx}^A C_{ee}^A - (C_{xe}^A)^2}{C_{ee}^A} < 0 \tag{39}$$

Next we differentiate (37) w.r.t. x and τ :

$$p_{\tau x}^A(x,\tau) = C_{xe}^A/C_{ee}^A < 0 \tag{40}$$

$$p_{\tau\tau} = e_\tau^0 - e_\tau^x < 0 \tag{41}$$

where the latter holds by Assumption 1. Differentiation of (11) with respect to τ yields

$$x_\tau = -\frac{p_\tau + p_{x\tau}x}{p_{xx} + 2p_x} = -\frac{(e^0 - e^x) + C_{xe}^A x/C_{ee}^A}{p_{xx} + 2p_x} \tag{42}$$

Proof of formula (21): If firm A was successful, the social cost is given by

$$\begin{aligned} SC(\tau) &= \int_0^x \left[C^A(e^{\widetilde{x}},\widetilde{x}) + F(\widetilde{x})\right] d\widetilde{x} + cx + (1-x)C^0(e^0) \\ &\quad + S\left(\int_0^x e^{\widetilde{x}} d\widetilde{x} + (1-x)e^0\right) \end{aligned}$$

The first order condition w.r.t. the tax rate is:

$$\begin{aligned} SC'(\tau) &= \left\{C^A(e^x,x) + F(x) + c - C^0(e^0)\right\} x_\tau \\ &\quad + \int_0^x C_e^A \frac{de^{\widetilde{x}}}{d\tau} d\widetilde{x} + (1-x)C_e^0 \frac{de^0}{d\tau} + S'(E)\frac{dE}{d\tau} \\ &= \left\{-(p-c) + \tau[e^0 - e^x]\right\} x_\tau - \tau\frac{\partial E}{\partial \tau} + S'(E)\frac{dE}{d\tau} = 0 \end{aligned}$$

In the last expression we have employed (8), (9), and (10) as an equality. Solving for τ yields the result.

Proof of Lemma 3: Differentiating (17) w.r.t. L yields i). Differentiating (17) w.r.t. x yields

$$e^x - e^0 + \left[\int_0^x e_\sigma^{\widetilde{x}} d\widetilde{x} + (1-x)e_\sigma^0 \right] \sigma_x = 0$$

Solving for σ_x yields ii). To show iii) differentiate (18) with respect to L and solve for x_L:

$$x_L = -\frac{[p_{x\sigma}x + p_{\sigma\sigma}\sigma_x x + p_\sigma]\sigma_L + p_\sigma \sigma_{xL} x}{[p_{xx} + 2p_{x\sigma}\sigma_x + p_{\sigma\sigma}\sigma_x^2 + p_\sigma \sigma_{xx}]x + 2[p_x + p_\sigma \sigma_x]}$$

where $\sigma_x = (e^0 - e^x)/E_\sigma < 0$, $\sigma_L = 1/E_\sigma$, and $\sigma_{xL} = (e_\sigma^0 - e_\sigma^x)/E_\sigma^2 < 0$. The denominator is negative by the second order condition of the monopolist which we assume to be satisfied. The last term of the numerator is negative by inspection. σ_L is also negative. The terms in the bracket are positive apart from the first one. If we take the first and the third together we obtain $C_{ex}^A x/C_{ee}^A + (e^0 - e^x) > 0$ by condition (12). Hence the numerator is negative and we obtain $x_L < 0$.

Proof of Proposition 5: i) Denote by $x^M(\tau)$ the monopoly output under a tax regime. Then clearly

$$p(x^M(\tau), \sigma(x^M(\tau), E(\tau)) = p(x^M(\tau), \tau)$$

Then the two inverse demand functions intersect at the point $x^M(\tau)$. However the inverse demand function under permits is more elastic than under taxes since marginal revenue is given by

$$[p_x + p_\sigma \sigma_x]x < p_x x$$

Hence the monopolist's output under permits must be to the left of $x^M(\tau)$. Since the number of permits remains constant when the monopolist raises his price, we have $\sigma(x^M(L), L) > \tau$ for $L = E(\tau)$.

ii) follows from i) since the monopolist's reaction $x^P(L)$, is always lower than under taxes with $E(\tau) = L$.

iii) Numerical examples can be obtained by the author on request.

References

Arrow, K. [1962]: "Economic Welfare and the Allocation of Resources for Innovations," in: R. Nelson (ed.): *The Rate of Direction of Inventive Activity*, Princeton University Press.

Biglaiser, G. and J.K. Horowitz [1995]: "Pollution Regulation and Incentives for Pollution-Control Research," *Journal of Economics and Management Strategy*, 3 (4), 663-684.

Denicolo, V. [1999]: "Pollution-Reducing Innovations under Taxes or Permits," *Oxford Economic Papers*, 51, 184–199.

Downing, P.B. and L.J. White [1986]: "Innovation in Pollution Control," *Journal of Environmental Economics and Management*, 13, 18–29.

Fisher, C., Parry, I. and W. Pizer [1999]: "Instrument Choice for Environmental Protection When Technological Innovation is Endogenous," Resources for the Future, Discussion Paper 99-04.

Jaffe, A., Newell, G. and R. Stavins [2000]: "Technological Change and the Environment," NBER Working Paper 7970, October.

Jung, Ch., Krutilla, K. 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, 95–111.

KNEESE, A.V. AND C.L. SCHULZE [1975]: “Pollution, Prices and Public Policy”, Washington D.C. Brookings.

LANJOUW, J.O. **and** A. MODY [1995]: ”Innovation and the international diffusion of environmental responsive technology,” Research Policy, 25, 549-571.

MILLIMAN, S.R. AND R. PRINCE [1989]: “Firms Incentives to Promote Technological Change in Pollution Control,” *Journal of Environmental Economics and Management*, 17, 247–265.

PARRY, I. [1995]: “Optimal Pollution Taxes and Endogenous Technological Progress,” *Resource and Energy Economics*, 17, 69-85.

REQUATE, T. [1995]: “Incentives to Adopt New Technologies Under Different Pollution–Control Policies.” *International Tax and Public Finance*, 2, 295–317.

REQUATE, T. **and** W. UNOLD [2003]: “On the Incentives of Environmental Policy to Adopt Advanced Abatement Technology – Will the True Ranking Please Stand up?” *European Economic Review,* forthcoming.

REQUATE, T. **and** W. UNOLD [2001]: “On the Incentives of Policy Instruments to Adopt Advanced Abatement Technology if Firms are Asymmetric” *Journal of Institutional and Theoretical Economics.*

WEITZMAN, M. [1994]: ”Prices vs. Quantities,” *Review of Economic Studies*, 41, 477-491.

ZHAO, J. [2001]: ”Irreversible Abatement Investment under Cost Uncertainties,” forthcoming in *Journal of Public Economics.*

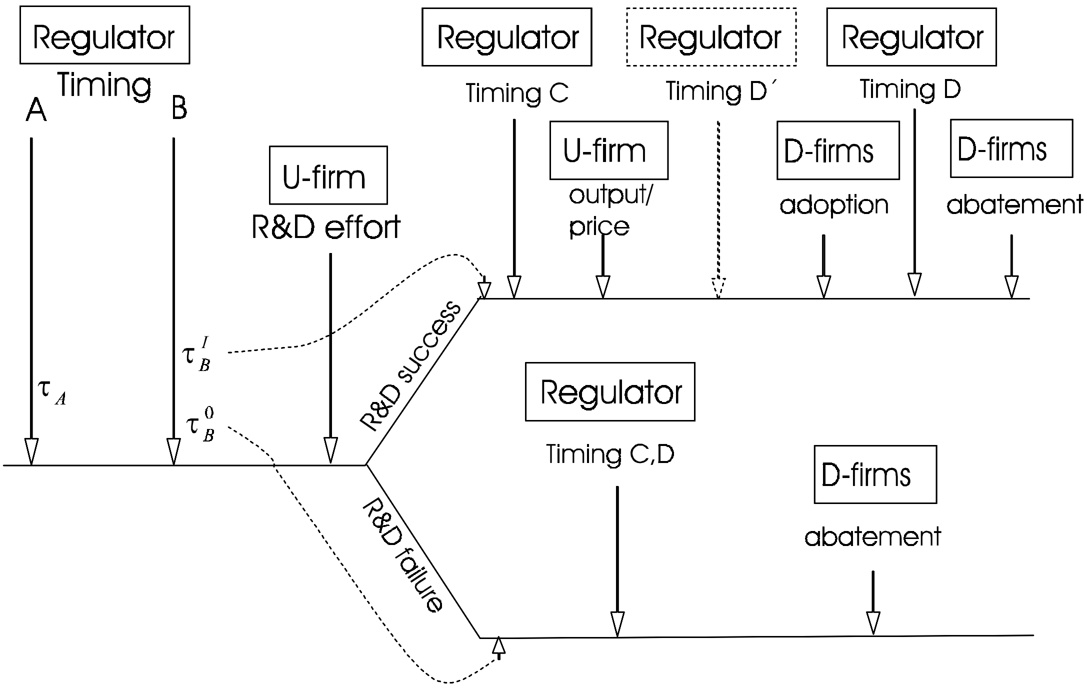

Figure 1: *The possible game structures between the regulator and the firms. U-firm stands for the upstream monopolist. D-firms stands for the regulated polluting downstream firms.*

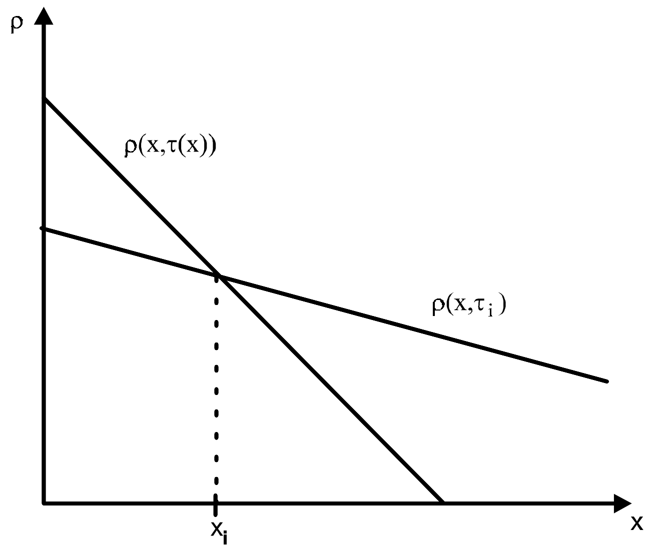

Figure 2: *The inverse demand functions under timing B (the flatter one) and timing C.*

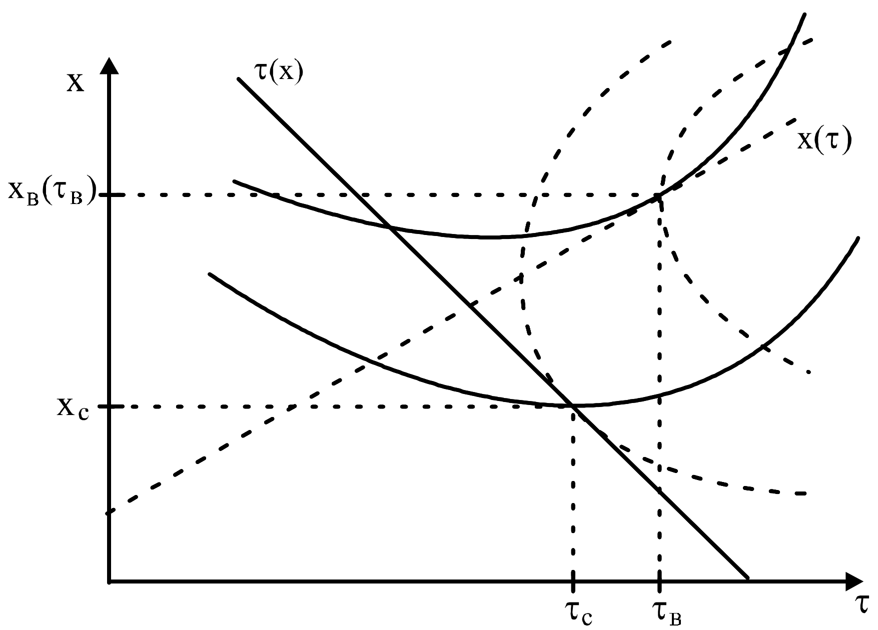

Figure 3: *The reaction curves of the regulator and upstream firm. The dotted lines belong to the upstream firm.*