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

by

Till Requate

Interdisciplinary Institute of Environmental Economics
University of Heidelberg
Bergheimer Str. 20 69115 Heidelberg
Germany
Phone: (++49) 6221 – 548010,
Email: REQUATE@mail.eco.uni-heidelberg.de

June 11, 2001

Abstract

In this paper we investigate the interplay between environmental policy, incentives to *adopt* new technology and repercussions on *R&D*. We consider a model where a polluting downstream industry is regulated either by emission taxes or by tradeable permits. A separate monopolistic (or duopolistic) upstream industry engages in R&D and, in case of R&D success, sells an advanced abatement technology to the downstream firms. We study three different timings of environmental policy, 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 finally ex ante commitment before and independent of R&D success. We show that ex interim commitment always dominates ex post environmental policy. Moreover, ex interim second best taxation dominates ex interim second best optimal permit policy. There is no unique ranking, however, between ex ante and ex interim commitment. Among the ex ante scenarios, taxes dominate permits for flat damage functions, whereas permits dominate taxes for steep damage functions. Finally, restoring first best is possible by a combination of three policy instruments, an emission tax (or permit policy), a subsidy on adoption of the new technology, and a tax on the upstream monopolist's gross profit. In this case, too, the timing matters for the size of both the subsidy and the profit tax. We also tackle briefly an upstream R&D duopoly.

1 Introduction

An important criterion for the appropriate choice of environmental policy instruments is their (static) efficiency. Maybe equally important are the long term incentives to adopt and to develop new, less polluting technology. Conceptually, the distinction between *adoption* and *R&D* is important.

The incentives of environmental policy instruments to *adopt* advanced abatement technology are meanwhile well understood. In a series of papers Downing and White (1987), Milliman and Prince (1989), Jung et al. (1997), Requate and Unold (1999a,1999b) have investigated those incentives. Especially Requate and Unold were able to show 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, both auctioned and free permits lead to under-investment. Those authors have also demonstrated that under competitive conditions the regulator can achieve first best by optimally responding to diffusion of the new technology. In all those models the new technology was assumed already being available.

In this paper we investigate the interplay between adoption, pricing of new technology, and the incentives to engage in R&D to develop a new, less polluting technology. We treat R&D as a public good. Once the new technology is developed, it is, apart from incurring a fixed cost, suitable for all the polluting firms. In the model we distinguish between the polluting and the R&D industry. This assumption is supported by empirical evidence by Lanjouw and Mody (1995) who found that only 5% of new developments in air pollution abatement technology by the machinery construction sector is used in that same industry. The remaining 95% of innovations are sold to other industries.

Hence, we study a model where an R&D monopolist engages in research to find a new, less polluting technology, which, in case of R&D success, can be sold to another industry which is subject to environmental regulation. In particular we study regulation by emission taxes and tradeable permits. We do not only pay attention to different policy instruments. Above all we focus on timing and commitment. In contrast to most of the literature which either assumes ex ante commitment to a certain policy level or ex post optimal setting, we study three different timings: first, *ex post* optimal setting of the tax rate or issuing permits, respectively, second *ex interim* *commitment*, and third *ex ante commitment* to a certain level of a policy instrument. Ex ante commitment means that the regulator fixes the tax rate or the number of permits, respectively, *before* R&D and thus before R&D success is guaranteed. In contrast, ex interim commitment means that the regulator sets the tax rate or issues a quota of permits, respectively, *after* observing R&D success, albeit *before* adoption and diffusion of the new technology. Ex interim commitment is different from ex post since with ex post regulation the R&D monopolist can influence the choice of the tax rate or the number of permits, respectively, by his price or output policy. If he holds the price per unit of the new technology high, there is little demand, and thus the aggregate marginal abatement cost curve is higher than socially optimal. Thus, also the ex post (second best) optimal tax rate will be higher than socially optimal.

Under ex interim commitment, the regulator has some room for discretion. If (or as long as) there is no R&D success, he wants to set a high tax rate, or the quota of permits, respectively. In case of R&D success, he charges a low tax rate or issues a small number of permits. Under ex ante commitment, in contrast, the regulator commits to exactly one tax rate (or one number of permits, respectively) for both cases, R&D success and no success. At first glance this seems to be clearly inferior to ex interim regulation. However, it is not in general since under ex ante regulation, the regulator accounts for the R&D effort cost whereas under ex interim regulation those cost are sunk, and thus are irrelevant for the choice of the tax rate or number of permits. Hence, there is a trade off between taking account for R&D cost, on the one hand, and flexible reaction on R&D success, on the other.

As a main result we can show that ex interim commitment always dominates ex post regulation. Among ex ante and ex interim regulation, however, no unique ranking is possible. We present numerical examples where either the ex ante second best optimal tax policy dominates the ex interim second best optimal tax policy and vice versa. The same holds for permit policies. Concerning a comparison between tax and permit policy we find that ex interim tax policy always dominates ex interim permit policy. Here the reason is that the R&D monopolist can influence the price for emissions by his price or output policy whereas under a tax policy he cannot.

Under ex ante commitment, in contrast, there is no unique ranking between taxes and permits. Here we find that for relatively flat damage functions taxes dominate permits whereas for relatively steep damage function the opposite holds true. This should not come out as a big surprise in the light of Weitzman's (1976) seminal paper. For there is uncertainty in the model since the R&D success is random. Thus, as in the Weitzman model, the marginal abatement cost curve may be high or low.

Little can be said in general concerning a comparison of the optimal tax rates (or permit prices) in the three different timings . Taxes can be higher or lower under ex post regulation compared to under ex interim regulation. The same holds true for a comparison between ex ante and ex interim regulation. 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. This stands in contrast to the Shumpeterian 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 considered the impact of environmental policy on R&D only. In a separate section we show not surprisingly that the regulator can achieve first best by the choice of three policy instruments: Emission taxes or permits for pollution, a subsidy for the R&D monopolist per unit of equipment sold to the polluting industry, plus a profit tax. However, neither an individual profit nor output subsidies (or subsidies for adoption of certain technology) seem to be very realistic and often are not allowed. Just recently the EU commission took a new German law for supporting - i.e. subsidizing - the use of renewable resources under heavy fire. Hence, it is important to study the impact of pure pollution control policies on R&D, as is done in this paper.

Other writers have contributed to this topic in the past. There is a large number of papers on adoption, some of them being mentioned above. There is bulk of literature on R&D competition in general. Closest to our set-up is a paper by Biglaiser and Horowitz (1995) who 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. Biglaiser and Horowitz consider ex post regulation only. They also study R&D prizes as an additional instrument. They restrict their analysis to linear damage functions, however, thus neglecting important features of policy adjustment, commitment and timing. Ulph (1997) considers R&D effort as a strategy issue of international trade policy.

This paper is organized as follows. The next section sets up the model. In the basic model we assume that there is only one R&D firm. 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, in particular the second best tax rate, and the quota of permits to be issued, respectively. We compare those policies as far as this is possible in general. In section 6.3 we present a number of (counter-)examples. In section 7 we briefly study restoring first best by a combination of 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, gives some policy conclusions, and presents some outlook for generalizations and modifications of the model.

2 The Model

We consider a model with two industries, a competitive, polluting downstream industry which is subject to environmental regulation, and a monopolistic upstream industry which engages in R&D to develop a new, environmentally more friendly technology and sells it to the polluting downstream firms.

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[1] which have positive and decreasing marginal abatement costs as long as emissions fall short of the maximal, or laisser-faire emission level $e^0_{\max}$. Formally the abatement cost function $C^0(e)$ satisfies $-C^0_e(e) := dC^0(e)/de > 0$ and $C^0_{ee}(e) := d^2C^0(e)/(de)^2 > 0$ for $e \leq e^0_{\max}$.

[1]It is not necessary to explicitly model the output market of the downstream firms whose output adjustment upon environmental regulation is already implied in the abatement cost function. We assume the downstream industry to be perfectly competitive.

An upstream monopolist engages in research and development. With a certain probability y, contingent on R&D effort, the upstream firm develops a new, exogenously given technology with abatement cost function $C^A(e,x)$, where x is a firm specific parameter of downstream firm x. The new technology induces both, lower variable abatement cost, i.e.

$$C^A(e,x) < C^0(e) \quad ,$$

and lower *marginal* abatement costs, i.e.

$$-C^A_e(e,x) < -C^0_e(e)$$

for all $e \leq e^0_{\max}$ and all $x \in [0,1]$..

The cost functions $C^A(e,x)$ satisfy the same properties as $C^0(e)$, i.e. $-C^A_e(e,x) > 0$ and $C^A_{ee} > 0$ for $e < e^x_{\max}$. The new technology, however, is of different value for the downstream firms. The crucial assumption is $C^A_x \geq 0$ and $-C^A_{ex} \geq 0$, which means that the closer the firm specific parameter x to 0, the more suitable is the technology for that downstream firm. For technical reasons we assume C^A to satisfy the convexity condition

$$C^A_{ee}C^A_{xx} - [C^A_{ex}]^2 > 0 \tag{1}$$

(1) implies $|C^A_{ex}|$ not being too large.

Finally, we assume that besides the variable costs $C^A(e,x)$, the downstream firms face a fixed *investment cost* $F(x)$ to install the new technology. Here we assume $F(0) = F$, and $F'(x) \geq 0$. This again means that the fixed cost of the new technology A is the smaller, the closer the firm specific parameter x to 0.

In the decentralized situations the downstream firms will also have to pay a price p to the upstream monopolist. We will treat the decentralized decisions below.

2.2 R&D and Production Costs of Upstream Firms

The upstream R&D firm faces a cost $R(y)$ if it wants 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 technology.

Let π^M denote the upstream firm's gross monopoly profit after R&D success, i.e. without the R&D costs. Hence, ex ante the expected profit is given by

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

2.3 Social Costs

We are now ready to define welfare, or respectively, the social cost of pollution, R&D, and the adoption of new technology.

For this purpose we define $SC^A = SC^A(x, e_0, \{e^{\tilde{x}}\}_{\tilde{x}\in[0,x]})$ as the social cost of pollution in case that the upstream firm is successful in R&D. Thus:

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

In this case those downstream firms represented by the interval $[0, x]$ install the new technology, facing total costs represented by the integral. 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. Total emissions are given by

$$E = \int_0^x e^{\tilde{x}} d\tilde{x} + (1-x)e^0 \quad (3)$$

and are evaluated by a convex damage function $D(\cdot)$ which depends on total emissions only.

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

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

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

$$TSC(y, x, e_0, \{e^{\tilde{x}}\}_{\tilde{x}\in[0,x]}) = ySC^A + (1-y)SC^0 + R(y) \quad (4)$$

3 Socially Optimal Allocations

The social planner would proceed 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 $\{e^{\tilde{x}}\}_{\tilde{x}\in[0,x]}$.

To solve the problem of minimizing total social costs, we start backwards. Clearly, emissions must satisfy the rule

$$-C_e^0(e^0) = D'(E) \tag{5}$$

and

$$C_e^A(e^x, x) = D'(E) \text{ for all } x, \tag{6}$$

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

Next we determine the *optimal share* x of firms to *adopt* the new technology given that the upstream firm was successful. In this case we maximize SC with respect to x. This yields the first order condition

$$C^A(e^x, x) + F^A(x) + c - C_0(e^0) = D'(E)[e^0 - e^x] \tag{7}$$

Finally, we determine the optimal level of R&D: Employing the envelope theorem we can neglect the indirect effect on x and $e^0, \{e^{\tilde{x}}\}_{\tilde{x}\in[0,x]}$. The first order condition is simply given by

$$SC^0 - SC^A = R'(y) \quad . \tag{8}$$

4 Timing of Regulatory Policies:

In the following sections we are going to study the impact of downstream regulation on upstream R&D effort. It will turn out that the timing of regulation will be crucial. In other words, we will try to answer the question, whether or not and at which state of the game the regulator should make a commitment to a certain policy level. We will study three different timings: **(A)** ex ante commitment before R&D, **(B)** ex interim commitment after R&D, but before adoption of new technology, and finally **(C)** ex post regulation after R&D and adoption. In all three cases we will study both regulation by prices (taxation) and regulation by quantities (issuing tradeable permits). It is easy to see that the two policies must be equivalent in scenario

(**C**). This is so because when the regulator is the last to move, he knows both the marginal damage and the aggregate marginal abatement costs. Hence he is able to implement each aggregate emission target by either charging a tax or issuing the corresponding number of permits. More precisely, the order of the three timings goes as follows:

A: Ex ante Commitment before R&D:

1. The regulator fixes a tax rate τ, or issues a number of tradeable permits L, respectively.
2. The innovating upstream firm engages in R&D.
3. In case of R&D success the upstream monopolist sets its price (or quantity) for the new product.
4. A certain share of the downstream firms adopts the new technology.
5. The downstream firms adjust their emissions to the tax rate or the market price of permits, respectively. In case of permits the market for permits clears.

In this case the regulator minimizes the expected social costs, i.e. she minimizes (4). Note that this policy is not time consistent in general. For, if there is no R&D success, the regulator would like to set a higher tax rate than the one being optimal ex ante.

B: Ex Interim Commitment after observing R&D success: In this case the regulator first observes whether or not the upstream firm has been successful in R&D. Knowing the new technology, the regulator fixes its policy level and commits to this level before the downstream firms adopt the new technology. Thus the timing of this game is as follows:

1. The innovating upstream firm engages in R&D.
2. The regulator observes R&D success and commits to a tax rate τ, or to a number of tradeable permits L, respectively.

3. - 5. Same as in timing A.

Note that in this case commitment is not time consistent, either, because the regulator has to take into account the imperfectly competitive behavior of the upstream firm which will set a price for the new technology higher than socially optimal and thus will serve too few downstream firms. Thus, as we will see, the regulator will set the tax rate higher than the Pigouvian level. In this case, too, the second best optimal tax policy is not time consistent. For once the firms have adopted the new technology, the regulator would like to cut the tax rate.

C: Ex post regulation after R&D success and adoption: In this case the regulator observes both R&D success and how many firms have adopted the new technology. Then he sets the optimal tax rate or issues the corresponding quota of permits, respectively. Thus the timing of this game is like this:

1. The innovating upstream firm engages in R&D.
2. In case of R&D success the upstream firm sets the price (or quantity) for its new product.
3. A certain share x of the downstream firms adopts the new technology.
4. The regulator observes both, R&D success and x, and then fixes a tax rate τ, or issues a number of tradeable permits L, respectively.
5. Same as in A and B.

This policy scheme is clearly time consistent but it is not optimal from an ex ante or ex interim point of view. From a positive point of view ex interim commitment seems to be the most relevant one: For example, US regulators in several cases made commitments to transgenetic firms, promising to ban certain pesticides if a new transgenetic brand is available which is resistent against certain deceases.

One could expect that in the following we will analyze the three different cases each separately. We choose a different way, by treating first the behavior of the downstream firms, second the behavior of the upstream firms, and finally we make normative analysis by studying second best taxation. This line of study is more efficient since the downstream firms' behavior is always the same, and the upstream firms' behavior is equal for the timings A and B. We begin with the downstream firms in the next section.

5 The Firms' Behavior

5.1 Behavior of Polluting Downstream Firms

When studying environmental policies we start with the behavior of the downstream firms.

5.1.1 Final Stage: How much to Emit with Given Technology

Irrespective of the timing, in the last stage of all the 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 permits case works analogously), i.e.:

$$-C_e^0(e) = \tau \tag{9}$$

and

$$-C_e^A(e, x) = \tau \tag{10}$$

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

Assumption 1 $d[e^0(\tau) - e^x(\tau)]/d\tau < 0$

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. 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.

5.1.2 Investment Decision

Next consider the decision whether of not to adopt the new technology. Let p denote the price of the advanced technology charged by the upstream firm. Then a downstream firm decides to invest if

$$C^A(e^x, x) + \tau e^x + F(x) + p \leq C^0(e^0) + \tau e^0 \tag{11}$$

The firm is indifferent between investing or not if

$$C^A(e^x, x) + \tau e^x + F(x) + p = C^0(e^0) + \tau e^0 \tag{12}$$

holds. Clearly, if it pays for firm x to adopt the new technology, it pays for any firm $\tilde{x} < x$ since both the variable abatement cost and the fixed cost are lower for firm $\tilde{x}$ then for firm x. Thus (12) defines the demand for new technology as a function of the tax rate. At the same time (12) defines an inverse demand or willingness to pay function $p(x, \tau)$ of the downstream firms which satisfies the following properties:

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

Thus we get a downward sloping inverse demand function in the quantity. Moreover, the willingness to pay for the new technology increases with rising tax rates. The proof is given in the appendix.

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

At this point the different timings do play a role. Under the timings A and B, the monopolist takes the tax rate as given, whereas in timing C he can influence the tax rate, or permit price, respectively. The monopolist can also manipulate the permit price under timing A or B.

Tax Regime under ex ante or ex interim Regulation (Timing A or B): Given 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 given by

$$\pi_x(x, \tau) = p_x + p(x, \tau) - c = 0 \tag{13}$$

Comparative statics of the monopoly output x as a reaction on τ yields $x_\tau > 0$, (see appendix, equation 37) which is quite intuitive. For raising τ enhances the downstream firms' willingness to pay for the new technology. Thus the monopolistic supplier of new technology can charge a higher monopoly price.

Tax Regime under ex post Regulation (Timing C): Clearly the regulator sets the tax equal to marginal damage. Hence we obtain

$$\tau = D'(E) \tag{14}$$

In the monopoly case aggregate emissions E depend on x, and since the regulator draws last, the tax rate τ depends on x, too. To see the impact of x on τ we differentiate (14) with respect to x. This yields

$$\frac{d\tau}{dx} = D''[e_x - e_0] + \frac{d\tau}{dx}\frac{\partial E}{\partial \tau} \tag{15}$$

where

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

is the change of emissions as a result of a tax raise with the share of adopting firms being held constant. Note that both $\frac{de(\tilde{x},\tau)}{d\tau}$ and $\frac{de_0}{d\tau}$ are negative. Solving (15) for $d\tau/dx$ yields

$$\frac{d\tau}{dx} = -\frac{D''(E)[e^0 - e^x]}{1 - D''(E)\frac{dE}{d\tau}} < 0 \tag{16}$$

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

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

The first order condition for profit maximum is now given by

$$\pi'(x) = [p_x + p_\tau \tau'(x)]x + p - c = 0 \tag{17}$$

Note that since $p_x + p_\tau \tau'(x) < p_x$ the upstream 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 and B).

Permit Regime under ex ante or ex interim Regulation (Timing A or B): We now study regulation by issuing an amount of permits L. The downstream firms take the price for permits σ as given thus setting their emissions according to $-C_e^0(e) = \sigma$ and $-C_e^A(e, x) = \sigma$, respectively. The last equation again defines e^x. The permit market clears according to

$$\int_0^x e^{\widetilde{x}} d\widetilde{x} + (1 - x)e^0 = L \tag{18}$$

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

Lemma 2 *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

$$C_{ex}^A x + C_{ee}^A (e^0 - e^x) > 0 \tag{19}$$

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 influence the permit price by selling more or less units of her new technology. iii) gives the total reaction of the upstream monopolist's output on increasing supply of permits.

Note that (19) is a coarse sufficient but my no means 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 is given by

$$[p_x + p_\sigma \sigma_x]x + p - c = 0 \tag{20}$$

Note that this equation is similar to (17). Note, however, that σ_x and τ_x are different since under a permit regime in scenario A and B, the emissions remain constant whereas in timing C emissions can be influenced by the monopolist.

Permit Regime under ex post Regulation (Timing C): Here is no difference to regulation by taxes since if the regulator draws last, 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.

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 $j = A, B, C$. 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

$$R'(y) = \Pi_j^M \tag{21}$$

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

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

For permits we obtain $\frac{d\Pi^M}{dL} = p_\sigma \sigma_L x < 0$, i.e. *reducing (!)* the quota of permits enhances the upstream monopolist's profit.

6 The Regulator's Problem

We are now ready to study the regulator's problem under the different regimes. Clearly in Scenario C 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. Therefore in the next section we study second best taxation under timing B:

6.1 Second Best Tax Rule for Timing B

Given R&D success the regulator minimizes the social cost under the constraints (9), (10), and (13). Thus the objective function is given by (2) where x and e^x, e^0 are all functions of the tax rate. It is then straightforward to calculate the second best tax rate:

$$\tau_B = D'(E) - \frac{(p-c)x_\tau}{dE/d\tau} = D'(E) + \frac{p_x(x,\tau)x \cdot x_\tau}{dE/d\tau} \tag{22}$$

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 $E_\tau = \frac{\partial}{\partial\tau}\left[\int_0^x e(\tau,\tilde{x})d\tilde{x} + (1-x)e_0(\tau)\right] < 0$ is the reaction of the downstream firms on the tax rate given the share of adopting firms x. Formula (22) is proved in the appendix. We can derive the following result:

Proposition 3 *Under timing B, with R&D success*

i) the second best tax rate τ_B is higher than marginal damage.

ii) If in this timing the regulator charges the second best tax rate from scenario C, i.e. τ_C, then the monopolist supplies more units of the new technology than under timing C, formally $x_B(\tau_C) > x_C$.(where x_C is the share of adopting firms under optimal taxation in timing C).

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

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

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

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 is always equal to marginal damage. However, since the monopolist produces fewer units under ex post regulation marginal damage is higher under timing C than under timing B.

Proof: i) follows immediately from the signs $x_\tau > 0$ and $E_\tau < 0$. The reason for ii) is that the monopolist's inverse demand function under timing B is less elastic if the tax is given as fixed. On the other hand, the two inverse demand functions $p(x, \tau_C)$ for timing B and $p(x, \tau(x))$ for timing C cross at $x = x_C$ (see Figure 1). Hence the new optimal point for the monopolist must be on the right of x_C. iii) follows from ii) and is proven in the appendix (see also Figure 2). iv) Follows from the slopes of the reaction functions and Figure 2. Since $x_\tau > 0$ and $\tau'(x) < 0$, the regulator is clearly better off when moving first. In Figure 2 τ_C is smaller than τ_B. It is obvious that τ_C can also be greater than τ_B. We also give numerical examples where τ_C is smaller or greater than τ_B. Qed.

6.1.1 Second Best Permit Rule for Timing B

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

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

The first order condition for the second best number of permits is expressed as

$$\begin{aligned} \sigma &= D'(L) - (p-c)x_L \\ &= D'(L) + [p_x + p_\sigma \sigma_x] x \cdot x_L \end{aligned} \tag{23}$$

Since $\frac{dE}{d\sigma}\sigma_L = 1$, in order to compare the expression with (22),.we can rewrite x_L as

$$x_L = \frac{x_\sigma \sigma_L}{\frac{dE}{d\sigma}\sigma_L}$$

Now we are ready to compare the performance of taxes versus permits:

Proposition 4 *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_B^P, is smaller than the resulting share of adopting firms under taxes $x(\tau_B)$.*

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

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

The result, to be proved in the appendix, seems to be surprising at first glance. For 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 raises the price if permits are issued as a substitute for taxes. Thus 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 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 (see Figure 3). Since the monopolist supplies less than the optimal number of units of the new technology, welfare must be lower under permits than under taxes.

6.2 Second Best Tax Rule for Timing A

In this case the regulator commits to his tax rate *before* the upstream firm starts R&D. This means that the tax rate remains the same irrespective of whether or not the upstream firm is successful. In this case the regulator maximizes (4) with respect to the tax rate taking the behavior of up- and downstream firms as given through the equations (9), (10), (13) and (21). Some tedious but straightforward calculations yield the second best optimal tax formula:

$$\tau_A = \frac{1}{y\frac{dE^I}{d\tau} + (1-y)\frac{dE^0}{d\tau}}[y \cdot \left(D'(E^I)\frac{dE^I}{d\tau} - p_x(x,\tau)\frac{dx}{d\tau}\right) + (1-y)D'(e^0)\frac{de^0}{d\tau} + (SC^A - SC^0 + R'(y))\frac{dy}{d\tau}] \quad (24)$$

where E^I are total emissions after successful innovation, and e^0 is the emission level in case of no R&D success.

Note that the tax formula boils down to (22) 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.

We would like to compare the second best optimal values, i.e. the tax rate, welfare, and the other variables of timing A and timing B. However, such a comparison is ambiguous, that is, the second best optimal tax rate of timing A may exceed or fall short of the second best optimal tax rate of timing B. Note also that theoretically the two tax formulas (22) and (24) cannot be ranked. For the ambiguity see examples 5 and 8.

6.2.1 Second Best Permit Rule for Timing A:

The second best permit rule is similar as the second best tax rule. In this case, however, the price of permits is uncertain while the emissions, and thus the marginal damage are certain. Similar calculations as in the tax case lead to the following rule:

$$\overline{\sigma} = D'(L) + y \cdot [p_x + p_\sigma \sigma_x]x_L + [SC^A - SC^0 + R'(y))]y_L \quad (25)$$

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

In the permit case, too, it is difficult to compare the second best permit rules of timing A and timing B. On the one hand, there is only one permit quantity for both cases, research success and no success. This drives the amount of permits up. For if there is no success, a small number of permits leads to high economic abatement cost. Moreover, the second term of (25) is smaller than the second term of (23) because the latter is multiplied by the probability of success y. On the other hand, the last term on the RHS of (25) is positive.

6.3 Examples

In a series of numerical examples we build on the following specification of functions:

$$\begin{aligned} C^0(e^0) &= \frac{(a_0 - b_0 e^0)^2}{2b_0} \\ C^A(e^A, x) &= \frac{(a_A - b_A e^A)^2}{2b_A} \\ F(x) &= F_0 + xF_A \\ S(E) &= s_1 E + s_2 \frac{E^2}{2} \\ R(y) &= \alpha \frac{y}{1-y} \end{aligned}$$

Example 5 $a_0 = 10,\ b_0 = 1.0,\ a_A = 10,\ b_A = 2,\ s_1 = 0,\ s_2 = 1,\ F_0 = 5,\ F_A = 10,\ c = 1,\ \alpha = 0.1$

	tax, σ_I MAC	E_I	MD	x	y	S.V.	Π^M	E S.V.	$E\ \Pi^M$
S.O.	3.59876	3.60	3.60	0.8756	0.8686	5.7969	–	4.3741	–
T,P:C	4.36343	4.36	4.36	0.4517	0.8160	4.3799	2.9543	3.1306	1.9672
T: B	4.61306	3.81	3.81	0.5872	0.8297	4.9965	3.4488	3.6584	2.3742
T: A	4.67699	3.74	3.74	0.5958	0.8322	4.9878	3.5500	3.6373	2.4583
P: B	4.91400	3.96	3.96	0.4428	0.8331	4.1215	3.5889	2.9345	2.4908
P: A	4.75320	4.14	4.14	0.4219	0.8268	4.0954	3.3325	2.7805	2.2779

Table 1: First row: social optimum; second row: scenario C. third row: optimal taxes under scenario B; 4th row: optimal taxes under scenario A; 5th optimal permit policy under scenario B; 6th row: optimal taxes under scenario A.

Observe that in this example the tax regime with ex interim regulation (timing B) performs best among the decentralized regimes under consideration. Moreover, all tax regimes perform better than all the permit regimes. Observe, further the tax ranking: $\tau_A > \tau_B > \tau_C$. Not surprisingly, emissions under ex ante permit regulation are greater than under ex interim regulation since ex ante the regulator has to account for the case that research is not successful and therefore (marginal) abatement costs are high. In the tax regime, in contrast, emissions are higher under ex interim taxation than under ex ante taxation. This is typical for most of the examples I was running.

Example 6 *Like example 5 but $s_2 = 10$. The expected social values of innovation now rank:*

	S.O.	T.P:C:	T:B	T:A	P:A	P:B
Exp. Social Value	11.5296	8.0476	8.1530	8.0463	8.0489	8.0387

In this case the ex interim permit regime performs better than ex ante taxation. The reason is that in this example the damage function is extremely steep. Hence quantity regulation is better with respect to the damage side. The monopolist is best off under ex interim taxation.

Example 7 $a_0 = 10,\ b_0 = 0.25,\ a_A = 10,\ b_A = 0.5,\ s_1 = 0,\ s_2 = 5,\ F_0 = 0,\ F_A = 100,\ c = 0,\ \alpha = 0.9$

The expected social values of innovation now rank:

	S.O.	T.P:C:	T:B	T:A	P:A	P:B
Exp. Social Value	37.1118	26.2847	26.3342	26.2210	26.2836	26.2822

In this case ex ante issuing permits performs better than ex ante setting taxes. The reason is that the damage function is relatively steep. Even issuing permits ex interim performs better than ex ante taxation. However, it performs worse than ex interim and even worse than ex post taxation. The monopolist is best off under ex interim taxation (not shown in the table).

Example 8 $a_0 = 10,\ b_0 = 1.0,\ a_A = 10,\ b_A = 4.0,\ s_1 = 0,\ s_2 = 1,\ F_0 = 0,\ F_A = 100,\ c = 0,\ \alpha = 0.9$

	S.O.	T.P:C:	T:B	T:A	P:B	P:A
Exp. Social Value	1.4602	0.8589	0.9111	0.9122	0.8454	0.7917
tax rates		4.7430	4.8712	4.9682	–	–

Interestingly in this case ex ante taxation shows the best result. However the result is not very robust. For values of s_2, i.e. the second derivative of the damage function, smaller 0.9 and greater than 1.2 ex interim taxation (timing B) dominates ex ante taxation (timing A). I found the same phenomenon for other abatement cost parameters. So there is no such result saying that for flat damage functions ex ante taxation is better and for steep damage functions ex post regulation is better, or vice versa.[2] Observe further that the ex ante second best optimal tax rate, as in the former examples, is higher than the ex interim second best optimal tax rate.

[2] In this example the difference of the two welfare values is quite small. Changing F_I into 200, ex ante taxation dominates ex interim taxation by 25%!

Example 9 $a_0 = 1.0,\ b_0 = 0.25,\ a_A = 1.0,\ b_A = 1.0,\ s_1 = 0.6,\ s_2 = 0,$ $F_0 = 1.05,\ F_A = 0.15,\ c = 0.1,\ \alpha = 0.01$

	tax, σ_I MAC	E_I	MD	x	y	S.V.	Π^M	E S.V.	$E\ \Pi^M$
S.O.	0.6	0.72	0.6	0.733	0.5021	0.0403	–	0.0102	–
T,P:C	0.6	1.16	0.6	0.366	0.2958	0.0303	0.0202	0.0048	0.0018
T: B	0.6472	0.83	0.6	0.544	0.5257	0.0350	0.0445	0.0073	0.0123
T: A	0.6246	0.98	0.6	0.462	0.4413	0.0340	0.0320	0.0064	0.0062
P: B	0.6497	1.13	0.6	0.258	0.4481	0.0194	0.0328	0.0006	0.0066
P: A	$\overline{\sigma}$ =0.6	1.6	0.6	0.095	0.0	0.0081	0.0055	0.0	0.0

Table 2:

Whereas in all the other examples the social value of innovation exceeded the monopolist's value, in example 9 the monopoly profit under ex interim taxation does not only exceed the resulting social value but also the socially optimal value of innovation. This typically arises for flat marginal damage functions and fixed investment costs $F(x)$ which do not vary much with the firm specific parameter x (resulting in a rather inelastic inverse demand function for the new technology). Note that this stands in contrast to the Arrow [1962] result, according to which in a world without regulation the monopolist's value of innovation always falls short of the social value.

7 First Best Regulation

In this section we show that the regulator can enforce first best 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, of course, also works in this case. However, the timing and the choice of the environmental policy remain crucial 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 influence the tax by holding down or enhancing output. Even under ex interim permit policy, the monopolist is in a better position than under ex interim taxation. This again 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 sold of the advanced abatement technology, and 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

$$p_x x + p + \sigma - c = 0 \tag{26}$$

As usual the regulator has to set

$$\sigma^* = -p_x(x^*, \tau^*)x^* \tag{27}$$

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

$$\tau^* = S'(E_I^*) \tag{28}$$

is the optimal tax rate equal to marginal damage. Since the output price is given by

$$p = C^0(e^0) - C^A(e^x, x) - F^A(x) + \tau[e^0 - e^x] \tag{29}$$

(see 12), plugging (29), (28), and (27) into (26) yields the corresponding first order condition for the socially optimal share of adoption (7).

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:

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

7.2 Ex interim permit policy and ex post regulation

Let us now consider *ex interim* commitment to permits, accompanied by a subsidy on output and a profit tax. Clearly, it is necessary for a first best allocation that the regulator sets $L^* = E_I^*$. However, the profit after R&D is now given by $\pi(x) = [p(x, \sigma(x, L)) + \sigma - c]x$. The first order condition is now $[p_x + p_\sigma \sigma_x]x + p + \sigma - c = 0$. From this we see immediately that the optimal subsidy is now given by

$$\sigma^{**} = -p_x(x^*, \sigma(x^*, L^*)x^* - p_\sigma(x^*, \sigma(x^*, L^*) \cdot \sigma_x(x^*, L^*) > \sigma^* \tag{30}$$

Hence also the corresponding profit tax t^{**} must be greater than t^*.

A similar argument holds if the regulator fixes the tax rate or 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 $\sigma^{***} = -p_x x^* - p_\tau \tau'(x^*) > \sigma^*$.

We see that if subsidizing advanced abatement technology is feasible, however, an individual profit tax is not, then the regulator is better off by making an ex interim commitment to the tax level because in this case he needs to pay less subsidies to the monopolist than under ex interim commitment to a quota of permits or under ex post regulation with either taxes or permits.

8 Possible 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. The only difference is 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 is rather uninteresting, because in that case we could separate the problem into two subproblems. 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. The reason is that 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 respect to 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 may be considered as little plausible. One can modify the model by extending the one dimensional parameter space - the unit interval - to a 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 is indifferent between the technology of, say, upstream firm A and the conventional technology but prefer those two strictly to the technology of upstream firm B. In such a case, lowering the price by upstream firm A not only steels demand from firm B, but also sells more units to firms which otherwise did not want to buy new technology at all. The effects, discovered from our monopoly model, thus, carry over to this case: There is too little output by the duopoly. In this case, too, the regulator can restore first best by subsidizing adoption of the new technology. Of course, this subsidy is lower for duopoly than for monopoly.

Thus with the monopoly model we have worked out some 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 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 independently of R&D success. We found that ex interim regulation always dominates ex post regulation. Ex ante regulation may or may not dominate ex interim or ex post regulation. We have also seen that the regulator can restore the first best by a combination of three policy instruments: emission taxes, subsidies on adoption of the advanced abatement technology, and a profit tax on the R&D firms. Nevertheless, the timing did matter also in this case since it had an impact on the size of the subsidy. Under ex interim taxation the subsidy can be set lower than under both ex interim permit policy and ex post regulation. In section 8 we briefly discussed R&D duopolies.

What policy conclusions can be drawn from our results? First of all we see that some commitment may be good if the R&D sector has strong market power. On the other hand, ex interim commitment seems to be sufficient. Indeed for most parameter constellations we found superiority of ex interim commitment over ex ante commitment. This is good news because for ex ante regulation the regulator needs more information than under ex interim regulation. He has to know the R&D-success/cost function for ex ante regulation whereas this is not necessary for ex interim regulation. Note that for optimal ex interim regulation the regulator has to know the inverse demand function, thus still needs considerable amount of information. But even if that is not available, our results serve to establish useful rules of thumb which require to commit to a tax rate higher than marginal damage. Note finally that despite of many advantages of permit systems and despite equivalence of taxes and permits under many circumstances (see Requate and Unold 1999b), taxes turn out to be superior to permits under ex interim regulation. The reason again is that the upstream firm's inverse demand function under permits is more elastic leading to higher distortions. However, the more competition in the upstream sector the less severe these distortions.

In the model considered here, the number of upstream firms was exogenous. It would be worth for further research to endogenizing 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 (12) we get:

$$p^A(x,\tau) = C^0(e^0) - C^A(e^x, x) - F(x) + \tau(e^0 - e^x) \tag{31}$$

Differentiating yields:

$$\begin{aligned} p^A_x(x,\tau) &= -C^A_x(e^x, x) - F'(x) < 0 \\ p^A_\tau(x,\tau) &= e^0 - e^x > 0 \end{aligned} \tag{32}$$

Qed.

Note further:

$$\begin{aligned} p^A_{xx}(x,\tau) &= -C^A_{xx}(e^x, x) - F''(x) - C^A_{xe}e^x_x & (33)\\ &= -\frac{C^A_{xx}C^A_{ee} - (C^A_{xe})^2}{C^A_{ee}} - F''(x) < 0 & (34) \end{aligned}$$

Since $e^x_x := \frac{de^x}{dx} = -\frac{C^A_{ex}}{C^A_{ee}} > 0$, i.e. the higher the firm specific parameter x, the less advantageous the new technology, i.e. the higher the emissions e^x.

$$\begin{aligned} p^A_{\tau x}(x,\tau) &= \frac{C^A_{xe}}{C^A_{ee}} < 0 & (35)\\ p_{\tau\tau} &= e^0_\tau - e^x_\tau < 0 & (36) \end{aligned}$$

Differentiation of (13) with respect to τ yields

$$x_\tau = -\frac{p_\tau}{p_{xx} + 2p_x} > 0 \tag{37}$$

Proof of formula 22: If firm A was successful, the social cost is given by

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

Differentiating yields

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

In the last expression we have employed (12), (9) and (10). Setting the last expression equal to zero and solving for τ yields the result.

Proof of Lemma 2: Differentiating (18) w.r.t. L yields i). Differentiating (18) 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 (20) 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 assumption (19). Hence the numerator is negative and hence $x_L < 0$.

Proof of Proposition 4: 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) follows from examples 5 and 6.

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.

Biglaiser, G., Horowitz, J.K. and Quiggin [1995]: "Dynamic Pollution Regulation," *Journal of Regulatory Economics*, 8: 33–44.

Carraro, C. and D. Siniscalco [1994]: "Environmental Policy Reconsidered: The Role of Technological Innovation," *European Economic Review*, 38, 545-554.

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.

Gersbach, H. and A.Glazer [1999]: "Markets and Regulatory Hold-up Problems," *Journal of Environmental Economics and Management*, 37: 151–164

Gersbach, H. [1997]: "Organization of Permit Markets and the Market Solution to hold–up Problems," Department of Economics, University of Heidelberg, *mimeo.*

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.

LAFFONT, J.-J. AND J. TIROLE [1996a]: "Pollution Permits and Compliance Strategies," *Journal of Public Economics*, 62, 85–125.

LAFFONT, J.-J. AND J. TIROLE [1996b]: "Pollution Permits and Environmental Innovation," *Journal of Public Economics*, 62, 127–140.

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

MALUEG, D.A. [1989]: "Emission Credit Trading and the Incentive to Adopt New Pollution Abatement Technology," *Journal of Environmental Economics and Management*, 18, 52–57.

MARIN, A. [1989]: "Comment: Firms Incentives to Promote Technological Change in Pollution Control," *Journal of Environmental Economics and Management*, 21, 297–300.

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.

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 [1999a]: "On the Incentives of Environmental Policy to Adopt Advanced Abatement Technology – Will the True Ranking Please Stand up?" *Disc. Paper No. 297, Department of Economics, University of Heidelberg.*

REQUATE, T. **and** W. UNOLD [1999b]: "On the Incentives of Policy Instruments to Adopt Advanced Abatement Technology if Firms are Asymmetric" *Disc. Paper No. 320, Department of Economics, University of Heidelberg.*

ULPH, D. [1997]: "Environmental Policy and Technological Innovation," in: Carraro, C. and D. Siniscalco (Eds.): New directions in the economic theory of the environment, 43-68.

VERDIER, T. [1995]: "Environmental Pollution and Endogenous Growth: A Comparison between Emission Taxes and Technological Standards," in: Carraro, C. and J. Filar (Eds.): Control and Game-theoretic Models of the Environment, 175-200.

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

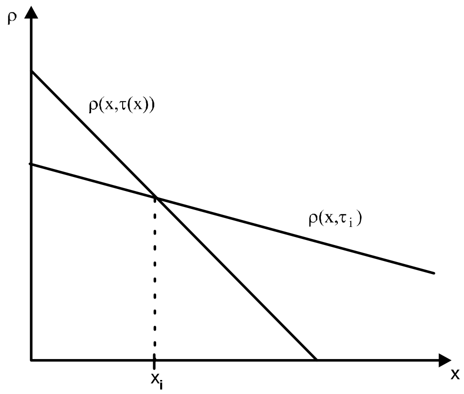

Figure 1: *The inverse demand functions und timing B (the flatter one) and timing C.*

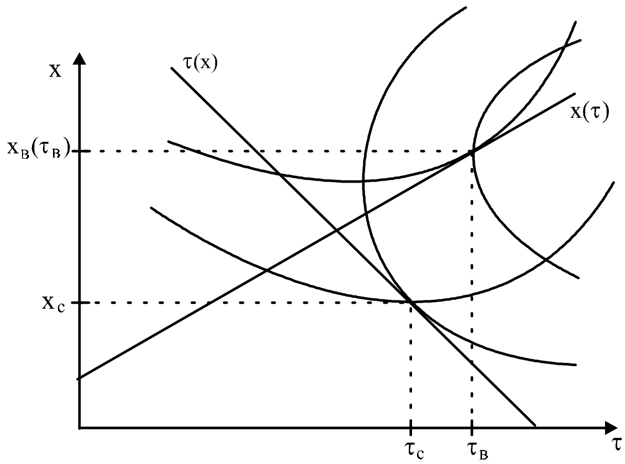

Figure 2: *The reaction curves of regulator and upstream firm.*

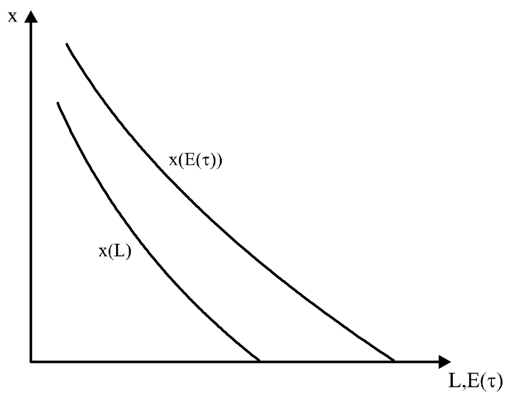

Figure 3: *The reaction curves of the regulator under taxes and permits in timing B.*