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

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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. We consider four different timing and commitment regimes of environmental tax and permit policies: ex post taxation (or issuing permits), interim commitment to a tax rate (a quota of permits) after observing R&D success but before adoption, and finally two types of *ex ante* commitment before R&D activity, one with a unique tax rate (quota of permits), the other one with a menu of tax rates (permit quotas). We study the second best tax and permit policies and rank these with respect to welfare. In particular, we find that commitment to a menu of tax rate dominates all other policy regimes.

Key words: commitment, emission taxes, environmental policy, R&D, technology adoption, time consistency, tradeable permits

JEL classifications: L5, Q2, Q28

1. Introduction

The most important criteria to evaluate environmental policy instruments are their 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. The aim of this paper is to investigate those long term incentives. In particular, we are interested in the interplay between *pricing* and *adoption* of new technology, on the one hand, and the incentives to engage in R&D to develop a new, less polluting technology, on the other. We not only address the question of instrument choice, but also ask how the timing of environmental policy and the ability of commitment to particular levels of policy instruments affects both the R&D effort and the incentive for technology adoption.

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 and thus time consistent setting of a tax rate or a quota of permits, respectively; second, *interim commitment* which means that the regulator makes a commitment to the level of his policy instrument after observing whether or not R&D has been successful, albeit before pricing and adoption of the new technology. Third, we study *ex ante commitment* to a single level of the policy instrument (tax rate or permit quota) *before* the R&D firm engages in research effort and before R&D success is guaranteed. Finally, we consider *ex ante commitment* to a *menu* of policy levels contingent on R&D success but before R&D is undertaken.

In our set-up, we distinguish between the regulated polluting sector which *employs* new abatement technology and the R&D sector which *develops* that 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 sector itself. The remaining 95% and 92% of innovations, respectively, are invented and developed for other industries. For simplicity we consider the case of a monopolistic R&D industry for the most part of this paper.

The policy regimes under consideration 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. Taxation dominates issuing permits under both, ex ante commitment contingent on R&D success and interim commitment. The reason for this is that the R&D monopolist can influence 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 ante commitment (either taxes or permits), independently of R&D success, on the one hand, and interim commitment, on the other, nor between the tax and permit policy under ex ante commitment independently of R&D success.

Moreover, we can show that the second best optimal tax rate usually exceeds marginal damage under interim regulation and can also exceed marginal damage under ex ante commitment. This result seems to be surprising 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 raising 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 regulation compared to interim regulation. The same holds true for a comparison between ex ante and 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, according to which in a world without externalities a monopolist's value of innovation always falls short of the social value.

This paper builds on two strands of literature. The eldest 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, 2003) 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. By 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 by optimally responding to diffusion of the new technology.

In all those models the new technology was assumed to be exogenous. 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 mainly. They also restrict their analysis to linear damage functions, and thus assume away 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. Denicolo considers a deterministic model with endogenous technology and compares ex post regulation to commitment. His kind of commitment corresponds to our regime of ex ante commitment with only one tax rate (or quota of permits). He also finds that taxes and permits are equivalent under ex post regulation but different under commitment, and in the latter case he finds that taxes are superior to permits. In contrast to my model, however, Denicolo always finds under-investment under commitment, whereas in my model over-investment can also happen. Fisher et al. (2003) study a model with only one innovator but no adoption by other firms. Zhao (2003) 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. In the next section we set up the model and we characterize the social optimum. In Section 3, we describe the possible timings of regulation in the decentralized settings. In Section 4, we investigate both the polluting firms' and the R&D monopolist's behavior under the different tax and permit policies. In Section 5, we study the second best optimal policy levels for the different timing and commitment regimes and compare those with respect to welfare. 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. We briefly sketch an extension to duopoly in the concluding section.

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] $C^0(e)$ which satisfies $-C_e^0(e) := -dC^0(e)/de > 0$ and $C_{ee}^0(e) := d^2C^0(e)/(de)^2 > 0$ for $e \leq e_0^{\max}$, i.e. we have positive but decreasing marginal abatement costs as long as emissions fall short of the maximal, or laissez-faire, emission level $e_0^{\max}$.

An upstream monopolist engages in R&D to develop advanced abatement technology for the polluting industry. With a certain probability y, contingent on R&D effort, the upstream firm develops a new, exogenously given technology A which leads to both lower abatement cost $C^A(e, x) < C^0(e)$ and lower marginal abatement costs, $-C_e^A(e,x) < -C_e^0(e)$ for all $e \leq e_0^{\max}$ and all x, which is a firm specific parameter of downstream firm $x \in [0, 1]$. If we refer to the emissions of firm 0 or x, we write e_0 and e_x, respectively. The cost functions $C^A(e, x)$ satisfy the same properties as $C^0(e)$, i.e. $-C_e^A(e,x) > 0$ and $C_{ee}^A > 0$ for $e < e_x^{\max}$, where the latter denotes maximal emissions of firm 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 zero, the more suitable is the technology for that downstream firm. For technical reasons we assume the cost function to be overall convex, implying $C^A_{ee}C^A_{xx} - [C^A_{ex}]^2 > 0$. The cost function $C^A(\cdot,\cdot)$ may also contain fixed set-up costs which need not be considered explicitly.

The reason why we introduced some heterogeneity of the investing firms is that under assumption of symmetry either all the firms want to invest or no firm wants to invest. This would generate a discontinuous, box like demand function, whereas by assuming ex post *asymmetry*, we obtain a downward sloping demand and thus more plausible results.[2]

If the downstream firms are regulated by a tax, denoted by τ, then, assuming interior solutions, they will set emissions according to the rule:

$$-C^0_e(e_0) = \tau, \tag{1}$$

$$-C^A_e(e_x, x) = \tau, \tag{2}$$

where solutions are denoted by $e^0(\tau)$ and $e^x(\tau)$, respectively. About these we will sometimes make the following assumption:
Assumption 1. *$d[e_0(\tau) - e_x(\tau)]/d\tau \leq 0$, for all $x \in [0, 1]$.*

The assumption says that the difference between emissions of the old and the new technology decreases if the price of emissions rises, or equivalently, if both firms reduce emissions keeping marginal abatement costs equal.[3] Note that Assumption 1 implies $e_x^{\max} < e_0^{\max}$ for all x.

Example 1. Let $C^0(e_0) = (a_0 - be)^2/2b$ *and* $C^A(e, x) = [a_I + x(a_0 - a_I)]^2/2b$. *Here we have* $e_0(\tau) = (a_0 - \tau)/b$ *and* $e_x(\tau) = [a_I + x(a_0 - a_I) - \tau]B$. *In this case we have* $d[e_0(\tau) - e_x(T)] = 0$.

2.2. R&D AND PRODUCTION COSTS OF UPSTREAM FIRMS

The upstream R&D firm incurs a cost $R(y)$ 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 cost the upstream firm has constant marginal production cost c 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. after the R&D costs are sunk. Hence, the ex ante expected profit is given by

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

2.3. SOCIAL COSTS AND EFFICIENT ALLOCATION

By virtue of $C^A_x \geq 0$ and $-C^A_{ex} \geq 0$ (see above), it is clear that if it is efficient for firm X to adopt the new technology, then is also efficient for any firm $x < X$ to adopt the new technology. Under decentralized policy settings, to be discussed below, this will be similar: if it pays for firm X to adopt the new technology, it will also pay for any firm $x < X$ to do so. Hence we denote by X both, the *marginal* firm which adopts the new technology and the *share* of firms that adopt the new technology.

Total emissions are then written as

$$E = \int_0^X e_x dx + (1 - X)e_0 \tag{3}$$

and are evaluated by a convex damage function $D(E)$ which depends on total emissions only. In order to define total social costs, we first define the social cost of pollution for the case that the upstream firm has been successful in R&D, and R&D costs are sunk:

$$SC_I = \int_0^X [C^A(e_x, x) + c]dx + (1 + X)C^0(e_0) + D(E). \tag{4}$$

In this case those downstream firms represented by the interval [0, X] adopt the new technology, incurring abatement costs plus the cost of producing the new technology c, 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. In case of no R&D success, the social cost is simply given by[4]

$$SC_0(e_0) = C^0(e_0) + D(e_0).$$

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

$$TSC\big(y, X, e_0, \{e_x\}_{x \in [0,X]}\big) = ySC_I + (1 - y)SC_0 + R(y) \tag{5}$$

2.3.1. *Efficient Allocations*

A social planner would proceed as follows. First, he chooses the level of R&D. Then, given success of the upstream firm, he chooses the share X of firms to adopt the new technology. Finally, he chooses emission levels $\{e_x\}_{x \in [0,X]}$ and e_0 of the downstream firms with new and old technology, respectively.

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

$$-C_e^0(e_0) = D'(E), \tag{6}$$

and in case of R&D success also:

$$-C_e^A(e_x, x) = D'(E) \text{ for all } x \leq X, \tag{7}$$

i.e. marginal abatement costs of each firm must be equal to marginal social damage.[5]

The *optimal share X* of firms to *adopt* the new technology, given R&D success, is given by the first order condition

$$C^A(e_X, X) + c - C^0(e_0) = D'(E)[e_0 - e_X] \tag{8}$$

Equations (6), (7), and (8) determine the socially optimal values for the share of adopting firms, denoted by X^*, and emissions, denoted by e_0^* and $\{e_I^*\}_{0 \leq x \leq X^*}$. Substituting these values into the social cost functions SC_0 and SC_I yields their optimal values denoted by SC_0^* and SC_I^*, respectively. Thus, we can define the *social value of innovation* by $SV = SC_0^* - SC_I^*$. Finally, from (5) the optimal level of R&D is simply determined by the first order condition

$$SC_0^* - SC_I^* = R'(y). \tag{9}$$

2.3.2. *First Best Policy*

Due to three potential market imperfections, pollution, too little output by the monopolistic R&D firm, and a gap between the social and the private value of innovation, the first best allocation could be achieved by the appropriate choice of three policy instruments: an emission tax, a subsidy on the purchase of the advanced abatement technology, and a tax (or subsidy) on the R&D monopolist's gross profit. Since subsidies are often legally not feasible, we will study pure environmental policy, i.e. pure downstream regulation, in the remainder of this paper.

3. Timing of Regulatory Policies

Since the focus of this paper is timing and commitment of regulation, we will first define the different games between the regulator and the firms. For this purpose look at Figure 1. Irrespective of regulation, the industry moves in the following order: first, the R&D firm chooses its R&D effort. In case of R&D success, it sets a price for the new technology. Third, 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 has different options to choose the point of time when to enact policy. We start backwards when explaining the different policy settings: With timing *D* (ex post regulation) the regulator moves after having observed both, R&D success and the rate of adoption of new technology. With timing *C* (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 before the upstream monopolist engages in R&D. The difference between the

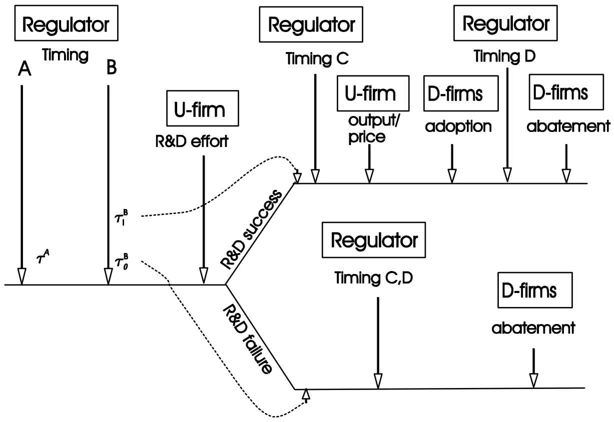

Figure 1. The structure of the different regulation games.

last two regimes is that with regime A the regulator makes a commitment to a unique level of his policy instrument, i.e. one tax rate, or one quota of permits, respectively, irrespective of R&D having been successful or not. Under regime B, by contrast, the regulator makes a commitment to a whole menu of policy levels. The latter form of policy is well known from the principal agent theory where the principal moves first by choosing a whole menu of rewards to pay the agent contingent on different outcomes.

In the following sections, we first analyze the behavior of firms, and then we study second best optimal tax and permit policies.[6]

4. The Firms' Behavior

We have already mentioned that the downstream firms choose their emissions according to (1) and (2).[7] Next, we study the downstream firms' decisions whether or not to adopt the new technology. Let p be the price of the advanced technology charged by the upstream firm. Then any downstream firm x decides to adopt the new technology if $C^A(e_x, x) + \tau e_x + p \leq C^0(e_0) + \tau e_0$. The marginal firm X, for which this relationship holds with equality, is indifferent between investing or not:

$$C^A(e_X, X) + \tau e_X + p = C^0(e_0) + \tau e_0. \tag{10}$$

By our assumption $C^A_x > 0$ and $-C^A_{ex} \geq 0$, it then also pays for any firm $x < X$ to adopt the new technology. Thus, (10) implicitly defines the demand for new technology as a function of price and the tax rate, or equivalently, it defines the downstream firms' inverse demand or willingness to pay function

$$p(X, \tau) = C^0(e_0) - C^A(e_X, X) + \tau[e_0 - e_X], \tag{11}$$

which has the following properties:

Lemma 2. *(i)* $p_X < 0$, *(ii)* $P_{XX} < 0$, *(iii)* $p_\tau > 0$, *(iv)* $p_{\tau X} < 0$, *(v) under Assumption 1* , $p_{\tau\tau} < 0$.

The proof is given in the appendix. Thus, the inverse demand function is downward sloping (i) and concave (ii). Moreover, a rising tax raises the willingness to pay (iii), though at a decreasing rate (v), and at the same time it tilts the inverse demand curve making it more elastic (iv).

4.1. OUTPUT AND PRICING OF R&D FIRM

We are now ready to study the behavior of the R&D firm, starting with the output decision given that R&D was successful. For this decision the regime of regulation matters. Under the timings *A*, *B*, and *C*, the monopolist takes the tax rate as given, whereas in timing *D* he can influence it. Under a permit regime, the monopolist can influence the permit price under any of the four timings.

4.1.1. *Tax Regime with Ex Ante and Interim Regulation (Timings A–C)*

Under timing *A* through *C*, the monopolistic firm maximizes his monopoly profit $\pi(X, \tau) = [p(X, \tau) - c]X$, which yields the usual first order condition for monopoly output:

$$\pi_X(X, \tau) = p_X X + p(X, \tau) - c = 0. \tag{12}$$

The **comparative statics effect** of the monopoly output X as a reaction on τ is ambiguous in general. Under a certain condition, however, the effect can be signed as the following result shows:

Lemma 3. *When the tax rises, the upstream monopolist produces more output if and only if*

$$p_\tau + p_{X\tau} X > 0 \iff (e_0 - e_X) C^A_{ee} + C^A_{xe} X > 0 \tag{13}$$

or equivalently:

$$-\frac{d(e_0 - e_X)}{dX} \cdot \frac{X}{e_0 - e_X} < 1. \tag{14}$$

Thus, the monopolist augments output as a reaction on a rising tax rate if the absolute value of the elasticity of the marginal firm's emission reduction, given by (14), is less than 1. The reason why $X_\tau := \partial X / \partial \tau$ cannot be signed unambiguously is that, on the one hand, the inverse demand curve shifts outwards since $p_\tau > 0$. This would allow the monopolist to charge a higher price if the elasticity of demand would stay constant. On the other hand, the inverse demand curve also tilts and becomes more elastic (steeper) since $p_{X\tau} < 0$, leading – other things being equal – to lower monopoly output. Note that (13), and thus (14), is more likely to be satisfied if the reduction of emissions through adoption of the new technology, i.e. $e_0 - e_X$, is relatively large and the heterogeneity of the adopting firms, represented by C^A_{xe}, is sufficiently small in absolute terms.

4.1.2. *Behavior Under Tax Regime with Ex Post Regulation (Timing D)*

Since with ex post regulation the R&D firm can influence the tax rate, or the permit price, respectively, we briefly have to look at the regulator's behavior. He clearly sets the tax rate equal to marginal damage:

$$\tau_D = D'(E). \tag{15}$$

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 (15) with respect to X, obtaining

$$\frac{d\tau}{dX} = D''(E) \cdot \left\{ [e_X - e_0] + \frac{d\tau}{dX}\frac{\partial E}{\partial \tau} \right\}, \tag{16}$$

where

$$\frac{\partial E}{\partial \tau} = \int_0^X \frac{\partial e_x}{\partial \tau} dx + (1 - X)\frac{de_0}{d\tau} < 0 \tag{17}$$

is the partial effect of a tax increase on emissions if the share of adopting firms is kept constant. Note that both $de_x/d\tau$ and $de_0/d\tau$ are negative. Solving (16) for $d\tau/dX$ yields

$$\tau_X := \frac{d\tau}{dX} = -\frac{D''(E)[e_0 - e_X]}{1 - D''(E)\frac{\partial E}{\partial \tau}} < 0. \tag{18}$$

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

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

and the first order condition for profit maximum is now given by

$$\pi'(X) = [p_X + p_\tau \tau_X]X + p - c = 0. \tag{19}$$

Since $p_X + p_\tau \tau_X < p_X$ the monopolist's effective inverse demand function is steeper in the case where he can influence the tax rate compared to the case where the firm has to take it as given (as is the case in the timings A through C).

4.1.3. *Behavior Under Permit Regimes*

For the permit regimes we denote by L the total supply of permits. The downstream firms take the price for permits σ as given and thus choose their emissions according to usual rule $-C_e^0(e) = \sigma$ and $-C_e^A(e, x) = \sigma$, respectively. The last two equations again define $e_0(\sigma)$ and $e_x(\sigma)$ for any $x \leq X$. The permit market is assumed to be competitive, and thus it clears:

$$\int_0^X e_x(\sigma)dx + (1 - X)e_0(\sigma) = L. \tag{20}$$

Note that the equilibrium price of permits is a function of both L and X.

Under ex post regulation (timing D), to begin with, there is no difference to regulation by taxes since if the regulator is the last to move and the share of adopting firms X is already fixed. Thus, we are in the ordinary situation of regulation under perfect competition and perfect information, for which we know that taxes and permits are equivalent.

If the regulator makes a commitment to the quota of permits L before the monopolist decides on output, i.e. under the timings A through C, the monopolist's profit can be written as

$$\pi(X) = [p(X, c) - c]X.$$

The first-order condition for profit maximization is then given by

$$[p_X + p_\sigma \sigma_X]X + p - c = 0, \tag{21}$$

where p_σ and σ_X are partial derivatives. This equation looks similar as (19). However, the monopolist's solution in X is different. The reason is that the functions $\tau(X)$ resulting from timing D, and the function σ *(X, L)* resulting from the permit instrument under timing C are different. Under timing D a change in X results in a different tax rate, and thus in a different total amount of emissions (or in a different quota of permits, respectively). Thus by changing the output, the innovator induces a change in total emissions under timing D. Under the permit regime with timing C, however, total emissions remain constant and are equal to L. Hence $d\tau(X)/dX$ must be different from $\partial\sigma(L, X)/\partial X$, and thus the solutions of (19) and (21) with respect to X must be different.

The response of the permit price $\sigma(L, X)$ on a change of L and X, and the reaction of the monopolist's output on a decrease of L are given by the following Lemma. Note that the partial response of emissions on the price of emissions $E_\sigma = \partial E/\partial\sigma$ with X held constant, is defined as in (17).

Lemma 4.

(i) $\frac{\partial\sigma(L,X)}{\partial L} = \frac{1}{E_\sigma} < 0.$
(ii) $\frac{\partial\sigma(L,X)}{\partial X} = \frac{e_0 - e_X}{E_\sigma} < 0.$
(iii) If (13) *holds, then* $\frac{dX}{dL} < 0.$

The proof is given in the appendix. (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 lower 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 under condition (13) as we would have expected. Note that in contrast to the case of taxes, (13) is a coarse sufficient but my no means a necessary condition for (iii) to hold.

4.2. 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 $j = A, \ldots, D$. Then the expected profit net R&D costs is given by

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

The first-order condition simply reads

$$R'(y) = \Pi_j^M. \tag{22}$$

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.[8] By employing the envelope theorem we obtain

$$\frac{dy}{d\tau} = \frac{(e_0 - e_X)X}{R''(y)} > 0. \tag{23}$$

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.

5. The Regulator's Problem

We are now ready to study the regulator's problem under the different regimes. Clearly under ex post regulation, i.e. timing 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 4.

5.1. SECOND BEST POLICIES FOR INTERIM REGULATION (TIMING C)

In this section, we study second best policies under timing C beginning with the tax regime.

5.1.1. *Tax Regime*

Given R&D success the regulator minimizes the social cost taking into account the behavioral conditions (1), (2), and (12), and considering R&D costs as sunk. Thus, the objective function is given by (4) where X, e_X, and e_0 are now considered as functions of the tax rate. Recall that in case of R&D success the regulator sets the tax *before* the monopolist decides on output or price. In the appendix, we establish that in this case the second best tax rate is given by the following formula:

$$\tau^C = D'(E) + \frac{p_X(X,\tau)X \cdot X_\tau}{dE/d\tau}, \tag{24}$$

where $dE/d\tau = (e_X - e_0)X_\tau + \partial E/\partial\tau$ is the total derivative of E with respect to τ which also captures the effect that more (or less) firms adopt the new technology. By contrast $\partial E/\partial\tau = \frac{\partial}{\partial\tau}[\int_0^X e_X(\tau)dx + (1-X)e_0(\tau)] < 0$ is the partial effect of a tax increase, i.e. the downstream firms' reaction on a tax raise with respect to emissions given the share of adopting firms X.

Let us denote by $X^C = X(\tau^C)$ the R&D-firm's response to the second best optimal tax rate. Accordingly let X^D denote the R&D firm's output under timing D and $\tau^D = \tau(X^D)$ the regulator's optimal response. Then we can derive the following result:

Proposition 5. Assume that the optimization problems of both, the regulator and the R&D firm are well defined and have interior solutions. Then under timing C, in case of R&D success

(i) The second best tax rate τ^C **exceeds marginal damage** if (13) holds.
(ii) The second best share of adopting firms X^C is less than socially optimal but greater than X^D.
(iii) 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.

The proof is given in the appendix. Result (i) follows immediately from the formula for the second best tax rate (24) which consists of two parts since under interim regulation the regulator accounts for two market imperfections: excessive pollution of the downstream firms and too little output of the R&D monopolist. To cope with the latter imperfection the regulator raises demand by increasing the tax rate. The monopolist will respond by augmenting output ($X_\tau > 0$) if the increased willingness to pay ($p_\tau > 0$) is not dominated by the effect that demand becomes more elastic ($p_{\tau X} < 0$). By the right-hand version of (13) this is the case if and only if the emission reduction through adoption of the new technology $e_0 - e_x$ is sufficiently large for the marginal firm, or if the heterogeneity of the downstream firms is sufficiently small, resulting in small values of $-C^A_{ex}(e,x)$. Moreover, $dE/d\tau$ is negative *if*

(13) holds. Note that the second best tax rate may exceed marginal damage even if X_τ is negative and the total effect on emissions $dE/d\tau$ is positive, which happens if the absolute value of X_τ is sufficiently large to guarantee that $(e_X - e_0)X_\tau$ dominates $-\partial E/\partial\tau$.

Result (iii) says that, once the technology is given, a commitment to an emission tax rate raises gross welfare (considering R&D costs as sunk) by increasing the monopolistic innovator's output.[9] Result (iii) is proven by studying the reaction curves of both, the regulator and the R&D firm (see Figure 3 in the Appendix). Result (ii) yields the main reason for (iii) to hold, namely higher output (lower prices) and thus more adoption of the new technology.

It is important to note, however, that result (iii) does not imply that interim regulation, i.e. commitment to a tax rate after observing R&D success, also leads to higher *net* welfare (including the cost of R&D) compared to ex post regulation. For, by taxation, the regulator artificially shifts up demand for the new technology. By this the R&D firm's profit may exceed the social value of innovation. Since the regulator does not account for the R&D costs, R&D effort may be too high, and thus net welfare may be lower under interim regulation compared to net welfare resulting from ex post regulation.

Finally, it is worth to mention that even if τ^C exceeds marginal damage, it may be less than τ^D, the ex post optimal tax rate which always equals marginal damage. The reason is result (ii). More output of the new technology leads to more adoption, and thus shifts down the aggregate marginal abatement cost curve. Hence, total emissions are lower, and as a consequence the marginal damage is lower under timing C than the corresponding value under timing D.

5.1.2. *Permit Regime*

We now study the second best rule for issuing permits. The regulator minimizes the social cost given by

$$SC(L) = \int_0^X [C^A(e_x, x) + c]dx + (1 - X)C^0(e_0) + D(L).$$

Using $(dE/d\sigma)\sigma_L = 1$, we can write $dX/dL = (dX/d\sigma) \cdot \sigma_L = (dX/d\sigma) \cdot \sigma_L/((dE/d\sigma)\sigma_L) = (dX/d\sigma)/(dE/d\sigma)$. Following a similar calculation as for the second best tax rule, the first order condition for the second best number of permits is given by

$$\sigma = D'(L) + \frac{[p_X + p_\sigma \sigma_X]X \cdot dX/d\sigma}{dE/d\sigma}. \tag{25}$$

The results of Proposition 5 carry over to the case of permits. Hence it is not necessary to repeat those here. In particular, we see from (25) that the permit

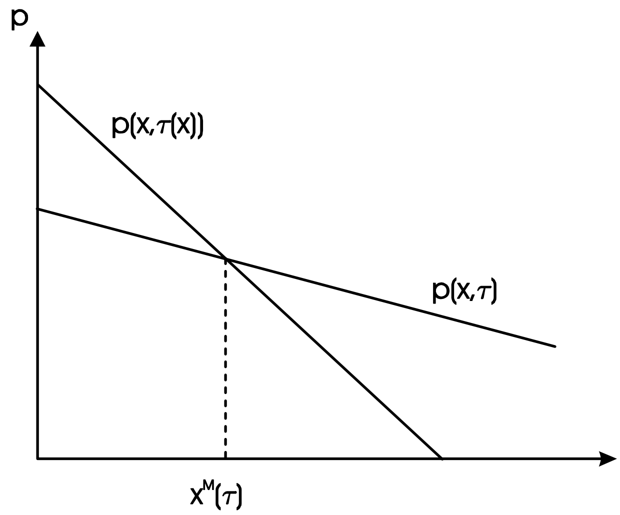

Figure 2. The monopolist's inverse demand curves under timing C and D .

price exceeds marginal damage under the same condition as in Proposition 5. In the next result, we compare the performances of the permit and the tax regime under timing C.

Proposition 6.

(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 $X(L) = X(E(\tau))$ is smaller than the resulting share of adopting firms $X(\tau)$ under taxes.

(ii) Once the new technology is given, the second best optimal permit regime yields lower welfare than the second best optimal tax regime.

Part (i) 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 under taxation (see Figure 2), the monopolist charges a higher price (produces less output) as in the case of taxes. Thus, for any emission target $\bar{E}$, there is less supply and thus less adoption of new technology if the target is achieved by permits $(L = \bar{E})$ compared to the case where it is achieved by a tax policy $(E(\tau) = \bar{E})$. Hence, under the second best optimal permit policy, welfare (not including the cost of R&D) must be lower compared to the corresponding tax regime. Or put

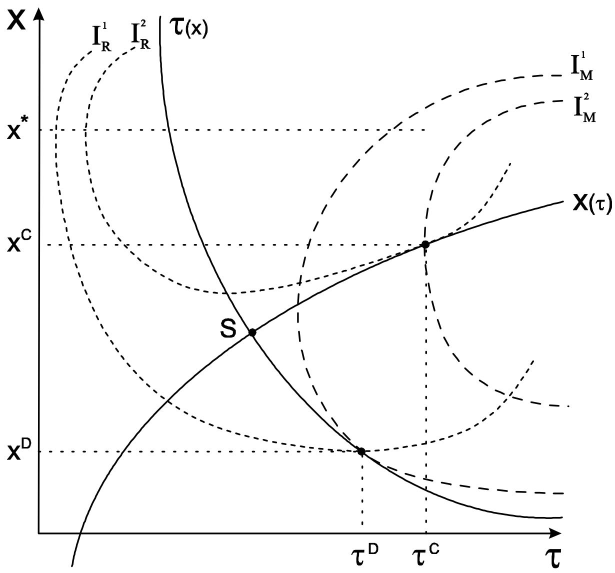

Figure 3. Indifference and reaction curves of regulator and upstream firm. Note that the indifference curves of the regualator have to be backward bending at the efficient level of adoption X^*.

differently, any given emission level can be achieved at a lower downstream cost by using taxes rather than permits because taxes induce a higher rate of adoption.

Note that the second best optimal number of permits can be higher or lower than the second best optimal emission level resulting from taxation. The reason is that the share of adoption is different in both regimes.

5.2. SECOND BEST TAX AND PERMIT RULES FOR TIMING B

In this game the regulator makes a commitment to a tax or permit policy *before* the firms engage in R&D, and thus he is able to account for the cost of R&D. However, we assume that the regulator can set two different tax rates τ_0^B and τ_I^B, or two different quotas of permits, L_0^B and L_I^B, respectively, contingent on R&D success. Although this policy structure is rarely applied in the theory of regulating firms, it is well known from the principal agent literature where a principal makes a commitment to a whole menu of rewards or payoffs to the agent, contingent on the agent's success which usually depends on his or her effort, but may also be subject to stochastic impacts. Here, applied to the tax regime, the regulator's problem is now:

$$\min_{\tau_0,\tau_I}\{ySC_I(\tau_I) + (1-y)SC_0(\tau_0) + R(y)\}$$

where again he takes into account the behavior of up- and downstream firms as given by Equations (1), (2), (12) and (22). Note that the monopolist's behavior is the same as in timing C. Since he does not make a profit in case of R&D failure, we obtain $\partial y/\partial\tau = 0$. Thus, following similar calculations as in regime C we obtain the solution for the two second best optimal tax rules

$$\tau_0^B = D'(E_0), \tag{26}$$

$$\tau_I^B = D'(E_I) + \frac{p_X X \cdot X_\tau}{\frac{dE_I}{d\tau_I}} + \frac{\frac{\partial y}{\partial \tau_I}}{y\frac{dE_I}{d\tau_I}}[SC_I(\tau_I) - SC_0(\tau_0) + R'(y)], \tag{27}$$

where E_0 denotes the optimal level of emissions in the absence of R&D success, whereas $E_I = \int_0^X e_x dx + (1 - X)e_0$ are total emissions after R&D success.

Clearly, if there is no R&D success, there is no further market imperfection, and the regulator should set the tax equal to marginal damage. Studying the tax rate τ_I^B, to be enforced in case of R&D success, we see that the first two terms are the same as for the second best optimal tax rule for timing C, given by (24). In addition, there is a term which accounts for the difference between the social and the private value of innovation and which would be zero in a first best allocation due to (9). It is not possible to sign $SC_I(\tau_I^B) - SC_0(\tau_I^B) + R'(y)$ in general for this second best scenario.

The case of permits is similar. The regulator now commits to two different quantities L_0^B and L_I^B satisfying the following rules:

$$\sigma_0^B = D'(L_0^B), \tag{28}$$

$$\sigma_I^B = D'(L_I^B) - [p_X + p_\sigma \sigma_X]X \cdot X_L + \frac{\frac{\partial y}{\partial \sigma}\frac{\partial \sigma}{\partial L}}{y}[SC_I(L_I^B) - SC_0(L_0^B) + R'(y)]. \tag{29}$$

Note, however, that despite the similarity between (27) and (29) the distortion is larger under permits since the innovating monopolist's inverse demand function is more elastic by the same reason as in regime C. Hence expected welfare must be larger under taxes than under permits.

5.3. SECOND BEST TAX AND PERMIT RULES FOR TIMING A

Finally, we consider the case where the regulator is not able to commit to a menu of different policy levels contingent on R&D success, but can only set a *unique* tax rate, or quota of permits, respectively, *before* the upstream firm starts R&D. Some tedious but straightforward calculations yield the second best optimal tax formula:[10]

$$\tau^A = \frac{1}{y\frac{dE_I}{d\tau} + (1-y)\frac{dE_0}{d\tau}} \left[y \cdot \left(D'(E_I)\frac{dE_I}{d\tau} + p_X(X,\tau)X\frac{dX}{d\tau} \right) \right.$$
$$\left. + (1-y)D'(E_0)\frac{dE_0}{d\tau} + \left(SC_I - SC_0 + R'(y) \right) \frac{dy}{d\tau} \right] \quad (30)$$

which takes into account the reaction of the 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 (24) if $y = 1$, which in equilibrium, however, cannot happen if we hold on to our assumption that R&D costs go to infinity as y goes to 1.

In **case of permits**, not the emissions and the marginal damage but rather the price of permits is subject to uncertainty. Similar calculations as in the tax case lead to the following, a bit simpler second best rule:

$$\bar{\sigma} = D'(L) + y \cdot [p_X + p_\sigma \sigma_X] X_L + [SC_I - SC_0 + R'(y)] y_L, \quad (31)$$

where, σ_I and σ_0 are the permit prices with and without R&D success, respectively, and $\bar{\sigma} = y\sigma_I + (1-y)\sigma_0$ is the expected price for permits.

5.4. 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) dominates all other policy regimes. It outperforms taxation with timing A since it can always mimic timing A by choosing $\tau_I^B = \tau_0^B = \tau^A$. Taxation with timing B also outperforms taxation with timing C and D because through ex ante commitment to a particular tax level the regulator can account for the R&D costs, which he is not able to do in both regimes C and D. Note that with timing B the regulator is also able to mimic the results of the regimes C and D since in both cases he can use two tax rates. It is also clear from our arguments put forward above that each tax regime under timing B and C dominates the corresponding permit regime. The reason is that in a permit regime the inverse demand function incurred by the R&D firm is more elastic, and thus the distortion under permits is more severe than in case of taxes. We summarize this as follows:

Proposition 7.

(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) Under each of the timings A, B, and C the tax regime always outperforms the corresponding permit regime.

There is little we can say concerning comparisons between A *versus* C, A versus D or even C *versus* D for either regime taxes or permits. The reason why regime A can be better or worse than the regimes C or D is that, on the one hand, with timing A the regulator is able to account for the social value of innovation and the R&D costs. On the other hand, there is always the wrong tax rate in case of R&D failure. Note also from an ex ante point of view no unique ranking between regime C and D is possible. Although, once R&D has been successful, C outperforms D, since the regulator can account for the monopolistic behavior of the R&D firm (see Proposition 5, (iii)), regime C may induce too much R&D effort since by shifting up the inverse demand curve for new technology the private value may exceed the social value of innovation.[11] Thus, from an ex ante view point interim commitment may be worse than ex post regulation.

Furthermore, no unique welfare ranking is possible between the tax and the permit regime under timing A. One can show, however, that for damage functions, which are relatively flat, taxes dominate permits whereas for damage functions, which are relatively steep, the opposite holds true. This is consistent with the well known Weitzman (1974) result. Note that we are in a situation similar to Weitzman's scenario since there is uncertainty on the aggregate abatement cost function due to random R&D success. Since timing A is dominated by timing B anyway, we do not further qualify and prove this result.

We have argued in Section 2.3 that the regulator can achieve first best allocations by the choice of three instruments: a tax on emissions, a subsidy on the purchase of advanced abatement technology, and a tax (or a subsidy) on the R&D monopolist's gross profits. Nevertheless, even with overall regulation, timing and choice of the environmental policy instrument does matter, namely for the amount of subsidies to be paid to the innovator. In the cases of ex post taxation and with interim or ex ante permit policy the regulator would have to pay higher subsidy rates than in case of interim taxation. Thus, if there is an excess burden of raising public funds, the regulator will prefer a timing which causes the highest tax revenues or the lowest amount of subsidies, respectively.

6. Conclusions

We investigated the interplay of environmental policy, incentives to adopt new technology, and the repercussions on R&D by studying an industry structure consisting of many competitive, but heterogenous polluting firms, on the one hand, and a monopolistic R&D sector, on the other. We have scrutinized different forms of timing and commitment strategies, in particular ex post regulation after adoption of new technology, interim regulation after observing R&D success but before adoption, and finally ex ante regulation with both, different tax rates (permit quotas) contingent on R&D success, and with a single tax rate (permit quota) independently of R&D success. We found, first, that ex ante commitment with different tax rates dominates all other regimes, and second, that tax regimes dominate permit regimes for both ex ante commitment contingent on R&D success (timing *B*) and interim regulation (timing *C*).

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. Second, taxes are unambiguously superior to permits since the R&D firm's inverse demand function is more elastic under permits and hence leads to larger distortions.

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 costs 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 our model. Whereas in Parry's model "*reducing* the tax rate drives down the licence fee, and hence *increases* diffusion", the opposite is true here: *raising* 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 usually exceeds marginal damage. Of course Parry's model is slightly different from mine as he allows for a continuum of different technologies but deterministic R&D and free entry of polluting firms. It seems to be hard to bring together the features of Parry's free entry model and features of firm heterogeneity since free entry is (almost) inconsistent with heterogeneity of firms.

In this model we have restricted our analysis to a monopolistic R&D sector only. It is straightforward, though technically a bit cumbersome, to generalized the results to R&D duopoly.[12] One can readily verify in such a model that more competition on the upstream level induces less distortions, and thus calls for lower emission taxes. It is a subject of further research to endogenize the number of R&D firms through a model of market entry and monopolistic competition. It would also be interesting to take advantage of these results for endogenous growth models where the *direction* of technological progress may be influenced by environmental policy.

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Notes

1. Since the downstream industry is perfectly competitive, it is not necessary to explicitly model the output market. This holds because the output adjustment upon environmental regulation is already implied in the abatement cost function. To see this, assume that firms have joint costs in output and abatement $\tilde{C}(q,e)$, yielding a profit of $\pi(q,e) = pq - \tilde{C}(q,e)$ (see Requate 1995). Holding emissions e fixed, the firms choose $p = \tilde{C}_q(q,e)$ where p is the output price. This gives $q(e)$ and a reduced profit of $\tilde{\pi}(e) = \pi(q(e),e)$. Under laissez faire, the firms choose maximal emissions $e_{\max}$ such that $\tilde{C}_e(q(e_{\max}), e_{\max}) = 0$, yielding the maximal profit $\pi_{\max}$. The abatement cost can then be defined as foregone profits through reducing emissions: $C(e) = \pi_{\max} - \tilde{\pi}(e)$. It can be shown that all properties of $\tilde{C}(q,e)$ with respect to e carry over to $C(e)$.
2. A referee criticized that it does not seem quite plausible why firms are symmetric *ex ante* but heterogenous ex post. Introducing heterogeneity of non-investing firms is possible but requires some technical clutter since it is necessary to order the firms according to the difference in abatement costs resulting from the old and the new technology, respectively (see Requate and Unold 2001). Since introducing ex ante heterogeneity does not change the results, I kept the model as simple as possible.
3. 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.
4. Note that in this case $E_0 = 1 \cdot e_0$ since the total number of firms has measure 1.
5. Note that (6) yields different values of e_0, depending on whether or not R&D has been successful.
6. 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.
7. In a permit regime, we get the same result by replacing the tax rate by the price of permits.
8. Under timing D this question does not make sense since for the monopolist the tax rate is not an exogenous variable.
9. Note that this result does not trivially follow from the order of the game. Although in many examples of regulation the regulator benefits from being the first mover, this need not always be the case. E.g. Petrakis and Xepapadeas (1999) consider a model where polluting firms choose their technology in the first stage (determinstic R&D) and (different from our model) exercise market power on the final goods market in a second stage. In that model it is sensitive to parameters whether or not the regulator is better off being the first mover.
10. Again E_I and E_0 are total emissions with or without R&D success.
11. This stands in contrast to Arrow's (1962) result according to which, in the absence of regulation, a monopolist's value of a process innovation always falls short of the social value of innovation.

12. The reason for the technical clutter is that, if we generalize our model to a Hotelling type of model with duopolist A serving the left-hand side and duopolist B serving the right-hand side of the set of firms, represented by the interval [0,1], we will have either two local monopolists – leading to the same results as above - or we will have full market coverage, which eliminates all output distortions since each downstream firm demands only one unit of the new technology. One can, however, obtain a proper duopoly model by enlarging the firms' parameter set to an (at least) two-dimensional space.

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Appendix

Proof of Lemma 1. Differentiating (12) with respect to X and τ yields:

$$p_X^A(X,\tau) = -C_x^A(e_X, X) < 0 \tag{32}$$

$$p_\tau^A(X,\tau) = [C_e^0(e_0) + \tau]\frac{de_0}{d\tau} - [C_e^A(e_X, X) + \tau]\frac{de_X}{d\tau} + (e_0 - e_X) \tag{33}$$

$$= e_0 - e_X > 0 \tag{34}$$

since $C_e^0(e_0) + \tau = 0 = C_e^A(e_x, x) + \tau$ by (1) and (2).

Next observe that $de_x/dx = -C_{ex}^A/C_{ee}^A > 0$, i.e. the higher the firm specific parameter x, i.e., the less advantageous the new technology, the higher the emissions e_x. Next we differentiate (32) w.r.t. X to obtain:

$$p_{XX}^A(X,\tau) = -C_{xx}^A(e_X, X) - C_{xe}^A\frac{de_X}{dX} \tag{35}$$

$$= -\frac{C_{xx}^A C_{ee}^A - (C_{xe}^A)^2}{C_{ee}^A} < 0 \tag{36}$$

Further we differentiate (33) w.r.t. X and τ to obtain:

$$p_{\tau X}^A(X,\tau) = p_{X\tau}^A(X,\tau) = C_{xe}^A/C_{ee}^A < 0 \tag{37}$$

$$p_{\tau\tau} = \frac{\partial e_0}{\partial\tau} - \frac{\partial e_X}{\partial\tau} < 0 \tag{38}$$

where the latter holds by Assumption 1.

Proof of Lemma 2. Differentiation of (12) with respect to τ yields

$$X_\tau = -\frac{p_\tau + p_{X\tau}X}{p_{XX}X + 2p_X} = -\frac{(e_0 - e_X) + C_{xe}^A X/C_{ee}^A}{p_{XX}X + 2p_X}. \tag{39}$$

Since the denominator is negative, the sign of (39) is determined by $(e_0 - e_X) + C_{xe}^A X/C_{ee}^A$.
Since $C_{ex}^A/C_{ee}^A = -de_X/dX = d(e_0 - e_X)/dX$, we can rewrite (13) as (14).

Proof of Lemma 4. Differentiating (20) w.r.t. L yields (i). Differentiating (20) w.r.t. X yields

$$e_X - e_0 + \left[\int_0^X \frac{de_x}{d\sigma}dx + (1 - X)\frac{de_0}{d\sigma}\right]\frac{\partial\sigma}{\partial X} = 0.$$

Solving for $\partial\sigma/\partial X$ yields (ii). To show (iii), we differentiate (21) with respect to L and solve for X_L:

$$X_L = -\frac{[p_{X\sigma}X + p_{\sigma\sigma}\sigma_X X + p_\sigma]\sigma_L + p_\sigma\sigma_{XL}x}{\left[p_{XX} + 2p_{X\sigma}\sigma_X + p_{\sigma\sigma}\sigma_X^2 + p_\sigma\sigma_{XX}\right]X + 2[p_X + p_\sigma\sigma_X]},$$

where $\sigma_X = (e_0 - e_X)/E_\sigma < 0$, $\sigma_L = 1/E_\sigma$, and $\sigma_{XL} = \left(\frac{\partial e_o}{\partial\sigma} - \frac{\partial e_X}{\partial\sigma}\right)/E_\sigma^2 < 0$ by Assumption 1.

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 term together we obtain $C_{ex}^A X/C_{ee}^A + (e_0 - ex) > 0$ by condition (13). Hence the numerator is negative and we obtain $X_L < 0$.

Proof of formula (24). If the R&D monopolist has been successful, the social cost is given by $SC(\tau) = \int_0^X [C^A(e_x, x)]dx + cX + (1-X)C^0(e_0) + D\Big(\int_0^X e_x dx + (1-X)e_o\Big)$.

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

$$\begin{aligned}&\{C^A(e_X, X) + c - C^0(e_0)\}X_\tau \\ &\quad + \int_0^X C_e^A \frac{de_x}{d\tau}dx + (1-X)C_e^0\frac{de^0}{d\tau} + D'(E)\frac{dE}{d\tau} = 0\end{aligned} \tag{40}$$

Now we use (11) to substitute $C^A(e_X, X) - C^0(e_0) = -p + \tau[e_0 - e_x]$. Further, we use (1) and (2), as well as $\int_0^X \frac{de_x}{d\tau}dx + (1-X)\frac{de_0}{d\tau} = \frac{\partial E}{\partial \tau}$ to obtain

$$\begin{aligned}SC'(\tau) &= \{-(p-c) + \tau[e_0 - e_X]\}X_\tau - \tau\frac{\partial E}{\partial \tau} + D'(E)\frac{dE}{d\tau}, \\ &= -(p-c)X_\tau + \tau\left\{[e_0 - e_X]X_\tau - \frac{\partial E}{\partial \tau}\right\} + D'(E)\frac{dE}{d\tau}, \\ &= p_X(X,\tau)X \cdot X_\tau + \{-\tau + D'(E)\}\frac{dE}{d\tau} = 0,\end{aligned} \tag{41}$$

where for the second equality we employed (12) and the relationship $\frac{dE}{d\tau} = (e_X - e_0)X_\tau + \frac{\partial E}{\partial \tau}$. Solving (41) for τ yields (24).

Proof of Proposition 5. (i) has already been proven in the text. To prove (ii) and (iii) we study the reaction functions of the regulator and the R&D-firm, respectively. We consider the case where $X_\tau > 0$, as displayed in Figure 3. Recall that the reaction function of the regulator is downward sloping by (18). Note that the indifference curves of the R&D firm are increasing to the right in the relevant range (a higher tax increases profits), whereas the indifference curves of the regulator are increasing upwards in the relevant range. (Higher output increases welfare as long as it is less than socially optimal. Hence the indifference curves are backward bending for $X > X^*$.)

In game D, the R&D firm chooses X^D, where it reaches the highest indifference curve (profit level) which has a common point with the regulator's reaction function. This induces the tax rate $\tau^D = \tau^D(X^D)$. Since the R&D firm's reaction function must be downward sloping at the point (τ^D, X^D) and has slope infinity on the reaction curve $X(\tau)$, the point (τ^D, X^D) must be to the right of the intersection point $S = (S_\tau, S_x)$. The regulator obtains a welfare level depicted by the indifference curve I_R^1. Since the R&D firm's reaction function $X(\tau)$ is above I_R^1, and the regulator's optimal choice in game C is the one, where he reaches the highest indifference curve (welfare level) which has a common point with the R&D-firm's reaction function, i.e. (τ^C, X^C) with $X^C = X(\tau^C)$ the corresponding indifference curve I_R^2 must be on a higher level than I_R^1. This proves (iii).

To see (ii), observe that I_R^2 is horizontal on $\tau(X)$. Hence it must be increasing at the point (τ^C, X^C). Hence the point (τ^C, X^C) must be on the right of S again. This proves $X^C > X^D$. Clearly X^C cannot be higher than optimal, since the regulator's tax rate is already higher than marginal damage. Thus, if X^C were higher than optimal, the regulator could improve welfare by relaxing the tax a bit, bringing X closer to the efficient level X^* and bringing marginal abatement cost closer to marginal damage.

The argument for the case $X_\tau < 0$ is similar and may be verified by the reader. For this case it is important to note that X_τ has to be flatter than $\tau'(X)$, otherwise the optimization problems of both players, the regulator and the R&D firm would not be well defined, contrary to what we have assumed. Note that the point (τ^C, X^C) is now to the left of S.

Proof of Proposition 6. (i) Denote by $X^M(\tau)$ the monopoly output under a tax regime. Then clearly

$$p\big(X^M(\tau), \sigma(X^M(\tau), E(\tau)\big) = p\big(X^M(\tau), \tau\big).$$

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^M (L) is always lower than under taxes with $E(\tau) = L$.