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Incentives to Innovate under Emission Taxes and Tradeable Permits

by

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Abstract

We consider a competitive industry with constant returns to scale and pollution. In a partial framework pollution control is implemented by either charging an effluent tax, or by issuing tradeable permits. The paper investigates the incentive to introduce a cleaner technology under either policy. Neither diffusion of the new technology, nor optimal agency response happens immediately. In contrast to former research this model pays explicit attention to the final output market, finding that it depends crucially on the parameters whether permits or taxes provide stronger an incentive to innovate. Moreover, the impact of optimal policy adjustment will be investigated.

(JEL: H23, L51)

Keywords: Effluent taxes, tradeable permits, innovation, incentives to innovate; diffusion of technology.

1 Introduction

This paper is about the value of a new technology in a world where production causes pollution of the environment, and where these externalities are internalized by regulatory policies like emission taxes or tradeable permits. The paper builds on two branches of research. The first and older one originates in ARROW'S [1962] seminal paper who's work has been extended essentially by DASGUPTA and STIGLITZ [1980a,b]. These authors investigate a single firm's value of a new, cost reducing technology contingent on the prevailing market structure. In these models there are neither (real) externalities, nor is there any kind of regulation. The second branch is based on articles by DOWNING and WHITE [1986], and more recently by MILLIMAN and PRINCE [1989] (for short [DW] and [MP] in the remainder) who offer a verbal/geometrical analysis of a firm's incentive to introduce a new abatement technology under different regulatory policies as effluent taxes, subsidies, different kinds of permits, and direct control. As fashionable in the earlier pollution control literature these writers concentrate merely on the pollution sector neglecting the output market completely.[1]

In this paper we jointly consider both, the output market, and the pollution sector, and we find that most of the results found in [DW] and [MP] do not generalize if the feedback on the output market is taken into account. By taking a more global view on the one hand, we sacrifice some generality on the other by assuming very simple, i.e. linear technologies. Before an innovative technology is introduced, all the firms are alike, producing with constant marginal costs c_0 and emitting the same pollutant at a constant rate d_0 proportional to output. At this status quo the social optimum is assumed to be implemented by an agency either setting an emission tax, or issuing a quota of tradeable permits. The output market as well as a possible market for permits are perfectly competitive. Then we let a single firm develop a new technology leading to a lower rate of pollution per output, $d_I < d_0$, but at the same time incurring a higher marginal cost, $c_I > c_0$. Clearly such a technology would never be introduced in a *laissez faire* world a la ARROW/DASGUPTA–STIGLITZ. Under a tax or permit policy, however, a competitive firm's value to innovate is positive if and only if $c_I + \tau d_I < c_0 + \tau d_0$, where τ denotes the tax rate, or the price of permits, respectively. We investigate the competitive firm's value to introduce this new technology under either policy, and we characterize these values dependent on a critical damage parameter which determines the steepness of the social damage function. This leads to a couple of surprising results which cannot be obtained without paying explicit attention to the output market. First we consider a situation where only one firm has developed the new technology,

[1] In the following I refer to this method as *partial partial* analysis.

and the regulator does not react immediately on innovative activity. We find that in such a situation taxes provide higher an incentive to innovate than permits if the social damage function is sufficiently flat, or if it is sufficiently steep. On the other hand, for an intermediate range of damage parameters the value of innovation is higher under permits. Moreover, for damage parameters sufficiently low the firm's value of innovation under taxes exceeds the social value of innovation whereas under permits the firm's value of innovation is zero. This contrasts also from one of the basic results of ARROW and DASGUPTA–STIGLITZ, stating that under constant returns to scale a competitive firm's value of a cost reducing innovation is always positive, but falls short of the social value. Moreover, in the Arrow–Dasgupta–Stiglitz model without externalities, as well as in the Downing–White–Milliman–Prince model without output markets, innovation always leads to an increase in welfare whereas in the model considered here innovation can even lead to welfare losses if the externalities are internalized by taxes. The reason for this is that the innovator possibly serves too big a market share compared to the social optimum.

Next we consider optimal agency response before the technology has been adopted by other firms. Conventional wisdom from "partial partial" analysis teaches that taxes have to be cut, or the corresponding number of permits has to be reduced. Taking into account the output market, this result generalizes only if the innovator engages in limit pricing. If, on the other hand, the innovation is drastic, i.e. the innovator's monopoly price is less than the conventional firms' marginal cost, and if the social damage function is sufficiently steep, the opposite holds. A similar result can be derived for permits: the adjusted number of permits can be lower, equal, or higher than the original one. After (optimal) agency response, the innovator's values of the new technology coincide under either policy. Finally, the innovator has no incentive to promote diffusion since constants returns to scale cancel all the profits if at least two firms with the new technology compete on the output market. Also this stands in contrast to the findings in [MP].

All these results strongly suggest that neglecting the output market may result in dangerous simplifications and policy recommendations based on such models have to be taken with care.

I would like to emphasize from the beginning that I do not model how much effort the firms invest in order to find a new technology. In other words, the model does not consider an R & D process, as for example MAGAT does it in his [1978] article. I rather follow ARROW, DASGUPTA & STIGLITZ as well as GILBERT & NEWBERRY [1982] by looking for the *value* of an innovation once it has been found or could be bought on some market.

The next section contains the set up of the basic model. Section 2.2 considers

the social optimum before innovation, and its implementation by taxes as well as by auctioned permits. In section 2.3 we characterize the socially optimal allocation of production if the new technology is available. Section 3 considers the competitive firm's incentive to innovate under the different policies. We also investigate optimal adjustment of the policy tools and look in what direction taxes or quotas have to be ratcheted. In the final section we summarize and briefly address *free* permits. Simple proofs are given in the running text, more technical ones are relegated to the appendix.

2 The Model

2.1 Basic Assumptions

We start with an industry consisting of n firms producing perfect substitutes and generating the same kind of pollution. Let q_i and e_i denote firm i's amount of output and emissions, respectively. The firms have linear technologies represented by pairs (c_i, d_i), where c_i denotes the constant marginal (private) cost, and d_i is the constant marginal pollution such that $e_i = d_i q_i$. Total output and emissions are written $Q := \sum_{i=1}^n q_i$, and $E := \sum_{i=1}^n e_i$, respectively.

Consumers' preferences are given by a bounded downward sloping inverse demand function P, where $\overline{p} := P(0)$ is the choke off price. Assuming $P' < 0$ on its support we can define demand by $D := P^{-1}$ for all $p \in [0, \overline{p}]$, and $D(p) = 0$ for $p > \overline{p}$. For second order conditions we further assume that P is not too convex:

Assumption 1 *For all $q > 0$ with $P(q) > 0$: $P''(q)q + 2P'(q) < 0$.*[2] *Moreover, $\lim_{q \to 0} P'(q)q = 0$.*

To evaluate utility and harm of output levels $(q_1, \dots, q_n)$ (which determine $(e_1, \dots, e_n)$) to the society, we assume to have a social welfare function W which is additively separable into consumers' net surplus, production cost, and damage from pollution, where the latter is given by a social damage function $S : \mathbb{R}_+ \times \mathbb{R}_+ \to \mathbb{R}_+$ which depends on aggregate emissions E and a damage parameter s. Employing the usual notation $S_1(E,s) := \frac{\partial S(E,s)}{\partial E}$ and so on, we make the following assumption.

Assumption 2 *o) S is at least twice continuously differentiable w. r. to E and s; in $(0,0)$ the right sided partial derivatives exist. i) $S(0,s) = 0\ \forall s \geq 0$. ii) $S(E,0) = 0\ \forall E \geq 0$. iii) $S_1(E,s) \geq 0\ \forall s > 0$ and strictly greater for $E > 0$. iv) $S_1(0,s) = S_1(E,0) = 0\ \forall E, s \geq 0$. v) $S_{11}(E,s) \geq 0\ \forall s > 0$ and strictly greater for $E > 0$. vi) $S_{12}(E,s) > 0\ \forall E > 0, s > 0$. vii) $\lim_{s \to \infty} S(E,s) = \lim_{s \to \infty} S_1(E,s) = \infty\ \forall E > 0$.*

[2] In terms of elasticity, the derivative of the inverse demand function has elasticity smaller than 2.

So, S is increasing and convex in E and marginal damage increases in s. Although s is an exogenous parameter of the model, parameterizing S via s allows us to characterize the social optimum as well as regulatory policies contingent on the damage function's steepness. Then W is given by

$$W(q_1,\ldots,q_n,s) \equiv \int_0^Q P(z)dz - S(E,s) - \sum_{i=1}^{n} c_i q_i \,. \tag{2.1}$$

In a dynamic framework, (2.1) can be interpreted as the *flow* value of welfare. The total discounted welfare in a time interval $[T_0, T_1]$ is then given by $\int_{T_0}^{T_1} W(q_1,\ldots,q_n,s)e^{-rt}dt$, provided that $(q_1,\ldots,q_n)$ remain constant for $t \in [T_0, T_1]$.

2.2 Perfect Competition, Social Optimum and its Implementation under Symmetry

In this section we assume that all the incumbent firms are alike owning the same technology (c_0, d_0). This may be the result of a former diffusion process. Under perfect competition the firms price at marginal cost such that aggregate output is $Q_{c_0} = D(c_0)$.[3] Due to the externality this outcome is clearly not efficient. The socially optimal output Q_0 rather satisfies

$$P(Q_0) = c_0 + d_0 S_1(d_0 Q_0, s)\,, \tag{2.2}$$

i.e., price equals private marginal cost plus social marginal damage. The optimal emission level is thus given by $E_0 = d_0 Q_0$.

Implementation by Taxes: It is well known from the literature that a perfectly informed government can enforce the social optimum by setting a Pigouvian tax τ per unit of emission equal to marginal social damage:

$$\tau = S_1(d_0 Q_0, s)\,. \tag{2.3}$$

Then the firms' marginal cost amount to $c_0 + \tau d_0$, and perfect competition leads to $p = c_0 + \tau d_0$, and $D(c_0 + \tau d_0) = Q_0$.

Implementation by Permits: As an alternative to a tax policy, the government could issue a number L of tradeable permits such that $L = E_0$, assuming that also the market for permits is perfectly competitive. This means that the firms behave as price takers, and they buy the permits just in time as they produce a corresponding unit of output. Thus no firm can preempt the market by buying all the other firms' permits in advance. This assumption is crucial for perfect competition. It stands in contrast to the recently developed noncompetitive models of permit trading in MØRCH VON DER FEHR [1993] and REQUATE [1993a,b].

If $\sigma(L)$ denotes the market price for permits, the firms' marginal costs are equal to $c_0 + \sigma(L)d_0$. The factor demand for permits, denoted by $L^D(\sigma)$, is thus given by $L^D(\sigma) := d_0 D(c_0 + \sigma d_0)$. Since D is downward sloping, so is $L^D(\sigma)$ as a function of σ. The supply of permits is completely inelastic and given by $L^S(\sigma) = E_0$. Hence, there exists a unique market clearing price equal to $\sigma_0 = S_1(E_0, s)$.

By virtue of the linear technology a permit regime in general generates capacity constraints. It could be argued that this leads to nonexistence of Nash-equilibria in pure strategies if one considers the market as a price setting game. Since we want to highlight perfect competition in this model, we assume an Arrow–Debreu world where consumers realize only the lowest price. Thus a firm faces no demand when pricing higher, and there is no need for a rationing rule in case that all the firms exhaust their capacities.[4]

The literature often distinguishes between *auctioned* permits and *free* permits. This distinction is somewhat misleading. In both regimes the price for permits is determined by supply and demand which are equal under both policies if firms are price takers. So there is auctioning actually in both regimes (also the market mechanism can be considered as an auction). Thus, there is no big difference in *how* the permits are allocated. The difference consists in final profits since under a system of *free* permits[5] the firms do not incur the cost of buying permits. For the most part of this paper we discuss auctioned permits, i.e., the firms do not own an initial endowment of those. This allows a better comparison to taxes. In section 4 we briefly address *free* permits.

2.3 The Social Value of Innovation

In this section we assume that one firm comes up with a new technology (c_I, d_I). As we will see, it does not matter in this model whether the innovating firm is an incumbent or an entrant. Before turning to the incentive to innovate under a tax or permit policy, we characterize the social optimum if the two types of technologies (c_0, d_0) and (c_I, d_I) were available. To make the analysis interesting we make

Assumption 3 . $d_I < d_0$ *and* $c_I > c_0$.

[3]The allocation among the firms may not be unique. If the customers split up equally, each firm has a market share of Q_0/n.

[4]This assumption can be justified by the limit result of ALLEN and HELLWIG [1986] who show that the market price converges in distribution to the competitive price in a Bertrand-Edgeworth price setting game if the number of firms becomes large.

[5]This is sometimes referred to as *grandfathering* (see TIETENBERG [1985]).

I.e., the innovator generates less pollutants per output but incurs a higher marginal cost.[6] Since we have constant marginal costs, and all the firms are alike apart from the innovator, we denote by q_0 the aggregate quantity produced by the conventional firms with technology (c_0, d_0), and by q_I the quantity produced by the innovator.

Then, the social planner has to solve the following program:

$$\max_{q_0, q_I} W(q_0, q_I, s) \equiv \max_{q_0, q_I} \int_0^{q_0+q_I} P(z)dz - S(d_0q_0 + d_Iq_I, s) - c_0q_0 - c_Iq_I \qquad (2.4)$$

s.t. $q_0 \geq 0$, $q_I \geq 0$. Let $(q_0(s), q_I(s))$ denote the solution of (2.4). Further let $Q_I(s) \equiv q_0(s) + q_I(s)$, and $E_I(s) \equiv d_0q_0(s) + d_Iq_I(s)$ denote the socially optimal aggregate output and emissions if the new technology is available. Finally we write $W(s) \equiv W(q_0(s), q_I(s), s)$. The following proposition yields the properties of the optimal solution:

Proposition 1 *Let*

$$\tilde{p} = \frac{d_0c_I - d_Ic_0}{d_0 - d_I} \qquad (2.5)$$

a) If $\tilde{p} \geq \bar{p}$, then for all $s \geq 0$ the new technology should not be introduced.
b) If $\tilde{p} < \bar{p}$, there are parameters $\underline{s}$ and $\bar{s}$, depending on c_0, c_I, d_0, d_I, with $0 < \underline{s} < \bar{s} \leq \infty$ ($\bar{s} < \infty$ iff $d_I > 0$) such that the solution of (2.4) is characterized by:

i) $\forall s \in [0, \underline{s}]$, we get $q_0(s) > 0$, $q_I(s) = 0$. $Q_I(s) = q_0(s)$ is decreasing in s, and

$$S_1(E(s), s) < \frac{c_I - c_0}{d_0 - d_I}.$$

ii) $\forall s \in (\underline{s}, \bar{s})$, we get $q_0(s) > 0$, $q_I(s) > 0$. Moreover, $q_0(s)$ is decreasing, $q_I(s)$ is increasing, $\tilde{Q} := q_0(s) + q_I(s)$ is constant in s, and $P(\tilde{Q}) = \tilde{p}$. Marginal pollution is given by

$$S_1(E(s), s) = \frac{c_I - c_0}{d_0 - d_I} \qquad (2.6)$$

iii) $\forall s \geq \bar{s}$, we get $q_0(s) = 0$, $q_I(s) > 0$. $Q_I(s) = q_I(s)$ is decreasing in s, and

$$S_1(E(s), s) > \frac{c_I - c_0}{d_0 - d_I}.$$

iv) Moreover, $Q_I(s)$, $E_I(s)$, and $W(s)$ are continuous, $E_I(s)$, and $W(s)$ are decreasing in s.

v) $\forall s > \underline{s}$ we have $Q_I(s) > Q_0(s)$.

vi) $\exists s^* > \bar{s}$ such that $E_I(s) < E_0(s)$ for $s < s^*$, $E_I(s) > E_0(s)$ for $s > s^*$, and $E_I(s^*) = E_0(s^*)$.

Note that, according to b.ii), $\tilde{p}$ is the social (i.e. the private plus the external) marginal cost of production if both firms produce. If this cost is greater than the choke off price $\bar{p}$ (part a)), the new technology should not be introduced for any damage function S. If $\tilde{p} < \bar{p}$ (part b)), and if the social damage from pollution is low, clearly the conventional lower private cost technologies should serve the whole market. For intermediate values of s, a *partial* innovation is socially desirable, and production should be shifted continuously from the old to the new technology as s increases, keeping total output constant. If social damage from pollution is sufficiently high, the old technology should be replaced completely by the new one. These properties are displayed in Figure 1. The parts a) and b), i)–iv) of Proposition 1 are derived by solving (2.4) taking into account the Kuhn–Tucker conditions with respect to the constraints $q_0 \geq 0$ and $q_I \geq 0$ (for details see REQUATE [1993a]). v) says that aggregate output does not fall through innovation. This is certainly not surprising. It may be surprising, however, that emissions do rise if the damage parameter is sufficiently high (vi). The intuition for this is as follows: since the only way to reduce pollution in this model is to reduce output, $Q_0(s)$ is close to zero if S is extremely steep. Since under the new technology one more unit of pollution generates much more units of output than before, the output ratio $Q_I(s)/Q_0(s)$ becomes relatively large, such that also $d_IQ_I(s) > d_0Q_0(s)$. To put it another way, for s very large and $Q_0(s)$ very small, marginal utility of consumption is close to its maximum, such that after innovation the gain received from more consumption more than outweighs the damage from one more unit of pollution. v) and vi) will be proved in the appendix.

Figure 1 about here.

Finally we define the *social (flow) value of innovation* simply by the difference of the socially optimal welfare values after and before innovation:

$$\begin{aligned} V_{soc}(s) \equiv & \int_0^{q_0(s)+q_I(s)} P(z)dz - S(E_I(s), s) - c_0q_0(s) - c_Iq_I(s) \\ & - \int_0^{Q_0(s)} P(z)dz + S(E_0(s), s) + c_0Q_0(s) \end{aligned} \qquad (2.7)$$

3 Incentives to Innovate under Regulatory Policies

If $c_I > c_0$, and if there is no regulation, firms have no incentive to come up with a new discovered or developed technology. This is different if the industry is regulated by

[6] The other cases are more are less trivial.

taxes or permits. Throughout this analysis we will assume that the status quo is such that the regulator has established *optimal* tax or permit policies with respect to the conventional technology (c_0, d_0). Although this is not completely realistic (see MARIN's [1991] criticism), this assumption serves as a useful benchmark. As an alternative we could assume that the regulator simply wants to meet a certain emission target. Our analysis includes this case, as Theorem 1' at the end of this section shows. Hence the *status quo tax* is given by (2.3), the *status quo number of permits* is $L_0(s) = E_0(s)$. Of course, these policies might not be optimal any longer as soon as some firm has come up with a new technology. On the other hand, by at least two reasons it is reasonable to assume that regulating authorities are not able to adjust tax or permit policies immediately. First, it takes time for the regulator to gather information necessary for calculating the new optimal levels. Secondly, decision processes take time in most democratically governed societies (not only there).

Further it is assumed that the new technology will not immediately be adopted by other firms. (Under Bertrand competition, it is enough that one other firm has adopted the new technology.) We handle diffusion on a very abstract level here. The process of diffusion is not relevant and not the issue of this paper. There may be even several different ways one may think of: First, the new technology is available on the market. For instance, firms could purchase a scrubber in order to reduce emissions of SO_2. There could be uncertainty, however, about cost and performance of the new technology. Now one pioneering firm might have an informational advantage or might be courageous and successful in introducing the new technology first. If it turns out that the scrubber works properly and provides a cost advantage, other firms may follow. Under perfect competition an incumbent competitor is even forced to follow quickly since otherwise he would lose all demand if the innovator can produce at a lower cost under the current policy. According to this story the time period where the innovator faces a comparative advantage is likely to be small. Secondly, we could imagine that the innovating firm itself develops the new technology which can be protected by a patent for some time. In this case, the comparative advantage is likely to last relatively long.

Hence, we study first the incentive to innovate before taxes or permits have been adjusted and before the technology has been adopted by any other firm. This will be done in section 3.2. Later in section 3.3 we consider optimal agency response and the innovator's value of the new technology after ratcheting. If we talk of the firm's *value* of the innovation this is to be interpreted as the *flow value* at each instant of time. In contrast, the *total value* of innovation, received by integrating over time, will we briefly considered in section 3.4. But before we do all this, we need some auxiliary results.

3.1 Some Cornerstone Lemmas

Let x be a tax rate or a permit price. An innovating firm has a cost advantage if and only if

$$c_I + xd_I < c_0 + xd_0 \,. \tag{3.1}$$

Since the innovator is the only firm enjoying the cost advantage we cannot assume that the outcome will be perfectly competitive. Rather, the conventional firms will take the role of a competitive fringe. Here we follow DASGUPTA AND STIGLITZ [1980] by employing the standard Bertrand model which predicts that the innovator charges the limit price $c_0 + xd_0$ and gets the whole demand. Denote the tax or permit price for which the two firms' marginal costs break even by

$$\tau^{be} \equiv \sigma^{be} \equiv x^{be} \equiv \frac{c_I - c_0}{d_0 - d_I} \,.$$

Further, we denote by $p_I^m(x)$ the innovator's monopoly price under a tax or a permit price x, and by $q_I^m(x) = D(p_I^m(x))$ the corresponding monopoly output. If the innovator's monopoly price $p_I^m(x)$ is smaller than the conventional firms' cost $c_0 + xd_0$, the innovation is called "drastic", following ARROW [1962]. Note carefully, however, that the concept of a *drastic* innovation is to be taken relatively to the current tax policy here. The following lemma states that the innovator engages in limit pricing for low taxes (permit prices), and in monopoly pricing for taxes (permit prices) sufficiently high.

Lemma 1 *There is a tax τ', or a permit price σ', respectively, with $\tau' \equiv \sigma' \equiv x'$ and $x^{be} < x' < (\bar{p} - c_0)/d_0$ such that*

$$p(x) = \begin{cases} c_0 + xd_0 & \text{for} \quad x^{be} < x \leq x' \,, \\ p_I^m(x) & \text{for} \quad x' \leq x < (\bar{p} - c_0)/d_0 \,. \end{cases}$$

Proof: See the appendix.

The profit of the innovator under limit pricing is then given by

$$\pi_I(x) = [c_0 - c_I + x(d_0 - d_I)]Q_0(s) \,, \tag{3.2}$$

and under monopoly pricing by

$$\pi_I(x) = [p_I^m(x) - (c_I + d_I x)]q_I^m(x) \,. \tag{3.3}$$

The next lemma drives the main results of this paper. It states that the profit of the innovator as a function of the tax or permit price has a unique maximum.

Lemma 2 *There is a unique tax rate τ^*, or permit price σ^*, respectively, with $\tau^* \equiv \sigma^* \equiv x^*$ and $x^{be} < x^* \leq x'$, which maximizes $\pi_I(\cdot)$, where x' is given by Lemma 1.*

Proof: See the appendix.

Figure 2 about here.

Whereas in a "partial partial" model a tax increase only increases costs and lowers profits for both, the innovator and the non-innovators, here raising the tax (or permit price) above the break-even level increases the cost advantage of the innovator and thus *increases* his profits up to some x^*. For $x \geq x'$, the firm engages in monopoly pricing. In that region a rising tax increases the monopolist's costs, and thus clearly *decreases* his profits. If x^* is strictly less than x', the profit falls even under limit pricing for $x \in (x^*, x')$.

In the last two lemmata the permit price was taken as fixed. The third lemma tells us what price will settle after innovation, contingent on the number of permits. It is important to note that we still assume that all the firms including the innovator behave competitively on the permit market. The timing is as follows. The innovator makes a decision on the output market by announcing a price for the commodity. Then both types of firms bid up the price for permits on the permit market. When the innovator makes his decision on the output market, he takes into account that the permits market clears. Thus the innovator cannot preempt the market by buying all the permits in advance.

Denote by $\overline{L} \equiv E_I(\underline{s})$, and $\underline{L} \equiv E_I(\overline{s})$ the socially optimal emission levels for $s = \underline{s}$, and $s = \overline{s}$, respectively, after the new technology is available.

Lemma 3 *For each supply of permits L there is a unique competitive equilibrium on the permits market given by a market clearing price $\sigma_I(L)$, and an allocation of permits $(e_0(L), e_I(L))$ among the conventional firms and the innovator,[7] satisfying:*

i) there is $L' < \underline{L}$ such that for limit pricing $\sigma_I(L)$ is given by

$$\sigma_I(L) = \begin{cases} \frac{P(L/d_0)-c_0}{d_0} < \sigma^{be} & \text{for } L > \overline{L}, \\ \sigma^{be} & \text{for } L \in [\underline{L}, \overline{L}], \\ \frac{P(L/d_I)-c_0}{d_0} > \sigma^{be} & \text{for } L \in [L', \underline{L}], \end{cases} \tag{3.4}$$

and for monopoly pricing, i.e. for $L \leq L'$,[8] by the solution of

$$\frac{L}{d_I} = q^m(c_I + \sigma(L)d_I) \ , \tag{3.5}$$

[7] Again, the allocation of permits among the conventional firms is not unique.
[8] At L' the innovator switches from limit to monopoly pricing.

ii) $(e_0(L), e_I(L))$ satisfy

$$\begin{array}{llll} e_0(L) = L & , \ e_I(L) = 0 & , & \text{if } L > \overline{L} \ , \\ e_0(L) = d_0 \frac{L - d_I \tilde{Q}}{d_0 - d_I} & , \ e_I(L) = d_I \frac{d_0 \tilde{Q} - L}{d_0 - d_I} & , & \text{if } L \in [\underline{L}, \overline{L}] \ , \\ e_0(L) = 0 & , \ e_I(L) = L & , & \text{if } L < \underline{L} \ . \end{array}$$

Proof: See the appendix.

The lemma says that if the supply of permits is sufficiently large, i.e. $L > \overline{L}$, its price stays below σ^{be} such that the innovator cannot compete with the conventional firms. Those buy all the permits. For L between $\underline{L}$ and $\overline{L}$, the price settles at σ^{be} such that the marginal costs of both types of firms break even. It may be surprising at first glance that the permit price is constant for a whole interval of permit quotas. However, similar to the social optimum (cf. Proposition 1.b.ii, the marginal cost of both types of firms break even for a whole interval of different allocations of emissions (production). Note further that for $L \in [\underline{L}, \overline{L}]$ the allocation of permits and thus the allocation of production among the firms varies with the number of permits. Although several allocations of permits are consistent with $\sigma = \sigma^{be}$, and the *price* cannot enforce a unique allocation of permits for $L \in (\underline{L}, \overline{L})$, market clearing yields a unique matching between supply and demand of permits. For $L \geq \overline{L}$ the conventional firms hold all the permits, the innovator gets none. As L falls, the number of permits held by the innovator rises. Finally, if L does not exceed $\underline{L}$, the innovator gets all the permits, engaging in limit pricing for $L \geq L'$, and in monopoly pricing for $L \leq L'$ (equ. (3.5)). These properties are displayed in Figure 3.

Figure 3 about here.

3.2 Incentives to Innovate and Welfare Implications under the Original Tax or Permit Policies

In this section we investigate the incentive to innovate and look at welfare implications when taxes and number of permits are on the optimal levels before innovation, and only one firm has access to the new technology.

3.2.1 Innovation under Taxes

Denote by $\tau_0(s)$ the optimal tax policy w.r. to the conventional technology, satisfying equation (2.3).

MILLIMAN and PRINCE [1989] have been heavily criticized by MARIN [1989] for assuming optimal regulation. MARIN argues that this is not realistic, and that the levels of taxes or permits were set rather arbitrarily. This, of course, is not true, either. Even if policy tools are not set optimally in general, they can often be considered as resulting from a compromise between environmental departments which prefer high emission taxes and industrial departments which prefer no or low emission taxes. Certainly lobbying, sometimes even bribing, plays an important role.

However, since we want to investigate whether the value of innovation under regulatory policy possibly exceeds or falls short of the social value innovation, we need a criterion to measure this. Hence, as a benchmark, it is reasonable to look what happens if the conventional industry is regulated optimally. Thus in the next two subsections it is assumed that conventional industry is regulated by the optimal emission tax or by the optimal number of permits, respectively.

Proposition 2 *Under $\tau_0(s)$, the competitive firm's value of innovation is positive if and only if $\tilde{p} < \overline{p}$, and $s > \underline{s}$. The innovative firm serves the whole market.*

Proof: See the appendix.

In other words, if there is no fixed cost of innovation, the firm will innovate if and only if a partial *or* complete innovation is socially desirable. This seems to be good news.[9] However, the innovator serves the *whole* market after innovation, irrespective of this being desirable, i.e. $s \geq \overline{s}$, or not, i.e. $s \in (\underline{s}, \overline{s})$. This is bad news since it implies that innovation always leads to a decrease of welfare if s is sufficiently close to $\underline{s}$. For, by Proposition 1 the innovator should only produce a small share if s is greater but close to $\underline{s}$. We state this by

Corollary 1 *If $\tilde{p} < \overline{p}$, and $s > \underline{s}$ but s sufficiently small, decentralized innovation leads to a decrease in welfare under the original tax $\tau_0(s)$.*

One can show by examples that it is not possible to be more precise than this, i.e. if s is large, welfare may rise *or* fall through decentralized innovation via taxes. It may even be the case that welfare decreases through innovation for each s.

3.2.2 Innovation under Permits

Here we consider the incentive to innovate under the originally optimal permit policy $L_0(s) = d_0 Q_0(s)$. In contrast to an emission tax the market price for permits will change immediately after innovation since the demand for permits changes even before a policy maker adjusts the number of permits. Lemma 3 implies that the value to innovate is negative for $L > \overline{L}$, zero for $L \in [\underline{L}, \overline{L}]$, and positive for $L < \overline{L}$. This in turn yields the main argument for the following result.

[9]Note that it does not matter whether the innovating firm is one of the incumbents or an entrant.

Proposition 3 *Under the original permit policy $L_0(s)$,*

i) the value to innovate is negative for $s < \underline{s}$,

ii) there is an $\tilde{s} > \overline{s}$ such that the incentive to innovate is zero for $s \in [\underline{s}, \tilde{s}]$, and

iii) it is positive for $s > \tilde{s}$.

Proof: Prop. 1.b.vi) implies that there is $\tilde{s} > \overline{s}$ such that $L_0(s) = E_0(s) \in [\underline{L}, \overline{L}]$ for all $s \in [\underline{s}, \tilde{s}]$ (see Figure 4). By Lemma 3 the price for permits is smaller, equal, or greater than σ^{be} as $L_0(s) > \overline{L}$, $L_0(s) \in [\underline{L}, \overline{L}]$, or $L_0(s) < \underline{L}$, respectively (see Figure 3). Q.E.D.

Figure 4 about here.

This result is bad news, since for a considerable range of parameters the innovator's value of the new technology is zero, although partial or even complete innovation is desirable from a social point of view. In particular, if research and development of the innovation requires a fixed cost, the innovation will not take place for $s \in (\underline{s}, \tilde{s})$. In case that no fixed costs are incurred, or if the set up costs are already incorporated in c_I (c_I could imply the cost to install capacity of the new technology), and if we further assume that a firm will innovate whenever it is indifferent between innovating or not, we get (with some reservations) good news with the following result:

Proposition 4 *Under the original permit policy $L_0(s)$ welfare increases through decentralized innovation for all $s > \underline{s}$.*

Proof: See the appendix.

3.2.3 Comparing the Values of Innovation

We now compare the firm's different values of innovation under the two policies. In the following we refer to the innovating firm's value as the *private* value of innovation. Assure that the innovator's flow values of innovation, denoted by $V_f^{tax,0}(s)$ and $V_f^{per,0}(s)$ for taxes and permits, respectively, are given by its profits, i.e. by $V_f^{tax,0}(s) \equiv \pi_I(\tau_0(s))$ under the original tax $\tau_0(s)$, and by $V_f^{per,0}(s) \equiv \pi_I(\sigma_I(L_0(s)))$ under the original number of permits $L_0(s)$.

Proposition 5 *Under the original tax $\tau_0(s)$, or under the original number of permits $L_0(s)$, respectively, we have*

$$0 = V_f^{per,0}(s) < V_{soc}(s) < V_f^{tax,0}(s) \tag{3.6}$$

if $s > \underline{s}$ but sufficiently small.

So sufficiently close to $\underline{s}$, under permits a competitive firm's value to innovate is smaller than the social value. Under taxes, on the other hand, it exceeds the social value. This shows interestingly that the DASGUPTA–STIGLITZ [1980b] result, claiming that the social value of a cost reducing innovation always exceeds the firm's value, fails to hold if externalities are internalized by Pigouvian taxes.

Proof of Proposition 5: The first inequality follows from Propositions 1 and 3. For the second inequality it is sufficient to show that at $\underline{s}$ for the right sided derivatives $dV_{soc}(\underline{s})/ds < dV_f^{tax,0}(\underline{s})/ds$ holds. The envelope theorem implies $dV_{soc}(\underline{s})/ds = 0$. In the appendix we verify that $dV_f^{tax,0}(\underline{s})/ds > 0$. Q.E.D.

The next theorem shows, however, that the relationship (3.6) does not hold in general.

Theorem 1 *Suppose the original policies $\tau_0(\cdot)$ and $L_0(\cdot)$ are still valid. Then there exists an interval (s_a, s_b) of damage parameters, with $s_a > \bar{s}$,[10] such that*

i) for all $s \in (s_a, s_b)$ the private value of innovation is higher under permits than under taxes, i.e.

$$V_f^{tax}(s) < V_f^{per}(s) . \tag{3.7}$$

ii) for all $s \in (\bar{s}, s_a)$, and for all $s > s_b$ we have

$$V_f^{tax}(s) > V_f^{per}(s) . \tag{3.8}$$

iii) For $s = s_a$, and $s = s_b$ the values coincide.

I would like to emphasize that this result cannot be obtained without paying attention to the output market. In particular part ii) stands in stark contrast to the findings in [MP]. Before proving the result the following lemma is helpful. It states that after innovation the permit price falls below the original tax whenever the innovator engages in limit pricing. For s sufficiently high, on the other hand, the price for permits, $\sigma_I(L_0(s))$, exceeds the original tax and thus also rises compared to the permit price before innovation.

Lemma 4 *i) For all s for which the innovator engages in limit pricing under the original tax policy $\tau_0(s)$ we have:*

$$\sigma_I(L_0(s)) < \tau_0(s) . \tag{3.9}$$

ii) There is $s^* > \bar{s}$ such that for all $s \geq s^*$:

$$\sigma_I(L_0(s)) > \tau_0(s) . \tag{3.10}$$

[10] This means that complete innovation is optimal on (s_a, s_b).

Proof: See the appendix.

Part i) of the lemma is certainly not surprising. If there is less demand for permits, one should expect the price to go down (note that $\tau_0(s)$ is also the price for permits before innovation). But what does the price drive upwards if s is large and, hence, $L_0(s)$ is small? Actually the explanation is simple: For s sufficiently high the innovation is drastic, and the innovator engages in monopoly pricing, which is lower than $c_0 + d_0\tau_0(s)$. But if the monopolistic innovator wants to produce significantly more than the whole industry did before innovation, he possibly needs more permits. But there are no more. This causes the price for permits to go up.

Proof of Theorem 1: Recall that τ' is the tax rate where the innovator switches from limit to monopoly pricing. Let $s' = \tau_0^{-1}(\tau')$. Further recall that τ^* $(= \sigma^*)$ is the tax (permit price) which maximizes the innovator's profit. Let $s^* := \tau_0^{-1}(\tau^*)$, and $s^{**} := (\sigma_I \circ L_0)^{-1}(\sigma^*)$ be the corresponding damage parameters. By Lemma 4.i we have $\sigma_I(L_0(s')) < \tau_0(s')$. By virtue of Lemma 2 we get $s^* < s^{**}$ and $\bar{s} < s^* \leq s'$. Hence $\pi_I(\tau_0(s))$ adopts its unique maximum at s^*, whereas $\pi_I(\sigma_I(L_0(s)))$ adopts its unique maximum at s^{**}. Hence $\pi_I(\sigma_I(L_0(s^{**}))) > \pi_I(\tau_0(s^{**}))$, and by continuity of $\sigma(\cdot)$, $\tau(\cdot)$, and $\pi_I(\cdot)$ we have $\pi_I(\sigma_I(L_0(s))) > \pi_I(\tau_0(s))$ for a whole interval. Since by Proposition 5 we have $\pi_I(\sigma_I(L_0(s))) < \pi_I(\tau_0(s))$ for s sufficiently close to $\bar{s}$, the functions $\pi_I(\sigma_I(L_0(s)))$ and $\pi_I(\tau_0(s))$ must intersect at some point, say s_a. By part b) of Lemma 4 we have $\sigma_I(L_0(s)) > \tau_0(s)$ for s sufficiently high. For those s the innovator engages in monopoly pricing. Thus the marginal cost under permits is greater than under taxes and, therefore, the profit of the (monopolistic) innovator is lower under permits than under taxes for those sufficiently high values of s. By continuity, $\pi_I(\sigma_I(L_0(s)))$ and $\pi_I(\tau_0(s))$ must intersect at a second point, say s_b. This completes the proof. The argument is illustrated in Figure 5. Q.E.D.

Figure 5 about here.

Running several examples on the computer, I found that for s sufficiently high the *social* value of innovation always exceeds the *firm's* value to innovate under taxes (and by Theorem 1.ii, also under permits). I was not able to prove that this holds true in general. Hence I can only make the following conjecture.

Conjecture 1 *If the social damage function is sufficiently steep, the social value of innovation exceeds the firm's value to innovate under either policy.*

Although standard in the literature of partial analysis, some more applied economists refuse to determine optimal emission levels via social damage functions. They rather prefer to work with exogenously given emission targets. They argue that damage functions in terms of money cannot be determined, but that scientists should determine emission targets which are just on the limit to be acceptable (for example a critical pollution level of a lake just below the level where all life dies). Although I do not share this view at all, one can carry over the result of Theorem 1 to a model with exogenously given emission targets:

Theorem 1': [Charges and Standards Approach] Suppose E_0 is a given emission target. Let $\tilde{\tau}_0(E_0)$ denote the tax which implements this target before innovation, and $L_0 = E_0$ the corresponding number of permits. Then there are always targets $E_1 > E_2 > E_3$, such that i) for all $E > E_1$ the private value of innovation is negative under either policy, ii) for $L \in (E_1, E_2)$ and for all $E < E_3$ the private value of innovation is higher under taxes than under permits, iii) for all $E \in (E_2, E_3)$ the value is higher under permits than under taxes, iv) for E_2 and E_3 the values coincide.

To see this simply take for each E_0 the damage function for which $E_0(s)$ is the corresponding optimal emission level.

3.3 Optimal Agency Response

In this section we examine the properties of the optimally ratcheted tax, and the corresponding number of permits, respectively. In particular, we ask whether the new tax implements the social optimum, whether the tax decreases, as one would expect from [MP], or whether it rises. The same we do for permits. After that, we will investigate the innovator's gains or losses from adjustment.

3.3.1 Optimal Tax Adjustment before Diffusion

Since we assume that agency response and diffusion happens after some time lags, we denote by T_{IL} the length of the *institutional time lag*, and by T_{DL} the length of the *time lag for diffusion*. These lags are exogenously given.

Let us suppose first that $T_{IL} < T_{DL}$, that is, the regulator may react on the innovation before the new technology has been adopted by other firms.

Denote by $\tau_I(s)$ the new optimal tax *after innovation* but *before diffusion*. If innovation is not drastic relatively to the new tax, for $s > \bar{s}$, $\tau_I(s)$ satisfies

$$c_0 + \tau_I(s)d_0 = P(Q_I(s)) . \tag{3.11}$$

Otherwise it is implicitly given by

$$p^m(\tau_I(s)) = P(Q_I(s)) . \tag{3.12}$$

Proposition 6 *Let $T_{IL} < T_{DL}$. Then $\forall s > \bar{s}$, $\tau_I(s)$ implements the social optimum.*

Proof: See the appendix.

For $s \in (\underline{s}, \bar{s})$, marginal damage is constant in social optimum, and hence the optimal tax had to be constant. Thus the conventional firms' and the innovator's marginal cost would coincide. If we assume that customers split up equally among the firms in case that all the firms charge the same (competitive) price, the social optimum cannot be achieved in general for all $s \in (\underline{s}, \bar{s})$. Here the first best policy could be approximated by charging $\tau^{be} - \varepsilon$ for s close to $\underline{s}$, charging $\tau^{be} + \varepsilon$ for s close to $\bar{s}$, and τ^{be} for s somewhere in the interior of $(\underline{s}, \bar{s})$ (see Figure 7 below). This is similar to regulation of asymmetric Bertrand duopoly, investigated in REQUATE [1993b].

If agency response can be expected after some time, the innovating firm is not only interested in the current value of innovation, but has to take into account also the future value after taxes have been adjusted. Hence we investigate first whether the tax will rise or fall when being optimally adjusted. The intuition may suggest that a tax cut is always welfare improving since the innovator generates less pollutants per unit of output. At least this has been found in [MP]. In this model this is not true in general as the following proposition shows.

Proposition 7 *Suppose $s > \bar{s}$.*

i) If the innovation is not drastic w. r. to $\tau_0(s)$, i.e., $p_I^m(\tau_0(s)) > c_0 + \tau_0(s)d_0$, the tax <u>decreases</u> through adjustment, in particular:

$$\tau_0(s) > \tau_I(s) > \tau^{be} . \tag{3.13}$$

ii) There is always an $s^* > \bar{s}$ such that for all $s > s^*$ we have $\tau_I(s) > \tau_0(s)$, and the innovation is drastic w. r. to the original and the adjusted tax.

Proof: See the appendix.

The second part is certainly surprising and contrasts from [MP]. The intuition of this is the following. The higher is s the greater is the difference between the conventional firms' cost, $c_0 + \tau_0(s)d_0$, and the innovator's monopoly price. Thus the innovator produces more than optimal under the old tax. Hence, to restore the social optimum the tax has to be increased.

The converse of ii) does not hold, that is, a drastic innovation will not necessarily lead to a tax increase. (For a numerical example see REQUATE [1993c].)

3.3.2 The firm's value of innovation after tax adjustment:

In the "partial partial" analysis of [MP] the innovating firm always gains from a tax cut. In our model the conventional industry acts as a competitive fringe. Hence a tax cut not only lowers the innovator's cost but also the limit price $c_0 + \tau d_0$, and thus may be unfavorable for the innovator. On the other hand, a tax cut is clearly favorable for the innovator under a drastic innovation since lower taxes lead to lower marginal costs and thus increase monopoly profits. The next result characterizes the regions where the innovator gains from ratcheting, and where it does not.

Theorem 2 *There exists an interval (s_c, s_d), with $s_c > \bar{s}$ for which optimal tax adjustment is favorable for the innovator. In this region ratcheting results in a tax cut. On the other hand, for all $s \in (\underline{s}, s_c)$ and for all $s > s_d$, tax adjustment decreases the innovator's profit. (For $s = s_c$ and $s = s_d$ profits will not be affected.) Moreover, the innovator engages in limit pricing in a neighborhood of s_c, and in monopoly pricing in a neighborhood of s_d.*

Figure 6 about here.

The proof is driven by Lemma 2 and Proposition 7 and goes similarly to the one of Theorem 1. Hence I only sketch the main idea which can be captured from Figure 6: Tax adjustment leads to a tax cut for s not too high. Each tax policy $\tau_0(s)$ and $\tau_I(s)$ adopts the profit maximizing tax rate τ^* for different values of s, hence the maxima of $\pi_I(\tau_0(s))$ and $\pi_I(\tau_I(s))$ must be adopted for different values of s. Thus the two curves $\pi_I(\tau_0(\cdot))$ and $\pi_I(\tau_I(\cdot))$ must intersect once in the range of limit pricing. Since $\tau_0(\cdot)$ and $\tau_I(\cdot)$ intersect in the range of monopoly pricing, $\pi_I(\tau_0(\cdot))$ and $\pi_I(\tau_I(\cdot))$ must intersect a second time for high values of s.

Also this result cannot be obtained without taking into account the output market. It follows that the political conclusion from [MP] that innovators are likely to engage in lobbying for a tax cut, cannot be drawn in general! For a certain range of parameters – where innovation is non drastic – the innovator, if asked, would oppose optimal agency response, although this would result in a tax cut.[11] On the other hand, there is always a range of parameters where the innovator favors ratcheting, and where limit or monopoly pricing may happen. Not surprisingly, the innovator would oppose agency response which results in raising taxes in the range of parameters where the innovation is drastic, and he/she enjoys monopoly power.

3.3.3 Tax Adjustment after Diffusion

Finally we briefly consider the case where $T_{IL} \geq T_{DL}$, or where there is a second adjustment process after diffusion. Suppose the new technology has been adopted by the other firms, or at least by two firms, such that perfect competition has been restored. Denote by $Q_{I,D}(s)$ the socially optimal output if only the firms with technology (c_I, d_I)

[11] Thus the all American phrase "*I hate taxes*" has to be reconsidered.

produce. Then for each s there is clearly always a tax $\tau_{I,D}(s)$, optimal relatively to the diffused technology, satisfying

$$\tau_{I,D}(s) = S_1(d_I Q_{I,D}(s), s)\,. \qquad (3.14)$$

Assure, however, that complete diffusion is socially optimal only if $s > \bar{s}$. For $s \in (\underline{s}, \bar{s})$, Proposition 1 is still valid and only partial innovation would be optimal. Firms, however, have to switch technologies under an emission tax if they want to stay in the market. Note further that for all $s > \bar{s}$ we have $\tau_{ID}(s) > \tau_I(s)$. This is because the innovator as the only firm always wants to price higher than the competitive price before diffusion. Hence, the regulating tax has to be lower than under perfect competition. Interestingly, Proposition 7.ii implies that the new "competitive tax" $\tau_{I,D}(s)$ will be higher than the former tax $\tau_0(s)$ if s is sufficiently high. This is an other conclusion not to be obtained without paying attention to the output market. It follows that, if the institutional lag is shorter than the time of diffusion, and if s is large, the tax will rise twice, whenever optimally adjusted. For s sufficiently close to $\bar{s}$, on the other hand, first the tax goes down after innovation but before diffusion, and then it rises again (see Figure 7).

Figure 7 about here.

3.3.4 Adjusting the Number of Permits

In contrast to taxes, permits have to be adjusted only once as the following result shows:

Proposition 8 *If there is no fixed cost of innovation, and the firms innovate whenever they are indifferent between doing so or not, then, regardless of $T_{IL} < T_{DL}$ or $T_{IL} \geq T_{DL}$, for all $s \geq 0$ the social optimum is implemented by issuing a number of permits equal to the socially optimal pollution level, i.e. $L_I(s) = E_I(s)$.*

Proof: The proof follows almost immediately from Lemma 3. Q.E.D.

Note that before diffusion, for $s > \bar{s}$, only the innovator serves the whole market, possibly by charging the monopoly price whereas after diffusion perfect competition rules the market. Why do nevertheless both market structures induce the social optimum? The answer is *"by virtue of the market price for permits"*. Since the supply of permits is constant, the market price for permits always induces the monopolistic innovator to supply the right quantity.

We saw in the last section that tax adjustment may result in a rise as well as in a decrease of taxes. General wisdom from "partial partial" analysis teaches that the number of permits has to be cut down after innovation. Propositions 1.vi and 8, however, imply immediately that the adjusted permit policy, denoted by $L_I(s)$, may go up *or* down:

Corollary 2 *There is an s^0 such that $L_I(s) < L_0(s)$ ($L_I(s) = L_0(s)$, $L_I(s) > L_0(s)$), as $s < s^0$ ($s = s^0$, $s > s^0$). The innovator engages in monopoly pricing for $s \geq s^0$.*

3.3.5 Gains for the Innovator from Permit Adjustment

In comparison to taxes, the results under permits are (almost) reversed. Since the permit price equals σ^{be} for $s \in [\underline{s}, \bar{s}]$ by Lemma 3, the profit of the innovator continues to be zero for those s. Since for s greater but sufficiently close to $\bar{s}$, the number of permits will be reduced such that the price rises, the innovator gains from ratcheting. For large s, on the other hand, the number of permits is to be increased such that the price goes down, which is good for the monopolistic innovator. Note that for $s > \bar{s}$ taxes as well as permits implement the social optimum, and the market price for permits, denoted by $\sigma_I(L_I(s))$, and the adjusted tax, $\tau_I(s)$, must be equal. Hence, after optimal agency response, the profit of the innovator under permits is the same as under taxes. Thus, by arguing similarly as in Theorem 2 we get:

Theorem 3 *There exists an interval (s_e, s_f), with $s_e > \bar{s}$, for which optimal permit adjustment <u>decreases</u> the innovator's profit. In this region ratcheting results in decreasing the number of permits. On the other hand, for all $s \in (\bar{s}, s_e)$, and for all $s > s_f$ permit adjustment <u>increases</u> the innovator's profit. (For $s = s_e$ and $s = s_f$ profits will not be affected by adjustment.) Moreover, the innovator engages in limit pricing in a neighborhood of s_e, and in monopoly pricing in a neighborhood of s_f. (See Figure 8.)*

Note that s_f coincides with s_d from Theorem 1 whereas s_e does not necessarily coincide with s_c.

Figure 8 about here.

3.3.6 Ranking of the Values of Innovation after Ratcheting

Since after ratcheting but before diffusion, the new optimal tax $\tau_I(s)$ and the market price for permits $\sigma_I(L_I(s))$ coincide as we have seen in the last paragraph, also the values of innovation coincide. Since those are zero (or almost zero under taxes) for all $s \in (\underline{s}, \bar{s})$, after ratcheting the private value of innovation under taxes and permits falls short of the social value for all $s \in (\underline{s}, \bar{s})$, and also for some $s > \bar{s}$ but sufficiently close to $\bar{s}$. Whether this holds true also for very large values of s, we do not know.

After diffusion, trivially the private values of innovation under taxes and permits are zero, and hence they also coincide. This is so because perfect competition cancels all the profits.

3.4 The Total Values of Innovation

For the firms the *total* value of innovation rather than the *flow* value matters if they have to decide about introducing a new technology. To calculate this value we have to integrate over time, discounting future profits by some rate r. Thus the social value is given by

$$\tilde{V}_{soc}(s) \equiv \int_0^\infty V_{soc}(s)e^{-rt}dt \equiv V_{soc}(s)/r \tag{3.15}$$

where we assume that further innovations happen so far in the future that we can neglect their impact on welfare. In case where $T_{IL} < T_{DL}$, e.g. if the innovation is protected by a patent and ratcheting happens before the patent expires, the firm's total value of innovation under policy $pol \in \{taxes, permits\}$ is given by:

$$\begin{aligned} \tilde{V}_f^{pol}(s) &\equiv \int_0^{T_{IL}} V_f^{pol,0}(s)e^{-rt}dt + \int_{T_{IL}}^{T_{DL}} V_f^{pol,I}(s)e^{-rt}dt \\ &= \frac{1}{r}\left(\left[1 - e^{-rT_{IL}}\right] V_f^{pol,0}(s) + \left[e^{-rT_{IL}} - e^{-rT_{DL}}\right] V_f^{pol,I}(s)\right) \end{aligned} \tag{3.16}$$

where $V_f^{pol,0}$ and $V_f^{pol,I}$ denote the firms' flow values before and after agency response, respectively, but before diffusion. If $T_{DL} < T_{IL}$, the value reduces to $\tilde{V}_f^{pol}(s) = \int_0^{T_{DL}} V_f^{pol,0}(s)e^{-rt}dt$. Since the flow values differ only before agency response and diffusion, Theorem 1 carries over to the total values $\tilde{V}_{soc}$ and $\tilde{V}_f^{pol}$!

Proposition 5 holds for T_{IL} and T_{DL} sufficiently large. In other words, if s is large enough such that innovation is (at least partially) desirable but not too large, and if possible R&D costs of the new technology do not exceed the social value, there are always adjustment lags T_{IL}, and patent lengths T_{DL} such that, under the tax policy a firm invests into innovation if this is desirable. Under permits, on the other hand, a firm *never* develops a new technology if this incurs a positive fixed cost and if $s \leq \bar{s}$.

In case that the value to innovate under taxes *exceeds* the social value *before* ratcheting and *falls short* of it *after* ratcheting, one might be tempted to endogenize the reaction lag T_{IL}, and maybe also the patent length T_{DL}, such that the innovator's value coincides with the social value. On the other hand, once the innovation has been introduced, it is always optimal to adjust taxes or permits as fast as possible. Knowing this, firms, therefore, might never innovate although this would be socially optimal. Thus one might suggest the government to better committing itself to rules rather than pursuing a discrete adjustment policy (cf. KYDLAND and PRESCOTT [1977]). This, however, is not a first best solution, either. It would be better to adjust as early as possible and to reimburse the innovating firm for its fixed costs of innovation.[12] These considerations suggest that further research is necessary to explore more sophisticated incentive schemes in order to induce technological change.

4 Conclusions

We analyzed a model where a competitive industry with polluting firms is regulated by either effluent taxes or auctioned permits. One firm develops a new, cleaner technology. We investigated the incentives to innovate under either policy, assuming that neither diffusion nor policy adjustment happens immediately. We saw that taxes provide higher an incentive to innovate than permits for damage functions sufficiently flat *or* sufficiently steep. But there is also an intermediate range of slopes where permits always yield higher an incentive to innovate than taxes.

We further investigated the impact of agency response. Tax adjustment results in a tax cut for innovations that are non drastic. For drastic innovations the tax may rise if the damage function is sufficiently steep. Similarly, the number of permits to be issued has to be reduced for non drastic innovations. For drastic innovations and marginal damage sufficiently high it has to be increased.

Also the innovating firms' interest in optimal agency response is ambiguous. For damage functions sufficiently flat *or* sufficiently high the innovator opposes optimal agency response under taxes, but would support it under permits. For an intermediate range of slopes the opposite is true.

We concentrated on auctioned permits only because a comparison to taxes under *free* permits is a bit cumbersome, for, the firms' additional profit depends crucially on the number of incumbent firms. Since the price for permits goes down through innovation for s sufficiently small, a firm's incentive to innovate is smaller under *free* permits than under auctioned permits. By Lemma 4.ii, on the other hand, the price for permits goes up for s sufficiently large. Hence for a certain range of parameters where the innovation is drastic, the incentive to innovate under *free* permits is even higher than under auctioned ones. The difference between those two permit regimes becomes small, however, as the number of firms goes to infinity since than the initial endowment of permits goes to zero.

Higher incentives to innovate under taxes, raising taxes, issuing more permits after ratcheting, and firms hating tax cuts, all these results cannot be derived in the

[12] This, of course, causes moral hazard problems under asymmetric information, since the innovator is inclined to overstate its cost.

"partial partial" frameworks neglecting the output market.

Certainly, not all of the qualifications in the model presented here are completely satisfactory yet, leaving room for further research. Confining to linear technologies, for instance, might be criticized by at least two reasons. First it is not always realistic to assume that the innovator is able to serve the whole market. This criticism, however, in the same way applies to the Arrow–Dasgupta–Stiglitz' model, and to the best of my knowledge there is no literature so far concerned with incentives to innovate under increasing marginal costs. Secondly, firms may be able to reduce emissions by incurring further costs without affecting the output level. Assuming abatement technologies of this type, however, also results in abandoning the assumption of constant marginal costs. The difficulty here is to find a simple way to classify innovative technologies that are nonlinear (or the corresponding nonlinear reduced cost functions). There is no straightforward ranking from low to high costs, or low to high emissions as done here. I am currently working on this problem. Finally, what I called *optimal* agency response is only optimal in a static sense but may not be optimal in a dynamic framework. Our results suggest that intertemporal incentive schemes other than pure tax or permit regimes might prove more appropriate in a dynamic framework. Also this I have to leave for future research.

A Appendix

Proof of Proposition 1 v),vi): Ad v): Since $Q_I(\underline{s}) = Q_0(\underline{s})$, and $Q_0(s)$ is strictly decreasing,[13] ii) implies that $Q_I(s) = \tilde{Q} > Q_0(s)$ for $s \in (\underline{s}, \bar{s})$. Now let $s > \bar{s}$. Then we write $W_I(Q_0(s)) := \int_0^{Q_0(s)} P(z)dz - S(d_I Q_0(s), s) - c_I Q_0(s)$. Differentiating yields $\partial W_I(Q_0(s))/\partial Q_0(s) = P(Q_0(s)) - d_I S_1(d_I Q_0(s), s) - c_I > c_0 - c_I + d_0 S_1(d_0 Q_0(s), s) - d_I S_1(d_I Q_0(s), s) > c_0 - c_I + (d_0 - d_I) S_1(d_0 Q_0(s), s) > 0$, where the second equality follows by substituting $P(Q_0(s))$ from (2.2).

Ad vi): i) implies that $E_I(s) = E_0(s)$ for $s \leq \underline{s}$. Let $\tilde{s}$ be defined by $E_0(\tilde{s}) = E_I(\tilde{s}) = d_I \tilde{Q}$. Then we get $S_1(d_I \tilde{Q}, \tilde{s}) = (P(d_I \tilde{Q}/d_0) - c_0)/d_0 > (\tilde{p} - c_0)/d_0 = (c_I - c_0)/(d_0 - d_I)$. Since $S_{12} > 0$, and $L_0(s)$ is strictly decreasing, we obtain $\tilde{s} > \bar{s}$ implying $E_0(\bar{s}) > E_I(\bar{s})$. Now we show that $E_I(s) > E_0(s)$ for s sufficiently high. Abusing notation we write $W_I(E, s) := \int_0^{E/d_I} P(z)dz - S(E, s) - \frac{c_I}{d_I} E$. Hence

$$\partial W_I(E_0(s))/(\partial E) = P(E_0(s)/d_I) - d_I S_1(E_0(s), s) - c_I)/d_I \qquad (A.17)$$

If $E_0(s) > E_I(s)$ for all s, then the term in braces would always be negative. Further, $E_0(s)$ satisfies: $S_1(E_0(s), s) = \left[P\left(\frac{E_0(s)}{d_0}\right) - c_0\right]/d_0$. Substituting this into (A.17) yields

$$P(E_0(s)/d_I) - (d_I/d_0) \cdot P(E_0(s)/d_0) - c_0 - c_I < 0$$

$$\Leftrightarrow \quad d_0 P(E_0(s)/d_I) - d_I P(E_0(s)/d_0) < d_0 c_I - d_I c_0 = \tilde{p}(d_0 - d_I) \qquad (A.18)$$

But if s goes to infinity, $E_0(s)$ goes to zero. Thus $P(E_0(s))/d_j$ goes to $\bar{p}$ for $j = 0, I$. Hence, the L.H.S. of (A.18) converges to $(d_0 - d_I)\bar{p}$, contradicting $\bar{p} > \tilde{p}$. Q.E.D.

Proof of Lemma 1: Denote $\bar{\tau} := (\bar{p} - c_0)/d_0$. By definition of τ' we have $c_0 + \tau' d_0 = P(q_I^m(\tau'))$. On the other hand, $P(q_I^m(\tau'))$ satisfies the f.o.c. for monopoly: $P(q_I^m) + P'(q_I^m) q_I^m - c_I - \tau' d_I = 0$. Combining we get $c_0 + \tau' d_0 + P'(q_I^m) q_I - c_I - \tau' d_I = 0$, thus $\tau' = (c_I - c_0 - P'(q_I^m) q_I)/(d_0 - d_I) > (c_I - c_0)/(d_0 - d_I)$. Since $p(\tau)$ is increasing in τ, it remains to show that $p^m(\tau) < c_0 + \tau d_0$ for τ sufficiently high but smaller than $(\bar{p} - c_0)/d_0$. Note that $\bar{p} = c_0 + \bar{\tau} d_0 > c_I + \bar{\tau} d_I$. Since for any marginal cost $c < \bar{p}$ the monopoly price is smaller than $\bar{p}$, we get $p^m(\bar{\tau}) < \bar{p} = c_0 + \bar{\tau} d_0$. By continuity of $p^m(\cdot)$ we also get $p^m(\tau) < c_0 + \tau d_0$ for τ smaller than but sufficiently close to $\bar{\tau}$. Q.E.D.

Proof of Lemma 2: For τ close to τ^{be}, the innovator engages in limit pricing. Hence the profit function is $\pi(\tau) = [c_0 - c_I + \tau(d_0 - d_I)] D(c_0 + \tau d_0)$. Differentiating w.r. to. τ yields

$$\pi'(\tau) = (d_0 - d_I) D(c_0 + \tau d_0) + (c_0 - c_I + \tau[d_0 - d_I]) d_0 D'(c_0 + \tau d_0) .$$

[13]To see this, differentiate (2.2) w.r.to s, yielding $Q_0' = \frac{d_0 S_{12}}{P' - d_0^2 S_{11}} < 0$.

This gives $\pi(\tau^{be}) = 0$ and $\pi'(\tau^{be}) > 0$. The second derivative is

$$\pi''(\tau) = d_0(d_0 - d_I)[2D'(c_0 + \tau d_0) + [\tau - (c_I - c_0)/(d_0 - d_I)] d_0 D''(c_0 + \tau d_0)] .$$

If $D''(p(\tau)) < 0$, the second derivative is negative. If not, note that Assumption 1 implies $pD''(p) + 2D'(p) < 0$. Note further that $\tau = (p - c_0)/d_0$, and $(d_0 c_I - d_I c_0)/(d_0 - d_I) = \tilde{p}$, where $\tilde{p}$ is defined in Proposition 1. This yields:

$$\begin{aligned} \pi''(\tau) &= d_0(d_0 - d_I)[2D'(p(\tau)) + (p - \tilde{p}) D''(p(\tau))] \\ &< d_0(d_0 - d_I)[2D'(p(\tau)) + pD''(p(\tau))] < 0 . \end{aligned}$$

Hence the profit function is concave for $\tau < \tau'$ and continuous at τ'. On the other hand, the profit function is clearly decreasing for $\tau > \tau'$, since there we move within the monopoly region. Hence there must be a unique maximum $\tau^* \in (\tau^{be}, \tau']$ possibly at τ'. Note that π need not be differentiable at τ'. Q.E.D.

Proof of Lemma 3: We proceed indirectly. Suppose first $\sigma < \sigma^{be}$. Then $c_I + \sigma d_I > c_0 + \sigma d_0$, and the conventional firms serve the whole market, thus holding all the permits. This implies $L = d_0 D(c_0 + \sigma d_0) > d_0 D(c_0 + \sigma^{be} d_0) = \bar{L}$. Now let $\sigma = \sigma^{be}$. This yields $c_I + \sigma d_I = c_0 + \sigma d_0 = \tilde{p}$. Thus the conventional firms and the innovator share the market. Let α, with $0 \leq \alpha \leq 1$, and $1 - \alpha$ be the market shares of the conventional firms and the innovator, respectively. Then we get for the permits: $L = d_0 \alpha \tilde{Q} + d_I(1 - \alpha)\tilde{Q} = (d_0 - d_I)\alpha \tilde{Q} + d_I \tilde{Q}$. This implies $e_0(L) = d_0 \alpha \tilde{Q} = d_0 \frac{L - d_I \tilde{Q}}{d_0 - d_I}$. This term is nonnegative for $L \geq d_I \tilde{Q} = \underline{L}$. This implies $e_I(L) = L - e_0(L) = d_I(d_0 \tilde{Q} - L)/(d_0 - d_I)$, which is nonnegative for $L \leq d_0 \tilde{Q} = \bar{L}$. Finally assume $\sigma > \sigma^{be}$. Then $c_I + \sigma d_I < c_0 + \sigma d_0$, and the innovator engages in limit pricing for σ greater but close to σ^{be} (clearly, the innovator's monopoly price is greater than the limit price, if the conventional firms' and the innovator's cost are close). Hence $L = d_I D(c_0 + \sigma d_0) < d_I D(c_0 + \sigma^{be} d_0) = d_I \tilde{Q} = \underline{L}$. By Lemma 1 there must be a permit price σ' where the limit (commodity) price equals the monopoly price, i.e. $c_0 + \sigma' d_0 = p^m(c_I + \sigma' d_I)$. Since limit and monopoly prices are strictly increasing in σ there must be L' such that $L' = d_I D(c_0 + \sigma' d_0) = d_I q^m(c_I + \sigma' d_I)$ and $L = d_I D(c_0 + \sigma d_0)$ for $\underline{L} > L > L'$, and $L = d_I q^m(c_I + \sigma' d_I)$ for $L < L'$. This completes the proof. Q.E.D.

Proof of Proposition 2: Proposition 1 implies $S_1(d_0 Q_0(\underline{s}), \underline{s}) = (c_I - c_0)/(d_0 - d_I)$. Since $Q_0(s)$ is strictly increasing it follows that $\tau_0 = S_1(d_0 Q_0(s), s) > (c_I - c_0)/(d_0 - d_I)$. Q.E.D.

Proof of Proposition 4: case a) $s < \tilde{s}$ (recall that $\tilde{s}$ is defined by $L_0(\tilde{s}) = \underline{L}$), implying $L_0(s) \in (\underline{L}, \bar{L})$. Employing Lemma 3, we get: $W_I(L) - W_0(L) =$

$$\int_0^{\tilde{Q}} P(z)dz - S(L, s) - \left[c_0 \frac{L - d_I \tilde{Q}}{d_0 - d_I} + c_I \frac{d_0 \tilde{Q} - L}{d_0 - d_I}\right] - \int_0^{L/d_0} P(z)dz + S(L, s) - c_0 \frac{L}{d_0}$$

$$= \int_{L/d_0}^{\tilde{Q}} P(z)dz - \tilde{p}\left[\tilde{Q} - \frac{L}{d_0}\right] > 0 \, .$$

The last equality follows after some manipulations and by virtue of $(d_0 c_I - d_I c_0)/(d_0 - d_I) = \tilde{p}$. The last inequality follows since $\tilde{p} = \min_{z \in [L/d_0, \tilde{Q}]} P(z)$.

case b) $s \geq \tilde{s}$, implying $L_0(s) \leq \underline{L}$. Then $W_I(L) - W_0(L) =$

$$\int_{L/d_0}^{L/d_I} P(z)dz - \left[\frac{c_I}{d_I} - \frac{c_0}{d_0}\right] L = \int_{L/d_0}^{L/d_I} P(z)dz - \tilde{p}\frac{d_0 - d_I}{d_0 d_I} L >$$

$$P\left(\frac{L}{d_I}\right)\left[\frac{L}{d_I} - \frac{L}{d_0}\right] - \tilde{p}\frac{d_0 - d_I}{d_0 d_I} L = L\left[\frac{1}{d_I} - \frac{1}{d_0}\right]\left(P\left(\frac{L}{d_I}\right) - \tilde{p}\right) > 0 \quad \text{Q.E.D.}$$

Proof of Proposition 5: Write $G(s) \equiv V_I^{tax}(s)$. Using $\tau_0(s) = S_1(Q_0(s), s) = (P(Q_0(s)) - c_0)/d_0$, we can rewrite (3.2) into $G(s) = \frac{d_0 - d_I}{d_0}(P(Q_0(s)) - \tilde{p})Q_0(s)$. Differentiating we get $G'(s) = \frac{d_0 - d_I}{d_0}(P'(Q_0(s), s)Q_0(s) + P(Q_0(s)) - \tilde{p})Q_0'(s)$. Since $Q_0(\underline{s}) = \tilde{Q}$, and thus $P(Q_0(\underline{s})) = \tilde{p}$, we get $G'(\underline{s}) = \frac{d_0 - d_I}{d_0} P'(Q_0(\underline{s}))Q_0(\underline{s})Q_0'(\underline{s}) > 0$. Q.E.D.

Proof of Lemma 4: i) For $s \in [\underline{s}, \tilde{s}]$ we know from Lemma 3 that $\sigma_I(L_0(s)) = \sigma^{be} < \tau_0(s)$. For $s > \tilde{s}$ we have $\tau_0(s) = S_1(d_0 Q_0(s), s) = [P(L/d_0) - c_0]/d_0 > [P(L/d_I) - c_0]/d_0 = \sigma(L_0(s))$, where the last equality follows from Lemma 3.

ii) For s sufficiently high, $\tau_0(s)$ and $L_0(s)$ are such that the innovator engages in monopoly pricing. Hence the permit price satisfies

$$P(L_0(s)/d_I) + P'(L_0(s)/d_I) \cdot (L_0(s)/d_I) = c_I + \sigma d_I \, .$$

Since $\tau_0(s) = [P(Q_0(s)) - c_0]/d_0$, the permit price σ is greater than the tax if

$$\sigma = \frac{P\left(\frac{d_0}{d_I}Q_0(s)\right) - c_I + P'\left(\frac{L_0(s)}{d_I}\right)\frac{L_0(s)}{d_I}}{d_I} > \frac{P(Q_0(s)) - c_0}{d_0}$$

$$\Leftrightarrow \quad \frac{P\left(\frac{d_0}{d_I}Q_0(s)\right)}{d_I} - \frac{P(Q_0(s))}{d_0} + P'\left(\frac{L_0(s)}{d_I}\right)\frac{L_0(s)}{d_I^2} > \frac{c_I}{d_I} - \frac{c_0}{d_0} = \tilde{p}\frac{d_0 - d_I}{d_0 d_I}$$

$$\Leftrightarrow \quad d_0 P\left(\frac{d_0}{d_I}Q_0(s)\right) - d_I P(Q_0(s)) + P'\left(\frac{L_0(s)}{d_I}\right)\frac{d_0 L_0(s)}{d_I} > \tilde{p}(d_0 - d_I)$$

Now for s increasing, $L_0(s)$ as well as $Q_0(s)$ go to zero such that under Assumption 1 the LHS goes to $\overline{p}(d_0 - d_I)$, which is clearly greater than the RHS since $\overline{p} > \tilde{p}$.

Proof of Proposition 6: By Lemma 1, $\tau_I(s)$ has to satisfy (3.11) for values of s greater but sufficiently close to $\overline{s}$. This holds up to some $s' = (\tau_I)^{-1}(\tau')$. For $s \geq s'$, $\tau_I(s)$ satisfies (3.12). We are done if we can show that $\tau_I(s) > \tau^{be}$, since then none of the conventional firms interferes. Indeed, close to $\overline{s}$, $\tau_I(s)$ satisfies $c_0 + \tau_I(s)d_0 = P(Q_I(s)) = c_I + d_I S_1(d_I Q_I(s), s) > c_I + d_I\tau^{be} = c_0 + d_0\tau^{be}$, where $S_1(d_I Q_I(s), s) > \tau^{be}$ follows from Proposition 1.b.iii). Since $p(\tau)$ is continuous at τ', and τ is increasing by virtue of (3.11) and (3.12), it follows that $\tau_I(s) > \tau^{be}$. Q.E.D.

Proof of Proposition 7: ad i): Note that in this case the innovator sets $Q_I(\tau) = D(c_0 + \tau d_0)$ and that $Q_I(\tau_0(s)) = Q_0(s)$. Then we get

$$W^I(\tau_0(s), s) = \int_0^{Q_0(s)} P(z)dz - S(d_I Q_0(s), s) - c_I Q_0(s) \, .$$

Differentiating this expression with respect to the tax yields:

$$\partial W(\tau_0(s), s)/\partial\tau = [c_0 + \tau_0(s)d_0 - d_I S_1(d_I Q_0(s), s) - c_I] \cdot Q_I'(\tau_0(s)) \, .$$

Since $Q_I'(\tau)$ is clearly negative for $Q_I(\tau) > 0$, it suffices to concentrate on the term in brackets. But since $\tau_0(s) = S_1(d_0 Q_0(s), s) > S_1(d_I Q_0(s), s)$, the term in brackets is greater than $c_0 - c_I + \tau_0(s)[d_0 - d_I]$ which in turn is greater than zero by virtue of $\tau_0(s) > [c_I - c_0]/[d_0 - d_I]$. Q.E.D.

ad ii): Observe that $\lim_{E \to 0} S_1(E, s) = 0$ implies that $\forall s \geq 0$ we get $\tau_0(s) < (\overline{p} - c_0)/d_0$ (there is always some production). By Lemma 1 there exists an s sufficiently large such that $p^m(\tau_0(s)) < c_0 + \tau_0 d_0$. Now consider the change in welfare if we raise the tax at $\tau = \tau_0(s)$:

$$\partial W(\tau_0(s), s)/\partial\tau = [p_I^m(\tau_0(s)) - d_I S_1(d_I q_I^m(\tau_0(s)), s) - c_I] \cdot q_I^{m\prime}(\tau_0(s)) \, .$$

Again, $q_I^{m\prime}(\tau)$ is clearly negative. To show that the term in brackets becomes negative for s sufficiently large, observe that $\tau_0(s)$ converges to $(\overline{p} - c_0)/d_0$ if s goes to infinity. Hence the innovator's cost converge to $c_I + d_I(\overline{p} - c_0)/d_0 < \overline{p}$ (this follows from rearranging $\tilde{p} < \overline{p}$). Hence the monopoly price $p_I^m(\tau_0(s))$ is always bounded away from $\overline{p}$ which in turn implies that the monopoly output $q_I^m(\tau_0(s))$ is always bounded away from zero. Since $p_I^m(\tau_0(s)) - c_I$ is bounded by $\overline{p} - c_I$, and since by Assumption 2.vii), $S_1(E, s)$ becomes arbitrarily large for s sufficiently large, the term in brackets becomes negative for s sufficiently large. That the innovation is drastic w. r. to the original tax follows immediately from part i). That it remains drastic under the new tax follows from Lemma 1. Q.E.D.

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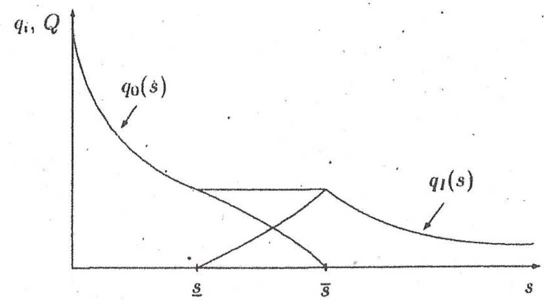

Figure 1: The socially optimal allocation of quantities.

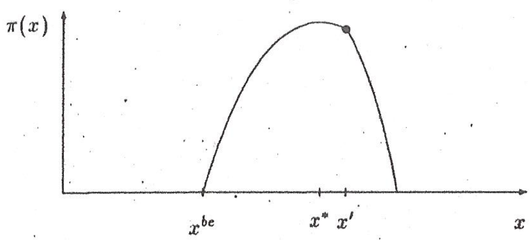

Figure 2: The innovator's profit as a function of the tax, or permit price.

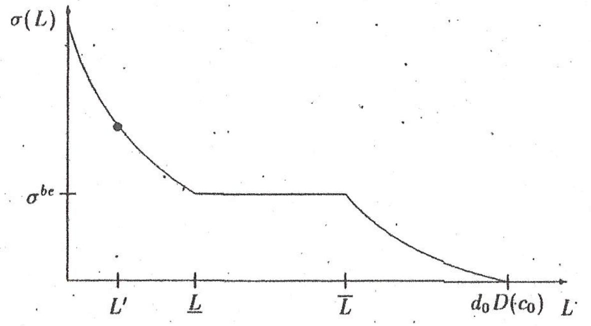

Figure 3: The price for permits after innovation

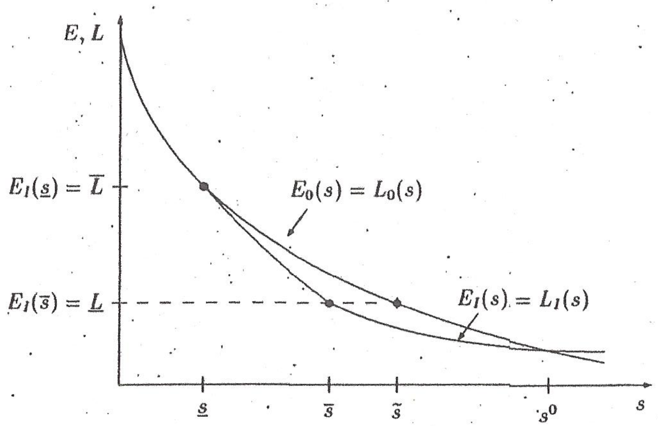

Figure 4: The optimal aggregate emissions (= optimal permit policy) before and after innovation.

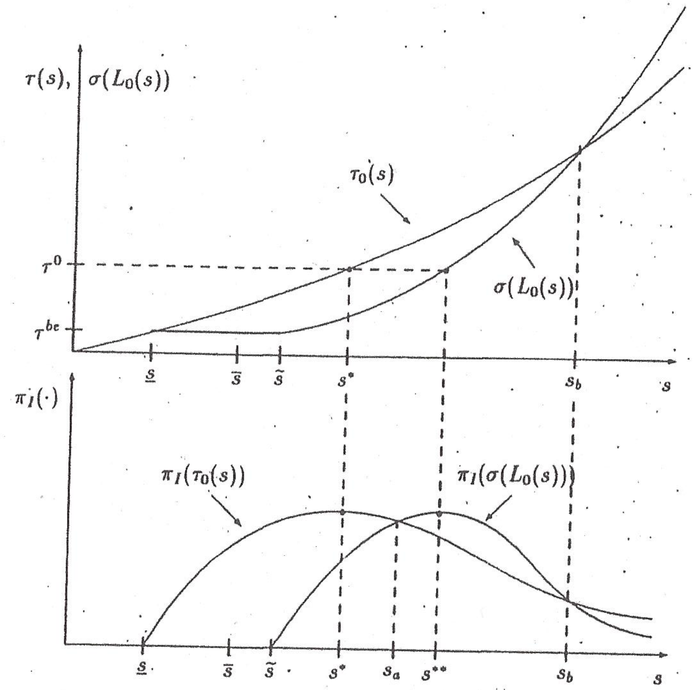

Figure 5: The innovator's profit before agency response and diffusion under taxes and permits.

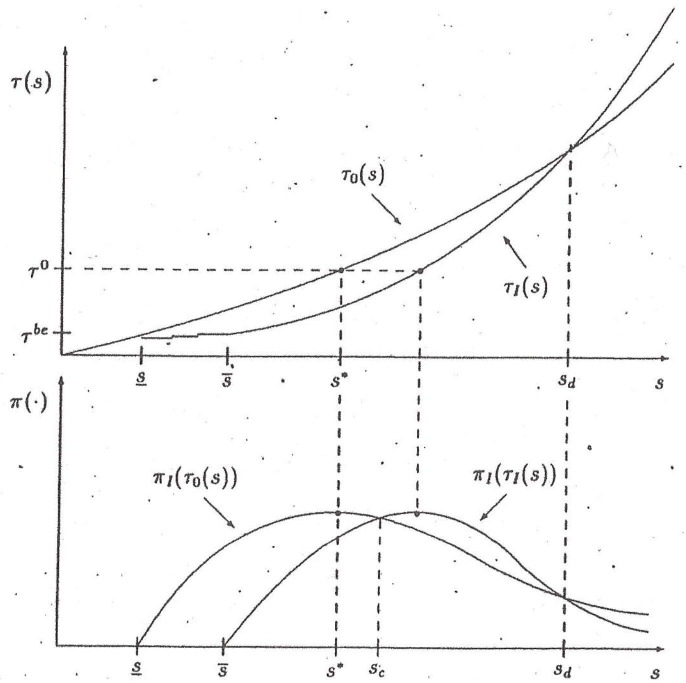

Figure 6: The innovator's profit before and after tax adjustment.

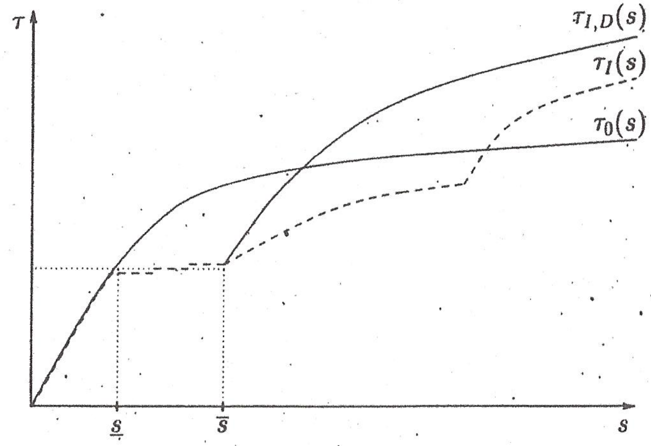

Figure 7: The different tax policies before and after diffusion and adjustment.

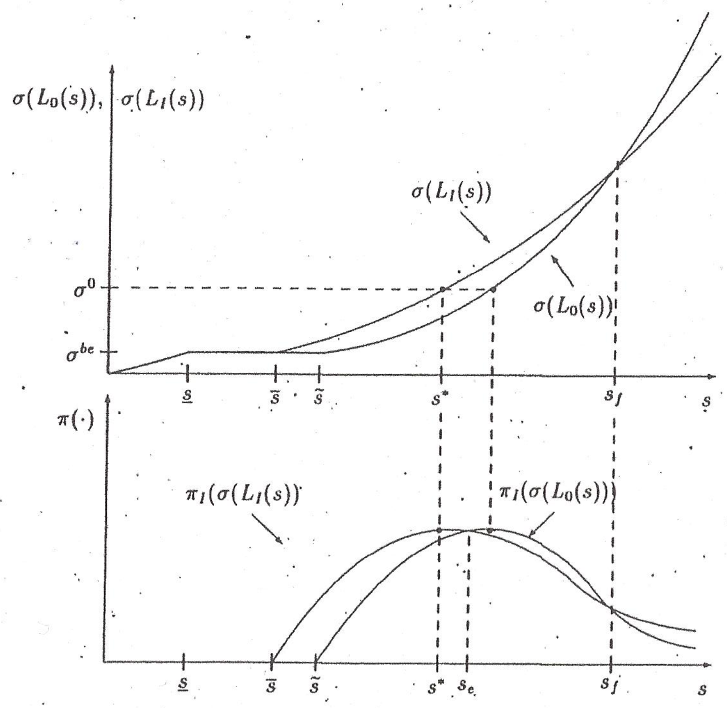

Figure 8: The innovator's profit under permits before and after agency response.