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The Merits of New Pollutants and How to Get Them When Patents Are Granted

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Abstract

The performance of market based environmental regulation is affected by patents and vice versa. This interaction is studied for a new type of innovation where new technologies reduce emissions of a specific pollutant but at the same time cause a new type of damage. A robust finding is that the efficiency of permits is affected by monopoly pricing of the patent-holding firm. This result carries over to other types of innovation. Taxes are inefficient if technologies produce perfect substitutes and share all scarce inputs. Moreover, the optimal tax on pollution might be negative.

JEL classification: Q55; L5; H23; O3

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1 Introduction

In the pursuit of a sustainable economy, innovation has a crucial role to play. Inducing technological progress that reduces damage to the environment per unit of output is at the heart of modern environmental policy. Hence, the dynamic performance of environmental regulation depends both on the incentives it creates to adopt existing advanced technologies (Milliman and Prince 1989, Jung et al. 1996, Requate and Unold 2003) and on the degree to which they stimulate R&D.[1]

The latter link so far has been explored only by a small number of papers. In a two-period, competitive output market model Laffont and Tirole (1996) study a very specific type of innovation where the new technology is perfectly clean. In this situation permits achieve static efficiency but completely expropriate the patent holding firm if the government can adjust policy after innovation has occurred. This type of analysis has been extended by Denicolò (1999). He considers a more general type of innovation where the new technology still emits pollution but has a lower emission-output ratio. Since private costs of production are assumed to be the same, the new technology is strictly superior to the established one. For the case without pre-commitment by the government and an exogenous quality of innovation he establishes the following results: Both taxes and permits implement the static first best allocation and induce positive and identical R&D incentives.[2] Fischer et al. (2003) concentrate on inflexible policies but informally confirm the equivalence result if the government is able to adjust regulation in the post-innovation period. In a recent paper, Requate (2005a) studies a situation with heterogeneous firms where partial adoption is socially optimal. In the case where policy adjustment is possible he finds that neither taxes nor permits are able to implement the static first best allocation due to monopoly pricing by the patent holding firm. Moreover, the two instruments are no longer equivalent. This contrasts the case of pure adoption, i.e. without patents, where permits always implement the optimal mix while taxes create multiple equilibria of which only one is efficient (Requate and Unold 2003). The literature has so far focused on very specific types of innovation and both static and dynamic efficiency of market based instruments is under debate.

The present paper contributes on the one hand by introducing a new type of innovation into the literature and thereby complementing the existing papers. On the other hand, it is shown that some of the results found carry over to the existing literature and qualify previous findings.

All previously mentioned papers have in common that the innovation process considered is vertical: Goods and pollutants produced by new tech-

[1] See Requate (2005b) for a recent review.

[2] The case considered by Laffont and Tirole (1996) is a special case where the equivalence still holds but research incentives are zero.

nologies are identical to those produced by old technologies, though emissions per unit of output are lower. Hence, unless the installation of the new technology involves real costs or firm heterogeneity (as in Requate (2005a)) complete adoption is optimal.

In practice, however, new technologies are often associated with new threats to the natural environment and human health. The development of technologies that reduce or eliminate existing types of pollution while causing new types of damages is frequently more realistic. In what follows, this type of innovation is referred to as horizontal environmental innovation. If the damages caused by established and new pollution types are sufficiently diverse as not to interfere with each other horizontal environmental innovation is nonetheless desirable. Given that marginal damages of each emission type are increasing, a mix of pollutants reduces marginal damages and enhances welfare.

Horizontal environmental innovation is very common. Most end-of-pipe technologies fit into this category. In automobiles catalytic converters reduce emissions of hydrocarbons and carbon monoxide but at the cost of higher sulphur oxide concentrations (Tietenberg 1992). Hydrocarbons are precursors of low level ozone, carbon monoxide is poisonous to humans and sulphur oxides cause acid rain. Scrubbers and electrostatic precipitators remove lead and particulate matter (PM) from exhaust air by converting them into waste water or solids.[3] Harrison and Antweiler (2003) find that the Canadian industry has made extensive use of end-of-pipe solutions and that significant shifts in the composition of pollution has occurred during the nineties.

In addition to end-of-pipe technologies, a number of innovations altering the production process itself or allowing input substitution constitute a horizontal environmental innovation. Chlorofluorocarbons (CFCs) blamed for the depletion of the ozone layer were once introduced to abandon their poisonous predecessors used in refrigeration. The Montreal Protocol effectively banning CFC production induced intensive research in substitutes such as so called HCFCs.[4] Although their ozone depleting potential is much lower than that of CFC, some (e.g. HCFC-123) are suspected to cause cancer and decay products like trifluoroacetic acid are toxic to humans and plants. Other examples include petrol and diesel engines used in cars, chlorine[5] and energy production.

Despite its practical importance, horizontal environmental innovation has received little attention in the economics literature so far. Moslener and Lange (2004) compare the prospects of a new technology with initially uncertain environmental effects to an established one that causes well known

[3]See Greenstone (2003)
[4]The-Economist (1992)
[5]See Snyder et al. (2003)

damages. Necessary and sufficient conditions for a new polluting technology to be desirable have recently been derived by Winkler (2005). Both Moslener and Lange (2004) as well as Winkler (2005) concentrate on socially optimal solutions. There is also a related growth literature where technologies using different environmental resources compete (Chakravorty et al. 1997) or innovation creates a new damage (Bretschger and Smulders 2001). However, the optimal mix of different damages that is central to horizontal environmental innovation is not considered.

In the tradition of Laffont and Tirole (1996), Denicolò (1999) and Requate (2005a) the present paper studies how taxes, permits and patents perform in regulating externalities and stimulating research, respectively. In contrast to the previous literature, this is done in the case of horizontal environmental innovation. However, some results have also important implications for vertical environmental innovation. The analysis concentrates on static post-innovation efficiency and the research incentives created. Explicit welfare rankings of instruments are not possible in the general framework used.

The remainder of this paper is organized as follows. Section 2 sets up the model. The social optimum is derived in Section 3. Section 4 analyzes permits, while taxes are treated in Section 5. Section 6 compares the performance of instruments. The last section concludes.

2 The Model

As in Denicolò (1999), consider two succeeding periods in a competitive market for a non-durable consumption or intermediate good Y. In the first period only one production technology, denoted by the subscript 1, is available. If the research firm successfully engages in R&D, a second technology, denoted by the subscript 2, producing a perfect substitute to Y and emitting a second type of pollution becomes available in period 2.[6] In Section 5.2 the assumption of perfect substitutes is relaxed for a special case. The market's downward sloping inverse demand function in each period is

$$P = P(Y)$$

where $Y = Y_1 + Y_2$ is the sum of technologies output.

Individual firms have U-shaped cost functions and are assumed to be small. Entry into the market is free. The industry's aggregate cost function is

$$C(Y_1, Y_2) = \bar{C}_1(Y_1, Y_2) \cdot Y_1 + \bar{C}_2(Y_1, Y_2) \cdot Y_2$$

[6] The assumption of perfect substitutes is realistic if the new technology is an end-of-pipe equipment or as far as consumers do not care about the origin of the electricity they use, the type of refrigant that cools their food and the type of fuel used by their cars.

where $\bar{C}_i\,(Y_1, Y_2)$ are non-negative and non-decreasing in both arguments and $\frac{\partial \bar{C}_i}{\partial Y_i} \geq \frac{\partial \bar{C}_j}{\partial Y_i}$. Hence, a marginal increase in output of the own technology increases average costs at least as much as a marginal increase in output of the other technology.

Each technology i emits pollution as a joint product at a constant ratio to output Y_i. Technology 1 - the established one - produces only emissions of type 1. The new technology 2 emits less or no of emission type 1 per unit of output and - this point is central to this paper - emissions of type 2. The social damage function D is assumed to be of the following form

$$D(Y_1, Y_2) = D_1(Y_1 + \alpha \cdot Y_2) + D_2(Y_2) \quad \text{with} \quad 0 \leq \alpha < 1$$

where both D_1 and D_2 are increasing and convex. α is an exogenous parameter indicating by how much technology 2 is cleaner than technology 1 with respect to emissions of type 1. In a richer game, the research firm can be expected to have some influence - but also uncertainty - on α. In what follows, it is assumed that the type of the new technology is common knowledge and not subject to strategic consideration by the research firm. By adding D_1 and D_2 the environmental damages of emission types are assumed to be independent, i.e. they do not increase or offset the damage done by the other pollutant. This form of the damage function allows on the one hand perfect horizontal environmental innovation where the new technology emits emissions of type 2 only (i.e. $\alpha = 0$) and on the other hand comes arbitrarily close to vertical environmental innovation if D_2 is very small compared to D_1.

In the first period research is undertaken by a single research firm. The probability ρ that the new technology is available in period 2 is a function of the effort R put into R&D (with $\rho(0) = 0, \rho' > 0, \rho'' < 0$ and $\lim_{R\to\infty} \rho(R) = 1$) measured by the firm's research expenditure.

In what follows, production and emission control in period 1 are ignored as there is nothing new to be learned. In the first period only the research investment matters. If the research firm's efforts remain fruitless, nothing changes compared to the first period. However, if research is successful and technology 2 becomes available in period 2 the timing is as in Laffont and Tirole (1996) and Denicolò (1999). After the new technology has arrived and its properties are known, the benevolent government adjusts regulation and grants a patent to the research firm. Regulatory adjustment is crucial as otherwise horizontal environmental innovation allows to substitute a regulated pollutant for a non-regulated one. This clearly creates inefficiencies (Devlin and Grafton 1994). Imitation of the new technology is ruled out. Second, the research firm chooses the level of the license fee f. Third, firms decide to enter or exit the industry, which technology to use and how much to produce.

The government uses either two pollutant specific tax rates or a permit quantity for each pollutant to regulate environmental externalities. The license fee set by the research firm is assumed to be linear in output of technology 2. As firms are small, identical and produce at an optimal scale this mimics a fixed fee per firm adopting the new technology.

3 The Social Optimum

The social planner's solution is presented as a benchmark in this section. Moreover, the last subsection indicates how it could be implemented using forms of research stimulation other than patents.

3.1 Static Post-Innovation Efficiency

Given the new technology has arrived, the social planner aims to achieve the static optimum in period 2. It therefore maximizes the static social welfare function

$$W_2(Y_1, Y_2) = \int_{l=0}^{Y} P(l)\mathrm{d}l - C(Y_1, Y_2) - D(Y_1, Y_2).$$

This yields the following first order conditions

$$P(Y) \le \frac{\partial C}{\partial Y_1}(Y_1, Y_2) + \frac{\partial D_1}{\partial Y_1}(Y_1 + \alpha Y_2) \quad (1)$$
$$P(Y) \le \frac{\partial C}{\partial Y_2}(Y_1, Y_2) + \frac{\partial D_1}{\partial Y_2}(Y_1 + \alpha Y_2) + \frac{\partial D_2}{\partial Y_2}(Y_2), \quad (2)$$

defining unique solutions Y_1^S and Y_2^S, where (1) is binding if technology 1 has a strictly positive output and (2) is binding if technology 2 has a strictly positive output.

The use of both technologies at the same time is desirable if and only if the marginal social cost of producing the first unit by technology i is smaller than the marginal social cost of producing the last unit by technology j. Formally

$$\frac{\partial C}{\partial Y_1}(Y_1^{ex}, 0) + \frac{\partial D_1}{\partial E_1}(Y_1^{ex}) > \frac{\partial C}{\partial Y_2}(Y_1^{ex}, 0) + \alpha \cdot \frac{\partial D_1}{\partial E_1}(Y_1^{ex}) + \frac{\partial D_2}{\partial Y_2}(0) \quad (3)$$
$$\frac{\partial C}{\partial Y_2}(0, Y_2^{ex}) + \alpha \cdot \frac{\partial D_1}{\partial E_1}(\alpha Y_2^{ex}) + \frac{\partial D_2}{\partial Y_2}(Y_2^{ex}) > \frac{\partial C}{\partial Y_1}(0, Y_2^{ex}) + \frac{\partial D_1}{\partial E_1}(\alpha Y_2^{ex}) \quad (4)$$

where $E_1 = Y_1 + \alpha Y_2$ are emissions of type 1 and Y_i^{ex} is the optimal output given technology i is used exclusively and therefore solves either

$$P(Y_1^{ex}) = \frac{\partial C}{\partial Y_1}(Y_1^{ex}, 0) + \frac{\partial D}{\partial Y_1^{ex}}(Y_1^{ex}, 0)$$

or

$$P(Y_2^{ex}) = \frac{\partial C}{\partial Y_2}(0, Y_2^{ex}) + \frac{\partial D}{\partial Y_2^{ex}}(0, Y_2^{ex}).$$

Condition (3) states that the established technology is not used exclusively in the static optimum and hence is a necessary condition for innovation to be desirable. Gains from innovation are more likely the lower the marginal costs of production of the first unit of output using technology 2, the more the emission of pollution type 1 is reduced (i.e. the lower α) and the lower the external damage caused by the first unit of emission of pollution type 2. Hence, for horizontal innovation to be beneficial the marginal damage of the first unit of pollution of type 2 is relevant. The steepness of the marginal damage curve is relevant in determining the size of the welfare gain only. If condition (4) is satisfied the new technology is not clean enough to be used exclusively in the static optimum. Note, that under perfect horizontal innovation, i.e. when $\alpha = 0$ conditions (3) and (4) are symmetric.

3.2 Dynamic Efficiency

Given that the social planner is able to implement the static optimum in the second period, how much should be spent on R&D in the first period? The optimization problem is

$$\max_R W = -R + \rho(R) \cdot \Delta W$$

where ΔW is the welfare gain of innovation in period 2 and discounting is ignored. The corresponding first order condition is

$$\rho'(R) \cdot \Delta W = 1. \tag{5}$$

This defines R^S where the marginal benefit from R&D equals the marginal cost of research. Conditions (1), (2) and (5) fully specify the social optimum under horizontal environmental innovation.

3.3 Implementation

In an ideal world where there are no restrictions on instruments used and the benevolent government is able to make credible commitments, the social optimum can be implemented using pollution specific permits $\bar{E}_1$, $\bar{E}_2$ and an R&D prize.

The equilibrium of the production stage is determined by

$$\begin{aligned} P(Y) &= \bar{C}_1(Y_1, Y_2) + \gamma_1 \\ P(Y) &= \bar{C}_2(Y_1, Y_2) + \alpha\gamma_1 + \gamma_2 \\ Y_1 &\leq \bar{E}_1 - Y_2 \\ Y_2 &\leq \bar{E}_2 \end{aligned}$$

where $\bar{C}_i$ is the average cost of technology i and γ_i is the permit price for emissions of type i. In equilibrium output is given by $Y_1 = \bar{E}_1 - \alpha\bar{E}_2$

and $Y_2 = \bar{E}_2$ and permit prices are $\gamma_1 = P(Y) - \bar{C}_1(Y_1, Y_2)$ and $\gamma_2 = (1-\alpha)P(Y) + \alpha\bar{C}_1(Y_1, Y_2) + \bar{C}_2(Y_1, Y_2)$. Hence, the government can control output of both technologies.

The optimal second period allocation can be implemented by setting

$$E_1^S = Y_1^S + \alpha Y_2^S, \qquad E_2^S = Y_2^S.$$

In addition, a research prize of size ΔW would induce the optimal research effort.

However, the use of a research prize involves at least two restrictive conditions. First, the government has to credibly commit that it indeed pays if the new technology arrives. Second, the size of the prize has to equal the welfare gain of innovation and has to be known to the research firm in period 1. Otherwise, the level of research efforts is inefficient (see equation (5)). Hence, either (a) the government has perfect information on the research cost and success functions and perfect foresight on social costs of the new technology, to correctly anticipate the welfare gain of innovation, or (b), it is able to commit on a whole plan of research prizes contingent on properties of the new technology and the research firm is able to anticipate the social cost function of the new technology.

PROPOSITION 1. If the government is able to commit and either (a) or (b) is satisfied, the first best allocation given by (1), (2) and (5) can be implemented using permit quantities E_1^S and E_2^S and a R&D prize of size ΔW.

In both (a) and (b), information and commitment requirements are substantial and restrictive. Hence, if the information and commitment ability of the government is constrained, research prizes fail to implement the first best optimum. Theory (Wright 1983) and their widespread use suggest that patents are usually better able to cope with these constraints. Commitment on patent law is easier to make credible than specific levels of research prizes, and information about future technologies can be private to innovators. Of course, patents come at a cost. Granting monopoly power in the post-innovation period is likely to cause distortions and research incentives are not bound to equal the social gain of innovation. In what follows, the analysis concentrates on how patents affect static efficiency in the case of horizontal environmental innovation in industries regulated by taxes or permits.

4 The Market Equilibrium with Patents and Permits

In this section patents stimulate research while tradeable permits are used to regulate environmental externalities. The timing is as follows. After arrival of the new technology, the government issues emission permits E_1 and E_2 to regulate pollution types 1 and 2, respectively. Second, the research firm sets a linear license fee f taking permit quantities as given. In the last stage, firms choose technologies and the market is cleared. The game is solved backwards.

4.1 Production - 3rd Stage

The free entry equilibrium of the production stage is where price equals average costs and permit constraints hold.

$$\begin{aligned} P(Y) &= \bar{C}_1(Y_1, Y_2) + \gamma_1 && \text{if} \quad Y_1 > 0 && (6) \\ P(Y) &= \bar{C}_2(Y_1, Y_2) + \alpha\gamma_1 + \gamma_2 + f && \text{if} \quad Y_2 > 0 && (7) \\ Y_1 + \alpha Y_2 &\leq E_1 && && (8) \\ Y_2 &\leq E_2 && && (9) \end{aligned}$$

where γ_1 and γ_2 are the equilibrium permit prices for pollution type 1 and 2, respectively. The equilibrium quantities Y_1^{per} and Y_2^{per} are determined by (6)-(9). In what follows, it is assumed that permit quantities are set such that they impose at least a weak constraint on output, i.e. given a zero license fee at least one of (8) or (9) is binding. Otherwise, permits have no effect on equilibrium outcomes. The level of the license fee f defines three situations with respect to the number and type of technologies used: exclusive production by the established or the new technology and a mix of technologies.

Technology 1 is used exclusively ($Y_2^{per} = 0$) if and only if either $E_2 = 0$ or if the average cost of the first unit produced by the new technology $\bar{C}_1(E_1, 0) + \gamma_1$ is at least as high as the average cost of the last unit of the established technology $\bar{C}_2(E_1, 0) + \alpha\gamma_1 + \gamma_2 + f$. Since $Y_2 = 0$, $\gamma_2 = 0$. γ_1 is defined by (6). Hence, if the license fee is sufficiently high, i.e.

$$f \geq \overline{f}^{per}(E_1) = (1-\alpha)P(E_1) + \alpha\bar{C}_1(E_1, 0) - \bar{C}_2(E_1, 0), \tag{10}$$

equilibrium quantities are $Y_1^{per} = E_1$ and $Y_2^{per} = 0$.

Technology 2 is used exclusively if the average cost of the first unit produced by the established technology is at least as high as the average cost of the last unit of the new technology, i.e.

$$\bar{C}_1\left(0, \hat{Y}_2(E_1, E_2, f)\right) + \gamma_1 \geq \bar{C}_2\left(0, \hat{Y}_2(E_1, E_2, f)\right) + \alpha\gamma_1 + \gamma_2 + f \tag{11}$$

where $\hat{Y}_2(E_1, E_2, f)$ is implicitly defined by $Y_1 = 0$, (7) and (8) if $E^{min} = \min\left[\alpha^{-1}E_1, E_2\right] = \alpha^{-1}E_1$ or by $Y_1 = 0$, (7) and (9) if $E_2 = E^{min}$. How the license fee threshold for exclusive production of the new technology is defined depends on if and which permit constraint on Y_2 is binding.

If f is such that permit constraints on the new technology are not binding, i.e. $\hat{Y}_2(E_1, E_2, f) < E^{min}$, then $\gamma_1^{per} = \gamma_2^{per} = 0$ and (11) yields

$$f \leq \bar{C}_1\left(0, \hat{Y}_2(E_1, E_2, f)\right) - \bar{C}_2\left(0, \hat{Y}_2(E_1, E_2, f)\right), \tag{12}$$

which implicitly defines the upper bound $\underline{f}_1^{per}(E_1, E_2)$. Only the new technology produces below this threshold.
If, however, the constraint is binding and if $\hat{Y}_2(E_1, E_2, f) = E_2$, the maximum license fee consistent with exclusive production by the new technology is

$$\underline{f}_2^{per}(E_2) = \bar{C}_1(0, E_2) - \bar{C}_2(0, E_2). \tag{13}$$

If $\hat{Y}_2(E_1, E_2, f) = \alpha^{-1}E_1$, (7) and (11) yield an upper bound on the license fee

$$\underline{f}_3^{per}(E_1) = (1-\alpha)P\left(\frac{E_1}{\alpha}\right) + \alpha\bar{C}_1\left(0, \frac{E_1}{\alpha}\right) - \bar{C}_2\left(0, \frac{E_1}{\alpha}\right). \tag{14}$$

Hence, the conditions for exclusive production by the new technology are summarized by

$$f \leq \underline{f}^{per}(E_1, E_2) = \begin{cases} \underline{f}_1^{per}(E_1, E_2) & : \hat{Y}_2(E^{min}, f) < E^{min} \\ \underline{f}_2^{per}(E_2) & : \hat{Y}_2(E^{min}, f) = E_2 \\ \underline{f}_3^{per}(E_1) & : \hat{Y}_2(E^{min}, f) = \alpha^{-1}E_1 \end{cases} \tag{15}$$

Furthermore, if $\alpha = 0$ the new technology produces exclusively if $E_1 = 0$ and $E_2 > 0$. Equilibrium quantities are $Y_1^{per} = 0$ and $Y_2^{per} = Y_1(E_1, E_2, f)$.

In all cases where aggregate output is positive but neither (10) nor (15) hold, i.e. $\underline{f}^{per} < f < \overline{f}^{per}$, both technologies are used in equilibrium. Equilibrium quantities are $Y_1^{per} = Y_1(E_1, E_2, f)$ and $Y_2^{per} = Y_2(E_1, E_2, f)$.

4.2 Setting of the License Fee - 2nd Stage

The patent holding firm maximizes profits $\pi = f \cdot \tilde{Y}_2$ with respect to f given the residual demand $\tilde{Y}_2(E_1, E_2, f)$ for the new technology. Output of the new technology ceases to be restricted by permit constraints for license fees above $\hat{f}^{per}(E_1, E_2)$ defined by

$$\bar{C}_1(\bar{Y}_1, E^{min}) + \gamma_1 = \bar{C}_2(\bar{Y}_1, E^{min}) + \alpha\gamma_1 + \gamma_2 + \hat{f}^{per}. \tag{16}$$

where either $\bar{Y}_1 = E_1 - \alpha E^{min}$ if the permit constraint is binding for the first pollutant or $\bar{Y}_1$ is determined by $P\left(\bar{Y}_1 + E_2\right) = \bar{C}_1\left(\bar{Y}_1, E_2\right)$ if E_1 is not binding and hence $\gamma_1 = 0$. Substituting γ_1 (see (6)) and $\gamma_2 = 0$ into (16) yields

$$\hat{f}^{per} = \begin{cases} (1-\alpha)P\left(\frac{E_1}{\alpha}\right) + \alpha\bar{C}_1\left(0, \frac{E_1}{\alpha}\right) - \bar{C}_2\left(0, \frac{E_1}{\alpha}\right) & : \quad E^{min} = \frac{E_1}{\alpha} \\ P\left(\bar{Y}_1 + E^{min}\right) - \bar{C}_2\left(\bar{Y}_1, E^{min}\right) & : \quad E^{min} = E_2 \end{cases} \quad (17)$$

Note, that $\hat{f}^{per}$ and $\overline{f}^{per}$ coincide only if $E_1 = 0$. Furthermore, if $E^{min} = \alpha^{-1}E_1$ then $\underline{f}_3^{per}(E_1) = \hat{f}^{per}$. Hence, the residual demand for technology 2 is given by

$$\tilde{Y}_2\left(E_1, E_2, f\right) = \begin{cases} Y_2(E_1, E_2, f) & : \quad \underline{f}_1^{per}(E_1, E_2) \leq f \leq \overline{f}^{per}(E_1) \\ \hat{Y}_2(E_1, E_2, f) & : \quad \hat{f}^{per}(E_1, E_2) < f < \underline{f}_1^{per}(E_1, E_2) \\ E^{min} & : \quad 0 \leq f \leq \hat{f}^{per}(E_1, E_2) \\ 0 & : \quad \text{else} \end{cases}$$

where $Y_2(E_1, E_2, f)$ and $\hat{Y}_2(E_1, E_2, f)$ are implicitly defined by (6) - (9) and (7) - (9), respectively. The equilibrium can be of four types. The equilibrium license fee f^{per} is either a corner solution with $f^{per} = \hat{f}^{per}$ or $f^{per} = \underline{f}_1^{per}$ or it is an inner solution with $f^{per} \in \left(\hat{f}^{per}, \underline{f}_1^{per}\right)$ or $f^{per} \in \left(\underline{f}_1^{per}, \overline{f}^{per}\right)$ where the necessary and sufficient conditions for a profit maximum hold. Formally,

$$-\frac{f^{per}(E_1, E_2)}{E^{min}}\frac{\partial \tilde{Y}_2}{\partial f} > 1 \quad , \quad f^{per} = \hat{f}^{per} \quad (18)$$

$$-\frac{f^{per}(\bullet)}{Y_2(\bullet)}\frac{\partial Y_2}{\partial f} > 1 \wedge -\frac{f^{per}(\bullet)}{\hat{Y}_2(\bullet)}\frac{\partial \hat{Y}_2}{\partial f} < 1 \quad , \quad f^{per} = \underline{f}_1^{per} \quad (19)$$

$$-\frac{f^{per}(E_1, E_2)}{Y_2(E_1, E_2, f^{per})}\frac{\partial \tilde{Y}_2}{\partial f} = 1 \quad , \quad f^{per} \in \left(\hat{f}^{per}, \overline{f}^{per}\right) \setminus \left\{\underline{f}_1^{per}\right\} \quad (20)$$

4.3 Optimal Policy - 1st Stage

Anticipating the license fee choice of the patent holding firm and the market clearing conditions the government maximizes the following objective function

$$\begin{aligned} W_2(E_1, E_2) \quad &= \quad \int_{l=0}^{Y^{per}(E_1,E_2)} P(l)\mathrm{d}l - C\left(Y_1^{per}(E_1, E_2), Y_2^{per}(E_1, E_2)\right) \\ &\quad -D\left(Y_1^{per}(E_1, E_2), Y_2^{per}(E_1, E_2)\right). \end{aligned} \quad (21)$$

In what follows, three cases are distinguished based on the number and type of technologies active in the static social optimum. It can be first best (a) to use only the established technology (condition (3) does not hold), (b) to use only the new technology (condition (4) does not hold) or (c) static efficiency requires a specific mix of technologies (both (3) and (4) hold). For each of these cases it is analyzed under which conditions the government is able to implement the first best static allocation.

(a) Exclusive Use of the Established Technology

If the static optimum requires exclusive production by the established technology, two steps have to be taken to implement the optimal allocation. The government has to rule out production by the new technology and given that, implement technology 1's optimal output.

The former is achieved by setting $E_2^* = 0$. The problem therefore reduces to equations (6) and (8). The static first best output can be implemented by $E_1^* = Y_1^S$.

Patent holder's profit and therefore research incentives are zero. This is dynamically efficient since the new technology does not provide any social gains (condition (3) does not hold).

PROPOSITION 2. If the new technology is not socially desirable, a government using permits and patents is able to implement the first best allocation. This holds both from a static and a dynamic perspective.

(b) Exclusive Use of the New Technology

If in the static first best allocation only the new technology produces, the government aims to rule out production by technology 1 and control output of technology 2. Both, however, is not always possible.

First consider the case where $\alpha = 0$. Since the new technology emits only pollution type 2, production by the established technology can be ruled out by setting $E_1 = 0$. The government's problem reduces to one with one technology and one pollutant where the former is owned by a monopolist, i.e. the patent holder. There are situations in which monopoly pricing by the patent holder restricts output of the new technology below the static optimal level. In these cases quantity restrictions such as permits are, for obvious reasons, not able to improve the allocation.

$$-\frac{\partial Y}{\partial f}\left(f_1^{per}\right)\frac{f_1^{per}}{Y^S} \quad \geq \quad 1, \tag{22}$$

where $Y^S = Y_2^S$ and $f_1^{per} = P\left(Y_2^S\right) - \bar{C}_2\left(0, Y_2^S\right)$, is a necessary and sufficient condition to achieve $Y_2^{per} = Y_2^S$. Otherwise, the patent holding firm sets $f > P\left(Y_2^S\right) - \bar{C}_2\left(0, Y_2^S\right)$ and thereby restricts output below Y_2^S. Inequality (22) is a condition on the price elasticity of the demand function. It states that the monopoly quantity has to be larger than the static optimum in order for the latter to be feasible under permits.

PROPOSITION 3.1 If the new technology is superior and $\alpha = 0$, permits implement the static optimum only if the corresponding output is below the *quantity preferred by the patent holding firm (see condition (22)). Otherwise, monopoly pricing excessively restricts output of the new technology.*

If $\alpha > 0$, i.e. the new technology emits both pollutants, $E_1 \geq \alpha Y_2^S$ is necessary to implement the static first best. Hence, there is no way to effectively rule out production by technology 1 by permit constraints alone.

If permits on pollution type 1 are the relevant constraint for technology 2 (i.e. $E_2 > \alpha^{-1}E_1$), emissions of type 2 are irrelevant for equilibrium considerations in stages 2 and 3. The problem reduces to one with two technologies and one pollutant. A special case of this situation ($\bar{C}_1(Y_1, Y_2) = \bar{C}_2(Y_1, Y_2) = c$) has been analyzed by Denicolò (1999). He finds that the government can implement the static first best allocation with permits. However, his result depends on the implicit assumption that equilibrium quantities are fixed and hence, in equilibrium all permits are used by the new technology.[7] However, the patent holding firm sometimes can increase profits by raising the license fee above the threshold level $\hat{f}^{per} = \underline{f}^{per}$ which reduces output of the new technology and triggers production by the established one (see appendix). This monopoly pricing results in three inefficiencies. First, aggregate output is below the social optimum. Second, the established technology produces although it should not. Third, marginal social costs of both technologies are not the same since the license fee is a pure transfer. The condition that all permits are used by the new technology and hence the static first best is implemented is

$$-\frac{\partial \tilde{Y}_2}{\partial f}\left(\hat{f}^{per}\right)\frac{\hat{f}^{per}}{Y_2^S} \quad \geq \quad 1, \tag{23}$$

which is a condition on the price elasticity of the residual demand function $\tilde{Y}_2$. The only difference to the case with $\alpha = 0$ is that production by the established technology is no longer ruled out ($E_1 > 0$) and hence enters production if the license fee is sufficiently high.

Now, assume that permits on pollution type 2 are the relevant constraint for technology 2 (i.e. $E_2 \leq \alpha^{-1}E_1$). This does not increase the control of the government on technologies output compared to the previous case. E_2 can only further restrict output of the new technology and thereby make things worse. Hence, if $\alpha > 0$, (22) is a necessary and sufficient condition that the government is able to implement the static social optimum. It is also necessary for the static equivalence of instruments and thereby qualifies a result by Denicolò (1999). Monopoly pricing restricts the performance of permits not only in the case studied by Requate (2005a). Moreover, both horizontal environmental innovation and pure emission reductions are affected by this interaction between patents and permits.

[7]Fischer et al. (2003) also assume full adoption of the new technology.

PROPOSITION 3.2 If the new technology is superior and $\alpha > 0$, condition (23) is necessary and sufficient to implement the static first best allocation with permits. Otherwise, monopoly pricing by the patent holding firm can excessively restrict output of the new technology and thereby limit government's control on output.

Dynamic efficiency is not warranted. The optimal license fee f^S that maximizes expected welfare, including the R&D stage, is given by $f^S = \frac{\Delta W}{Y_2^S}$. Where ΔW is the welfare gain of innovation (see Section 3.2). The equilibrium license fee depends on Y_2^S and the slope of the demand curve in the optimum. Properties of the established technology instrumental in determining the social gain of innovation and f^S are irrelevant. Hence, in general $f^{tax} \neq f^S$. The optimal license fee is not feasible in this case.

(c) Mix of Technologies

Assume that in the static optimum both technologies produce. Furthermore, assume that $E_1^* = Y_1^S + \alpha Y_2^S$ and $E_2^* = Y_2^S$. There is no combination of permit quantities that is able to implement the static first best, if this one fails to do so. Both permit constraints are binding in equilibrium iff the following conditions hold

$$
\begin{aligned}
P(Y^S) &= \bar{C}_1\left(Y_1^S, Y_2^S\right) + \gamma_1 &(24)\\
P(Y^S) &= \bar{C}_2\left(Y_1^S, Y_2^S\right) + \alpha\gamma_1 + f_2^{per} &(25)\\
-\frac{\partial \tilde{Y}_2}{\partial f}\left(f_2^{per}\right)\frac{f_2^{per}}{Y_2^S} &\geq 1 &(26)\\
\underline{f}_1^{per}\left(Y_1^S, Y_2^S\right) &< f_2^{per} < \overline{f}^{per}\left(Y_1^S, Y_2^S\right). &(27)
\end{aligned}
$$

Solving (24) for γ_1 and substituting into (25) yields $f_2^{per} = (1-\alpha)P(Y^S) + \alpha\bar{C}_1\left(Y_1^S, Y_2^S\right) - \bar{C}_2\left(Y_1^S, Y_2^S\right)$. Again, (26) is a restriction on the price elasticity of the residual demand of the patent holding firm. If it holds, the patent holding firm has no incentive to increase f and therefore reduce Y_2 below Y_2^S in order to raise profits.[8] This is restrictive since it imposes an upper bound on the slope of the residual demand curve in the static optimum. (26) is a necessary condition for the feasibility of the static first best allocation. Together with (27) it is sufficient. If (26) does not hold there are three types of inefficiency present. Aggregate output is too low, the relative shares of technologies are distorted and marginal social costs of technologies differ.

PROPOSITION 4. If a mix of technologies is statically first best, a government using permits and patents is able to implement the optimal allocation

[8] Note, that (23) is a special case of (26) with $Y_1^S = 0$.

if and only if conditions (26) and (27) hold. Otherwise, monopoly pricing by the patent holding firm limits the performance of emission permits.

However, in contrast to the case studied by Requate (2005a) with only one pollutant where permits are never able to implement the optimal mix, with horizontal environmental innovation this is possible under the conditions presented above. The second pollutant characteristic for horizontal environmental innovation generates an additional mean of controll available to the government. Using two instead of only one permit quantity, the government can impose different restrictions on the two technologies and thereby implement the static optimal mix at least in some cases. With respect to government's controll on output, horizontal environmental innovation is an intermediate case between vertical innovation with one pollutant and patents where permits are never optimal and pure adoption of advanced technologies without monopoly power where permits always implement the efficient mix (see Requate and Unold (2003)).

Again, dynamic efficiency is not warranted. The optimal license fee f^S is a function of the pre-innovation welfare, i.e. when only the established technology is used. The equilibrium license fee is not affected by this and hence in general $f^{per} \neq f^S$.

5 The Market Equilibrium with Patents and Taxes

In this section patents stimulate research while taxes are used to regulate environmental externalities. First, the subgame perfect equilibria are derived. Later subsections deal with the relevance of special cases and discuss qualifications.

5.1 Solving the Game

The timing is as follows. After the new technology has arrived, the government uses linear emission taxes τ_1 and τ_2 to regulate pollution types 1 and 2, respectively. Second, the research firm sets the linear license fee f taking tax levels as given. In the last stage, firms produce until price equals average costs. The game is solved backwards.

5.1.1 Production - 3rd Stage

The free entry equilibrium of the production stage is determined by

$$P(Y) = \bar{C}_1(Y_1, Y_2) + \tau_1 \qquad \text{if} \quad Y_1 > 0 \tag{28}$$

$$P(Y) = \bar{C}_2(Y_1, Y_2) + \alpha\tau_1 + \tau_2 + f \qquad \text{if} \quad Y_2 > 0 \tag{29}$$

where price equals average costs. The level of the license fee f again defines three situations in with only the established, only the new or both technologies produce.

Technology 1 is used exclusively if and only if the marginal costs of the new technology are above those of the established one. Hence, the license fee has to be sufficiently high, i.e. $f > \overline{f}^{tax}(\tau_1, \tau_2)$, where the threshold is defined by

$$P(Y_1^t) = \bar{C}_1\left(Y_1^t, 0\right) + \tau_1 = \bar{C}_2\left(Y_1^t, 0\right) + \alpha\tau_1 + \tau_2 + \overline{f}^{tax} \tag{30}$$

In this case the unique production equilibrium is given by $Y_1^{tax} = Y_1(\tau_1)$ and $Y_2^{tax} = 0$.

Technology 2 is used exclusively if and only if the marginal costs of the new technology are below those of the established one. Hence, the license fee has to be sufficiently low, i.e. $f < \underline{f}^{tax}(\tau_1, \tau_2)$, where the threshold is defined by

$$P(Y_2^t) = \bar{C}_1\left(0, Y_2^t\right) + \tau_1 = \bar{C}_2\left(0, Y_2^t\right) + \alpha\tau_1 + \tau_2 + \underline{f}^{tax}, \tag{31}$$

The unique production equilibrium is given by $Y_1^{tax} = 0$ and $Y_2^{tax} = Y_2(\tau_1, \tau_2 + f)$.

In all other cases where aggregate output is positive both technologies are used and both equations (28) and (29) hold. Equilibrium quantities are $Y_1^{tax} = Y_1(\tau_1, \tau_2 + f)$ and $Y_2^{tax} = Y_2(\tau_1, \tau_2 + f)$.

5.1.2 Setting of License Fee - 2nd Stage

The patent holding firm maximizes profits $\pi = f \cdot \tilde{Y}_2$ with respect to f given the residual demand $\tilde{Y}_2(\tau_1, \tau_2 + f)$ for the new technology. The latter is derived from the equilibrium conditions of the production stage.

$$\tilde{Y}_2(\tau_1, \tau_2 + f) = \begin{cases} Y_2(\tau_1, \tau_2 + f) & : \quad \underline{f}^{tax}(\tau_1, \tau_2) \leq f \leq \overline{f}^{tax}(\tau_1, \tau_2) \\ \check{Y}_2(\tau_1, \tau_2 + f) & : \quad 0 \leq f < \underline{f}^{tax}(\tau_1, \tau_2) \\ 0 & : \quad \text{else} \end{cases}$$

Note, that $\underline{f}^{tax}$ and $\overline{f}^{tax}$ coincide iff $\bar{C}_1(0, Y_2^t) - \bar{C}_2(0, Y_2^t) = \bar{C}_1(Y_1^t, 0) - \bar{C}_2(Y_1^t, 0)$, where Y_1^t and Y_2^t are defined by (30) and (31). Assume that condition

$$\bar{C}_1\left(0, Y_2^t\right) - \bar{C}_2\left(0, Y_2^t\right) \leq \bar{C}_1\left(Y_1^t, 0\right) - \bar{C}_2\left(Y_1^t, 0\right)$$

is met to rule out cases where $\underline{f}^{tax} > \overline{f}^{tax}$. However, both $\underline{f}^{tax}$ and $\overline{f}^{tax}$ can be zero or negative. If $\overline{f}^{tax} \leq 0$, the optimal license fee f is not uniquely defined ($f^{tax} \geq 0$) but equilibrium output of the new technology and hence

patent holder's profit are zero anyway, because only the established technology produces.
If $\overline{f}^{tax} > 0$, the equilibrium license fee will never exceed $\overline{f}^{tax}$ since output Y_2^{tax} and profit π would be zero. This can not be profit maximizing since a license fee that just undercuts $\overline{f}^{tax}$ yields positive output and profit.
There are four types of possible equilibrium license fee levels. The optimal f^{tax} can be an inner solution where only technology 2 produces, i.e. f^{tax} is defined by $-\frac{\partial \check{Y}_2}{\partial f}\left(f^{tax}\right) \cdot \frac{f^{tax}(\tau_1,\tau_2)}{\check{Y}_2(\tau_1,\tau_2+f^{tax})} = 1$ with $0 < f^{tax} < \underline{f}^{tax}$. The second equilibrium type where only the new technology is active is a corner solution where f^{tax} just undercuts the threshold $\underline{f}^{tax}$, i.e. $f^{tax} = \underline{f}^{tax} - \epsilon$. Third, the profit maximizing license fee can be an inner solution where both technologies produce. In this case f^{tax} is defined by $-\frac{\partial Y_2}{\partial f}\left(f^{tax}\right) \cdot \frac{f^{tax}(\tau_1,\tau_2)}{Y_2(\tau_1,\tau_2+f^{tax})} = 1$ with $\underline{f}^{tax} \leq f^{tax} < \overline{f}^{tax}$. Last, a mix of technologies might result from an equilibrium license fee equal to the upper bound $\overline{f}^{tax}$. Note, that total differentiating (31) or (30) and (31) and solving for $\frac{\partial Y_2}{\partial f}$ and $\frac{\partial \check{Y}_2}{\partial f}$, respectively yields a residual demand of the new technology decreasing in the license fee ($\frac{\partial \check{Y}_2}{\partial f} \leq 0$). Inner solutions are therefore indeed possible. Second order conditions are assumed to hold.

5.1.3 Optimal Policy - 1st Stage

Anticipating the license fee choice of the patent holding firm and the market clearing conditions the government maximizes the following objective function

$$\begin{aligned} W_2(\tau_1,\tau_2) &= \int_{l=0}^{Y^{tax}(\tau_1,\tau_2)} P(l)\mathrm{d}l - C\left(Y_1^{tax}(\tau_1,\tau_2), Y_2^{tax}(\tau_1,\tau_2)\right) \\ &\quad -D\left(Y_1^{tax}(\tau_1,\tau_2), Y_2^{tax}(\tau_1,\tau_2)\right). \end{aligned} \tag{32}$$

In what follows, the same three cases as in Section 4.3 are distinguished based on the number and type of technologies active in the first best static social optimum. For each case it is analyzed whether the government is able to implement the first best allocation.

(a) Exclusive Use of the Established Technology
If in the static optimum only the established technology produces, two steps have to be taken to implement it. The government has to rule out production by the new technology and given that, implement technology 1's optimal output.
If the new technology does not produce, the optimal tax on pollution type 1 is given by

$$\tau_1^* = P(Y_1^S) - \bar{C}_1\left(Y_1^S, 0\right). \tag{33}$$

This ensures that the average cost of the established technology is such that the first best quantity Y_1^S is implemented given the new technology does not produce. Hence, the second condition is met. To ensure that $Y_2^{tax} = 0$ the threshold $\overline{f}^{tax}(\tau_1, \tau_2)$ has to be less or equal to zero. Using (30) and substituting in (33) this yields

$$\tau_2^* \geq (1-\alpha)P(Y_1^S) + \alpha\bar{C}_1\left(Y_1^S, 0\right) - \bar{C}_2\left(Y_1^S, 0\right). \tag{34}$$

The government is able to implement $Y_1^{tax} = Y_1^S$ and $Y_2^{tax} = Y_2^S = 0$. Patent holder's profit and research incentives are zero. This is dynamically efficient since the new technology does not provide any social gains (condition (3) does not hold).

PROPOSITION 5. If the new technology is not socially desirable, a government using taxes and patents is able to implement the first best allocation. This holds both for static and dynamic efficiency.

(b) Exclusive Use of the New Technology

If in the static optimum only the new technology produces, two steps have to be taken to implement it. The government has to rule out production by the established technology and given that, implement technology 2's optimal output. This is the case if tax rates satisfy the following conditions

$$\begin{aligned} P\left(Y_2^S\right) &= \bar{C}_2\left(0, Y_2^S\right) + \alpha\tau_1 + \tau_2 + f & (35)\\ -\left[\frac{\partial f}{\partial \check{Y}_2}\left(Y_2^S\right)\right]^{-1}\frac{f}{Y_2^S} &= 1 & (36)\\ f &< \bar{C}_1\left(0, Y_2^S\right) - \bar{C}_2\left(0, Y_2^S\right) + (1-\alpha)\tau_1 - \tau_2 & (37) \end{aligned}$$

Equation (35) is the market clearing condition given only the new technology produces. Profit maximization of the patent holding firm is represented in (36), while (37) ensures that the equilibrium license fee is below the threshold $\underline{f}^{tax}$, i.e. that the established technology does not produce. Substituting (35) into (37) yields

$$\tau_1^* > P\left(Y_2^S\right) - \bar{C}_1\left(0, Y_2^S\right). \tag{38}$$

Substituting (36) into (35) the optimal tax on pollutant 2 is

$$\tau_2^* = P\left(Y_2^S\right) - \bar{C}_2\left(0, Y_2^S\right) - \alpha\tau_1^* + Y_2^S\frac{\partial f}{\partial \check{Y}_2}\left(Y_2^S\right). \tag{39}$$

Hence, there is a continuum of equilibria that implement the static first best allocation. In all these cases the equilibrium license fee is the same (see equation (36)). In contrast to permits, where the patent holding firm is able to manipulate equilibrium price and output, this is not possible with taxes. Using the tax rates on both pollutants the government can control the average costs of both technologies taking into account the profit maximizing behavior of the research firm. Denicolò (1999)'s result on taxes therefore can be generalized for cases with more general cost functions and multiple pollutants.

If the license fee thresholds $\underline{f}^{tax}$ and $\overline{f}^{tax}$ coincide there is an additional set of efficient subgame perfect equilibria. Given $\underline{f}^{tax} = \overline{f}^{tax}$ is positive it imposes a binding upper bound on the equilibrium license fee. If f^{tax} is a corner solution and thereby just undercuts $\underline{f}^{tax}$, equation (38) becomes an inequality. Together with (35) and instead of (36) and (37) the following conditions yield a static first best equilibrium

$$-\left[\frac{\partial f}{\partial \check{Y}_2}\left(Y_2^S\right)\right]^{-1}\frac{f}{Y_2^S} \quad < \quad 1 \qquad (40)$$

$$\bar{C}_1\left(0, Y_2^S\right) - \bar{C}_2\left(0, Y_2^S\right) + (1-\alpha)\tau_1 - \tau_2 - \epsilon \quad > \quad f. \qquad (41)$$

where ϵ is positive but arbitrarily close to zero. Again, substituting (35) into (41) yields

$$\tau_1^* = P\left(Y_2^S\right) - \bar{C}_1\left(0, Y_2^S\right) + \epsilon. \qquad (42)$$

Substituting (40) and (42) into (35), the optimal tax on pollutant 2 is

$$\tau_2^* > \underline{\tau}_2 = (1-\alpha)P\left(Y_2^S\right) + \alpha\bar{C}_1\left(0, Y_2^S\right) - \bar{C}_2\left(0, Y_2^S\right) + Y_2^S\frac{\partial f}{\partial \check{Y}_2}\left(Y_2^S\right).$$

Note, that f will never be negative, hence there is a second condition on the tax on pollutant 2

$$\tau_2^* \leq \overline{\tau}_2 = (1-\alpha)P\left(Y_2^S\right) + \alpha\bar{C}_1\left(0, Y_2^S\right) - \bar{C}_2\left(0, Y_2^S\right).$$

Given the license fee thresholds $\underline{f}^{tax}$ and $\overline{f}^{tax}$ coincide there is an additional continuum of static first best subgame perfect equilibria with τ_1^* defined by (42), $\tau_2^* \in (\underline{\tau}_2, \overline{\tau}_2]$, $f^{tax} = (1-\alpha)P\left(Y_2^S\right) + \alpha\bar{C}_1\left(0, Y_2^S\right) - \bar{C}_2\left(0, Y_2^S\right) - \alpha\epsilon - \tau_2^*$, $Y_1^{tax} = 0$ and $Y_2^{tax} = Y_2^S$. Note, that the equilibrium license fee and hence patent holder's profits are a function of the tax rate τ_2^* which is not uniquely defined.

Dynamic efficiency is not warranted whether the license fee thresholds coincide or not. The optimal license fee f^S that maximizes expected welfare, including the R&D stage, is given by $f^S = \frac{\Delta W}{Y_2^S}$, where ΔW is the welfare

gain of innovation (see Section 3.2). The equilibrium license fee is determined by equation (36) and depends on Y_2^S and the slope of the demand curve in the optimum. Properties of the established technology instrumental in determining the social gain of innovation and f^S are irrelevant. Hence, in general $f^{tax} \neq f^S$. Dynamic efficiency is not warranted.
If the license fee thresholds coincide there is an additional continuum of equilibrium license fees. Although increasing the number of possible matches, f^S might still not be feasible. To see this, assume that demand is not too elastic, the established technology is highly polluting and the new technology produces at negligible costs and is very, though not entirely, clean. The welfare gain of the new technology is therefore quite substantial, and so is f^S. The maximum equilibrium license fee $f^{tax}(\underline{\tau}_2)$, however, is bound from above by (40). But even if $f^S \in [0, f^{tax}(\underline{\tau}_2)]$, in the absence of commitment there is no way to warrant that the appropriate equilibrium is selected by the government in the post-innovation period. Dynamic efficiency is therefore not warranted. Moreover, note that the continuum of equilibria always includes $f^{tax} = 0$. This is the case, if $\tau_2^* = \overline{\tau}_2$. Hence, complete expropriation of the patent holding firm is always possible, given $\underline{f}^{tax} = \overline{f}^{tax}$.

PROPOSITION 6 If the new technology is superior to the established one, a government using taxes and patents is able to implement the first best static allocation.

This contrasts the permit case where monopoly pricing by the patent holding firm restricted government's control over the equilibrium allocation. Monopoly pricing does occur with taxes but the government can accommodate it using tax rates to manipulate patent holder's marginal revenue.

(c) Mix of Technologies
In order to implement the static first best allocation if both condition (3) and (4) hold the government has to rule out the exclusive use of one technology and given that induce the optimal mix of technologies $Y_1^S > 0$ and $Y_2^S > 0$.

A necessary condition for a technology mix is that $\underline{f}^{tax} \leq f^{tax} \leq \overline{f}^{tax}$. If the license fee threshold levels coincide, this condition is degenerated to $f^{tax} = \underline{f}^{tax} = \overline{f}^{tax}$. The patent holding firm, however, strictly prefers a license fee that just undercuts this threshold in order to supply the entire market instead of only a fraction. Hence, the government has to impose a lower bound on the license fee at $\underline{f}^{tax}$ to implement the mix. The only way to do this is to induce $\underline{f}^{tax} = 0$. In this case, however, the patent holding firm does not earn any profits regardless of its license fee choice. This has two implications. First, the government is unable to warrant a mix of technologies as the patent holding firm might opt for zero output of technology 2 instead of a zero license fee. Second, even if a zero license fee is chosen, any mix is an equilibrium of which only one is efficient. This situation is similar to the one in Requate and Unold (2003) where adoption without patents is analyzed. Third, anticipating the inability to recover expenditures the research firm will not invest in the first place. If the government conjectures that the patent holding firm sets a positive license fee, if $\underline{f}^{tax} = 0$, it prefers to implement a second best allocation where only the established or only the new technology produces. Propositions 5 and 6 hold analogous.

PROPOSITION 7.1 If a mix of technologies is statically first best and the license fee thresholds $\underline{f}^{tax}$ and $\overline{f}^{tax}$ coincide, a government using taxes and patents is not able to implement the optimal mix of technologies. The second best allocations are equivalent to the first best allocations in either 5.1.3 (a) or 5.1.3 (b) and can therefore be implemented.

Now consider the case where the license fee threshold levels do not coincide ($\underline{f}^{tax} < \overline{f}^{tax}$). Equilibria with an inner solution $\underline{f}^{tax} \leq f^{tax} < \overline{f}^{tax}$ or a corner solution $f^{tax} = \overline{f}^{tax}$ can exist. First, the case of an inner solution is analyzed.
In order to implement the first best static allocation the tax rates have to satisfy the following set of conditions

$$P\left(Y^S\right) = \bar{C}_1\left(Y_1^S, Y_2^S\right) + \tau_1 \quad (43)$$

$$P\left(Y^S\right) = \bar{C}_2\left(Y_1^S, Y_2^S\right) + \alpha\tau_1 + \tau_2 + f \quad (44)$$

$$-\left[\frac{\partial f}{\partial Y_2}\left(Y^S\right)\right]^{-1}\frac{f}{Y_2^S} = 1 \quad (45)$$

$$\underline{f}^{tax} \leq f < \overline{f}^{tax}. \quad (46)$$

(43) and (44) ensure market clearing in the production stage, while (45) originates from profit maximization of the patent holding firm in the second stage. Condition (46) ensures that both technologies are used and the equilibrium is indeed an inner solution. (43) gives the optimal tax rate on pollution type 1

$$\tau_1^* = P\left(Y^S\right) - \bar{C}_1\left(Y_1^S, Y_2^S\right). \quad (47)$$

Substituting this into (44) the optimal tax on pollutant 2 is

$$\tau_2^* = (1-\alpha)P\left(Y^S\right) + \alpha\bar{C}_1\left(Y_1^S, Y_2^S\right) - \bar{C}_2\left(Y_1^S, Y_2^S\right) + Y^S\frac{\partial f}{\partial Y_2}\left(Y^S\right). \quad (48)$$

Using the definitions of $\underline{f}^{tax}$ and $\overline{f}^{tax}$ and (47) and (48), (46) yields the following restriction on the cost functions

$$\bar{C}_1\left(0, Y_2^t(\tau_1^*)\right) \quad - \quad \bar{C}_2\left(0, Y_2^t(\tau_1^*)\right)$$

$$\leq \bar{C}_1\left(Y_1^S, Y_2^S\right) \quad - \quad \bar{C}_2\left(Y_1^S, Y_2^S\right) < \qquad (49)$$
$$\bar{C}_1\left(Y_1^t(\tau_1^*), 0\right) \quad - \quad \bar{C}_2\left(Y_1^t(\tau_1^*), 0\right).$$

Note, that $\bar{C}_1\left(0, Y_2^t\right) - \bar{C}_2\left(0, Y_2^t\right) < \bar{C}_1\left(Y_1^t, 0\right) - \bar{C}_2\left(Y_1^t, 0\right)$ follows from $\underline{f}^{tax} < \overline{f}^{tax}$. The additional restriction imposed by (49) is therefore on $\bar{C}_1\left(Y_1^S, Y_2^S\right) - \bar{C}_2\left(Y_1^S, Y_2^S\right)$. If (49) holds, there is a subgame perfect equilibrium that implements the first best static allocation. The government is able to accommodate monopoly pricing by the patent holding firm by appropriate choice of tax rates. However, this ability is limited by condition (49). The following analysis of the corner solution equilibrium will show that, given (49) holds, this equilibrium is unique.

In order to implement the first best static allocation by a corner solution equilibrium the following conditions have to hold in addition to (43) and (44)

$$-\left[\frac{\partial f}{\partial Y_2}\left(Y^S\right)\right]^{-1}\frac{f}{Y_2^S} \quad < \quad 1 \qquad (50)$$

$$\overline{f}^{tax} = \bar{C}_1\left(Y_1^t, 0\right) - \bar{C}_2\left(Y_1^t, 0\right) + (1-\alpha)\tau_1 - \tau_2 \quad = \quad f. \qquad (51)$$

Again, the optimal tax rate on pollution type 1 is given by (47). From (50) and the fact that the license fee is never negative it follows that

$$0 \leq f^{tax} < -Y_2^S \frac{\partial f}{\partial Y_2}\left(Y^S\right).$$

This yields a range of optimal tax levels on pollutant 2 $\tau_2^* \in (\underline{\tau}_2, \overline{\tau}_2]$ where $\underline{\tau}_2 = (1-\alpha)P\left(Y^S\right) + \alpha\bar{C}_1\left(Y_1^S, Y_2^S\right) - \bar{C}_2\left(Y_1^S, Y_2^S\right) + Y^S\frac{\partial f}{\partial Y_2}\left(Y^S\right)$ and $\overline{\tau}_2 = (1-\alpha)P\left(Y^S\right) + \alpha\bar{C}_1\left(Y_1^S, Y_2^S\right) - \bar{C}_2\left(Y_1^S, Y_2^S\right)$. Substituting (47) into (51) yields the following restriction

$$\bar{C}_1\left(Y_1^S, Y_2^S\right) - \bar{C}_2\left(Y_1^S, Y_2^S\right) \quad = \quad \bar{C}_1\left(Y_1^t, 0\right) - \bar{C}_2\left(Y_1^t, 0\right). \qquad (52)$$

It is possible to implement the first best static optimum as a corner solution if and only if (52) holds. If this is the case, there is a continuum of equilibria with τ_1^* given by (47), $\tau_2^* \in (\underline{\tau}_2, \overline{\tau}_2]$, $f^{tax}\left(\tau_2^*\right) \in \left[0, -Y_2^S\frac{\partial f}{\partial Y_2}\left(Y^S\right)\right)$, $Y_1^{tax} = Y_1^S$ and $Y_2^{tax} = Y_2^S$. Note, that for one of these equilibria $f^{tax} = 0$ and research incentives are therefore zero.

PROPOSITION 7.2 If a mix of technologies is statically first best and the license fee thresholds $\underline{f}^{tax}$ and $\overline{f}^{tax}$ do not coincide, a government using taxes and patents is able to implement the static optimal mix of technologies if and only if either (49) or (52) hold. If (49) holds, the subgame perfect *equilibrium is unique and provides strictly positive research incentives. If (52) holds, there is a continuum of subgame perfect equilibria that includes one where research incentives are zero.*

If (49) or (52) do not hold, the government is not able to implement the first best mix of technologies. The second best quantities Y_1^{sec} and Y_2^{sec} maximize (32) subject to the condition that either (49) or (52) hold for the second best quantities or only one technology produces.

Again, in contrast to the situation with one pollutant considered by Requate (2005a) where taxes never implement the optimal mix, with horizontal environmental innovation this is possible under the conditions presented above. The second tax rate, feasible due to the differentiation of pollutants, allows the government to individually address technologies in its regulatory effort. This results in improved controll and in more efficient allocations.

5.2 The Relevance of Coinciding License Fee Thresholds

In the previous subsection the case where license fee thresholds $\underline{f}^{tax}$ and $\overline{f}^{tax}$ coincide differed substantially from the general case. Similar to Requate and Unold (2003) the government is never able to implement a specific mix of technologies (Proposition 7.1). Moreover, all equilibria are characterized by exclusive production by one technology. If only the new technology produces, there is a continuum of equilibria including one with zero research incentives. Hence, research incentives depend crucially on the conjectures of the research firm on governments choice of τ_2^* and therefore predictions on dynamic efficiency are hard to come by even if all parameters are known.

Is this case of any practical relevance? It is, since a number of cost functions fit into this category. As said before, $\underline{f}^{tax} = \overline{f}^{tax}$ is equivalent to $\bar{C}_1\left(0, Y_2^t\right) - \bar{C}_2\left(0, Y_2^t\right) = \bar{C}_1\left(Y_1^t, 0\right) - \bar{C}_2\left(Y_1^t, 0\right)$ (see Section 5.1.2). This holds if both technologies exhibit constant returns to scale at the industry level, i.e. $\bar{C}_1(Y_1, Y_2) = c_1$ and $\bar{C}_2(Y_1, Y_2) = c_2$. Note, that this is in line with the previous assumption that individual firms have U-shaped average cost functions. Constant returns require that supply of all inputs is perfectly elastic in the relevant range and that firms are small. Laffont and Tirole (1996), Denicolò (1999) and Requate and Unold (2003) restrict their analysis to such situations.

More general technologies, where all inputs not in perfectly elastic supply are shared by both technologies, fit also into the relevant class. The corresponding cost functions $\bar{C}_1(Y_1, Y_2) = \hat{C}(Y_1 + \beta Y_2) + c_1$ and $\bar{C}_2(Y_1, Y_2) = \hat{C}(Y_1 + \beta Y_2) + c_2$ satisfy the necessary condition.

End-of-pipe equipments like scrubbers or catalytic converters are typical examples of such technologies. According to Harrison and Antweiler (2003) end-of-pipe technologies are of great practical importance in industry's abatement activities. The case where license fee thresholds coincide and hence static inefficiency of taxes is prevalent under horizontal environmental innovation is of significant practical relevance.

However, the results derived for coinciding license fee thresholds break down if technologies produce imperfect substitutes. Conditions (30) and (31) become

$$\begin{aligned} P_1\left(Y_1^t\right) &= \bar{C}_1\left(Y_1^t, 0\right) + \tau_1 \\ P_2\left(Y_1^t\right) &= \bar{C}_2\left(Y_1^t, 0\right) + \alpha\tau_1 + \tau_2 + \overline{f} \end{aligned}$$

and

$$\begin{aligned} P_1\left(Y_2^t\right) &= \bar{C}_1\left(0, Y_2^t\right) + \tau_1 \\ P_2\left(Y_2^t\right) &= \bar{C}_2\left(0, Y_2^t\right) + \alpha\tau_1 + \tau_2 + \overline{f} \end{aligned}$$

respectively. Hence, $\underline{f}^{tax}$ and $\overline{f}^{tax}$ coincide iff

$$P_2\left(Y_1^t\right) - \bar{C}_2\left(Y_1^t, 0\right) = P_2\left(Y_2^t\right) - \bar{C}_2\left(0, Y_2^t\right).$$

In contrast to the case with perfect substitutes, there are no cost functions that in general satisfy this condition unless $Y_1^t = Y_2^t$. Hence, if technologies produce imperfect substitutes coinciding license fee thresholds constitute no longer a special case.

5.3 Unavailability of Subsidies

If the tax rates τ_1 and τ_2 on pollution types 1 and 2 respectively are restricted to non-negative values, most of the propositions in this section break down. The only exception is Proposition 5. Although the presence of negative externalities alone require positive tax rates to internalize them, this does not hold with two types of market failure. In order to correct monopoly pricing by the patent holding firm and the externalities, negative tax rates are necessary in the following cases.

The general stand-alone equilibrium in Section 5.3.1 (b) is affected by an unavailability of subsidies on pollution because τ_2^* defined by (39) becomes negative if either the lower bound on τ_1^* becomes to high or the marginal change of the residual demand function evaluated at the optimal output becomes too close to zero. The continuum of equilibria in the case that $\underline{f}^{tax} = \overline{f}^{tax}$ can also vanish. τ_1^* can be negative, given an adequate cost function. Therefore Proposition 6 does not hold if subsidies are not available.

The invalidity of Proposition 6 also affects the last sentence of Proposition 7.1. Second best allocations where the new technology produces exclusively

are no longer warranted.
If a mix of technologies is statically first best, the tax rate on pollutant 2 can be negative. This applies to both the inner and the corner solution equilibria. Hence, if tax rates are bound to be non-negative, Proposition 7.2 does not hold.
The general performance of taxes is thus seriously reduced if subsidies are not available. Note, that in this context subsidies might face special political opposition. In contrast to the subsidies in the standard environmental regulation literature they are not on abatement but on pollution.

6 Ranking of Instruments

Having analyzed the performance of taxes and permits under horizontal environmental innovation individually, this section compares their relative performance with respect to (a) static efficiency, (b) research incentives and (c) welfare. However, in general the statements that can be made are very limited.

(a) Static Efficiency
If the established technology is used exclusively in the static optimum, i.e. condition (3) does not hold, both taxes and permits are able to rule out production by the new technology. Thereby the problem of regulation reduces to the standard textbook case of one technology and perfect information where the equivalence of price and quantity regulation is well known.
If the new technology is used exclusively in the static optimum, only taxes (not confined to non-negative values) can implement it without further restrictions. Permits sometimes fail to achieve the static first best due to the ability of the patent holding firm to raise the license fee and thereby the average costs of production above the optimal level. This reduces output of the new technology below the first best level and if $\alpha > 0$ triggers production by the established technology. Hence, taxes are preferred on grounds of static efficiency.
If a mix of technologies is socially optimal, neither taxes nor permits implement the optimal mix of technologies in all situations. Taxes can fail for two reasons. On the one hand, the cost functions can be such that the license fee thresholds coincide (see Section 5.2) or, on the other hand, monopoly pricing restricts the government's ability to implement the optimal mix (condition (49)). Permits also suffer from monopoly pricing by the patent holding firm. The sets of first best allocations that can be implemented differ between taxes and permits. In general, there is no clear ranking of instruments. However, for specific cases such a ranking does exist.

(b) Research Incentives
The incentives to undertake R&D are measured by the profits of the patent holding firm. In all cases where only the established technology is used in the first best allocation, both taxes and permits do not provide any research incentives as is socially optimal.
If the new technology is used exclusively in the first best allocation and both instruments implement it, the ranking with respect to research incentives is based on the license fee alone. With permits the equilibrium license fee is $f^{per} = P\left(Y_2^S\right) - \bar{C}_2\left(0, Y_2^S\right)$ while with taxes it is defined by (36).[9] They match only by coincidence. However, if license fee thresholds coincide under taxes, there exist equilibrium license fees clearly lower than that under permits since there is always an equilibrium with $f^{tax} = 0$. In this case multiplicity of equilibria makes predictions hard to come by. No ranking of instruments with respect to research incentives is feasible when only the new technology produces.
If a mix of technologies is first best and this can be implemented, both taxes and permits define unique license fee levels. Again, however, it is not possible to rank them.

(c) Welfare
Welfare rankings are even more blurred. Different static inefficiencies and problems to discriminate between excessive and under supply of R&D render a ranking of instruments impossible in general terms. However, both instruments are first best in cases where the new technology does not create any social benefits.
In order to compare the welfare effects of taxes and permits in other cases, more specific functional forms have to be assumed which in turn limit the generality of results. However, using the results presented in this paper, this can be done if an application justifies specific functional forms and parameter values.

7 Conclusion

Horizontal environmental innovation, where new technologies reduce pollution of one type while causing a new type of damage, is highly relevant but not sufficiently considered in the economics literature so far. The present paper considers such a situation to study the performance of taxes and permits in regulating externalities in the presence of patents.

Both taxes and permits can implement the static optimum in a large

[9] Note, that the residual demand functions for Y_2 differ under taxes and permits. Hence, no conclusions on f can be drawn from the profit maximizing condition of the patent holding firm.

number of cases. This includes situations where both technologies are used at the same time. Under vertical environmental innovation where only one pollutant is emitted, this is not possible (see Requate (2005a)). In contrast to horizontal environmental innovation, there the government can not differentiate its regulation across technologies.

However, both instruments sometimes fail to implement the static optimum. The performance of permits is restricted by their very nature to impose upper bounds on quantities. Although environmental externalities in general ensure that the social optimal output is below the unregulated output this does not necessarily hold here. There is an additional market failure in form of the monopoly created by patents. Hence, under certain conditions the patent holding firm restricts output below the social optimum by monopoly pricing. This creates up to three types of inefficiency: reduced aggregate output, suboptimal mix of technologies and different marginal social costs across technologies.
Taxes are less affected by monopoly pricing because they directly target prices instead of quantities. Inefficiency occurs only in situations where both technologies should be used at the same time. If, e.g. there are constant returns to scale at the industry level, taxes are not able to implement any specific mix of technologies. This, however, is also the case in the absence of patents (Requate and Unold 2003). Moreover, the optimal tax rate might be negative and hence pollution (not abatement) has to be subsidized.

In addition to the new insights created for horizontal environmental innovation, the present paper qualifies some previous results on vertical innovation. It is shown that monopoly pricing is also an issue in situations with only one pollutant and a strictly superior technology.

It is a general pattern that granting patents to induce private innovation incentives triggers monopoly pricing by the successful research firm. This in turn restricts the performance of economic instruments to regulate environmental externalities in the post-innovation period. In itself, this is not a surprising result. However, previous studies in this area have somewhat obscured this fact by basically assuming it away. Both, the evaluation of its empirical relevance and its effect on the desirability of patents compared to other instruments, await further research.

A Appendix

A.1 Proofs of Section 4.3

Assume that $Y_2^S = \alpha^{-1}E_1 < E_2$. This is the case considered by Denicolò (1999) but with more general cost functions. He claims that $f^{per} = \hat{f}^{per} = (1-\alpha)P\left(\alpha^{-1}E_1\right)+\alpha\bar{C}_1\left(0,\alpha^{-1}E_1\right)-\bar{C}_2\left(0,\alpha^{-1}E_1\right)$ is the unique equilibrium of stages 2 and 3 and the government has therefore control over output of the new technology. The static first best can be implemented in this case.

However, if the patent holding firm increases f above this threshold it faces a residual demand $\tilde{Y}_2(f)$ implicitly defined by

$$\begin{aligned} P(Y) &= \bar{C}_1(Y_1, Y_2) + \gamma_1 \\ P(Y) &= \bar{C}_2(Y_1, Y_2) + \alpha\gamma_1 + f^{per} \\ Y_1 + \alpha Y_2 &= E_1. \end{aligned}$$

The slope of the residual demand function is

$$\frac{\partial \tilde{Y}_2}{\partial f} = \left[(1-\alpha)\frac{\partial P}{\partial Y} - \alpha^2 \frac{\partial \bar{C}_1}{\partial Y_1} + \alpha \frac{\partial \bar{C}_1}{\partial Y_2} + \alpha \frac{\partial \bar{C}_2}{\partial Y_1} + \frac{\partial \bar{C}_2}{\partial Y_2} \right]^{-1}.$$

If marginal costs of production are constant (Denicolò 1999), this reduces to $\frac{\partial \tilde{Y}_2}{\partial f} = \left[(1-\alpha)\frac{\partial P}{\partial Y}\right]^{-1} < 0$. Hence, the patent holding firm can increase profits by raising f above $\hat{f}^{per}$ and thereby trigger production of the established technology iff

$$-\frac{\partial \tilde{Y}_2}{\partial f}\left(\hat{f}^{per}\right)\frac{\hat{f}^{per}}{Y_2^S} < 1.$$

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