Incentives for environmental R&D*

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Abstract

Since governments can influence the demand for a new and cleaner technology through their environmental policy, they may be able to expropriate the innovations in new abatement technology ex post. This suggests than incentives for environmental R&D may be lower than the incentives for market goods R&D. This in turn may be used as an argument for environmental R&D getting a larger share of public R&D spending. In this paper we systematically compare the incentives for environmental R&D with the incentives for market goods R&D. We find that the relationship might be the opposite: When the innovator is able to commit to a licence fee before environmental policy is resolved, incentives are always higher for environmental R&D than for market goods R&D. When the governmnet sets its policy before or simultaneously with the innovator's choice of licence fee, incnetives for environemtal R&D may be higher or lower than for market goods R&D.

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1 Introduction

The recent literature on environmental R&D suggests that the incentives for environmental R&D may be lower than the incentives for market goods R&D. By some authors this is also used as an argument for increasing the share of environmental R&D in public R&D budgets.[1] On the other hand, although the literature has looked at environmental R&D in a variety of settings, no contribution has yet systematically compared the incentives for R&D that reduces abatement costs with the incentives for R&D that reduces the production costs of market goods. Moreover, by closer inspection many models of environmental R&D turn out to be rather special, and hence, our aim is to conduct the comparison in a more general economic model of innovations.

There are many reasons why the incentives for R&D may be distorted such that the market outcome is socially inefficient. First, there likely are both positive and negative externalities in the production of new knowledge; examples of the former are the "standing-on-shoulders" effect and on the latter is the "stepping-on-toes" effect.[2] Second, due imperfect patent protection, the innovator may not be able to recover the initial R&D investment.[3] These market failures are equally relevant for environmental R&D and market goods R&D. Unless there is reason to believe there is a systematic difference in the magnitude of these market failures between the two cases, these market failures are not a justification for policies directed particularly towards environmental R&D.

Our point of departure is a more fundamental difference between the market goods case and the environmental technology case. In the market good case demand for an innovation is given from the underlying preferences of consumers or technology of firms, and governments normally does not interfere with demand. In the environmental technology case, we have the opposite situation: Through its environmental policy the government cannot

[1] See for example Montgomery and Smith (2007).

[2] See for instance Jones and Williams (2000).

[3] See for example Barro and Sala-i-Martin (2004), Section 6.2, Erosion of monopoly power", page 305.

help interfering with the demand for the new technology. This makes it possible for the government partly or fully to expropriate the innovation, and clearly, this may distort the private incentives for environmental R&D.

Several decades ago, Kydland and Prescott (1977) drew attention to inefficiency caused by dynamic inconsistency. This insight has proven essential for several policy areas - also to environmental economics. For example, Downing and White (1986) examine the ratchet effect; if a polluting firm discovers a less polluting process, the government may tighten the regulation of the firm. Consequently, the innovating polluting firm may not reap the (naively) expected benefits from their innovation, and R&D investments may not be profitable. Downing and White (1986) conclude that for all other environmental policy instruments than emission taxes, the ratchet effect may lead to too little innovation.

Unlike Downing and White, more recent contributions on environmental R&D distinguish between the regulated polluting sector, which employs new abatement technology, and the R&D sector, which develops new abatement technology. Laffont and Tirole (1996) was one of the first contributions including a model that separated the innovator from the polluting sector.[4] In Laffont and Tirole the government expropriate the innovation by setting a very low price on pollution permits. In order to sell the new technology, the innovator must accordingly set a very low licence fee which ruins the incentives for environmental R&D.

Laffont and Tirole (1996) analyze the case in which the government is able to commit to environmental policy before the innovator decides the price on the innovation. This may, however, not always be the mots realistic case as politicians seem to be adjust environmental policy quite frequently. We therefore include in our analysis both the case in which environmental policy is set simultaneously with the price on the innovation, and the case in which the innovator is able to commit to a price on the innovation.

Denicolo (1999) and Montero (2010) builds on Laffont and Tirole with

[4] Articles assuming that R&D is done by one or several R&D firms that differ from the polluting firms also include Parry (1995), Biglaiser and Horowitz (1995), Laffont and Tirole (1996), Denicolo (1999), Requate Requate (2005), and Montero (2010)

respect to the sequence of decisions, but their results differ in a number of ways. For instance, in Montero (2010) the government cannot decide the price on emission permits, but commits to issuing a certain number of emission permits. Moreover, the innovation does not necessarily remove all emissions like in Laffont and Tirole, but only a fraction of the emissions. Both these features of Montero's model changes the game, and allows the innovator to keep some of the monopoly rents from the innovation.

While in Laffont and Tirole (1996), and in Montero (2010) all polluting firms have the same benefit from the new technology, Requate (2005) includes heterogenous firms. This makes it much harder for the government to expropriate the innovation, and thus the ranking of policies is changed. Moreover, Requate (2005) also analyses different ordering of the decisions by the government and the innovator, however, he does not look at the simultaneous game. Lastly, Requate (2005) does not compare the incentives for innovation in the environmental technology case with the market good case.

In this paper we compare the incentives for R&D that reduces abatement costs with the incentives for R&D that reduces the production costs of market goods in a model taken from the general literature on innovations. We assume throughout the paper that the downstream sector that either produces a market good or pollutes and abates is competitive. However, in line with the observations made by Katz and Shapiro (1986) for general R&D and by Requate (2005) for environmental R&D, we assume that R&D takes place in separate R&D firms that sells its innovations in *technology markets*.[5] Each R&D firm is assumed to be so large that it is not a price taker in the market for its innovations. We show that the presentiment that incentives for environmental R&D are lower than incentives for market goods R&D is not generally true. When the innovator is able to commit to a licence fee before environmental policy (tax or quota) is resolved, incentives are always higher for environmental R&D than for market goods R&D. Moreover, when the government is able to commit, but the innovator is not, the relative size

[5] According to Requate (2005), empirical work shows that more than 90 percent of environmental innovations reducing air and water pollution are invented by non-polluting firms marketing their technology to polluting firms. A similar claim is made by Hanemann (2009, footnote 76). For market goods R&D, see also Khan and Sokoloff (2004).

of the incentives could go both ways.

The model is explained in Section 2, and is in Section 3 applied to the case in which an innovation reduces the costs of producing a regular market. In Sections 4 and 5 it is assumed that an innovation reduces the abatement cost of polluting firms. In this section we compare the incentives for environmental R&D and other R&D. In section 4 it is assumed that the policy instrument is a carbon tax, while we in Section 5 consider the case of quotas.

2 The model

2.1 The innovation sector

We consider a situation in which new knowledge becomes available. Old knowledge is supplied by a competitive sector, and embedded in the cost function of the downstream firms, while new knowledge is made available by the innovator in exchange for some payment. The formal model has a similar setup as in Laffont and Tirole (1996), Denicolo (1999), Requate (2005b), and Montero (2010), with only one innovating firm. With more R&D, the new technology is either better (i.e. lower costs) as in e.g. Montero (2010), or the probability of success (i.e. of obtaining the new technology) is higher, as in e.g. Laffont and Tirole (1996).

Before turning to the two cases of output being (i) a produced market good, and (ii) abatement, we shall briefly discuss how the innovator might be paid for its innovation by the competitive sector. Our point of departure is Katz and Shapiro (1986). In Katz and Shapiro each downstream firm pay a fixed licence fee in order to use the new technology, however, we might instead have that the licence payment is a variable fee depending on the use of the new technology by each firm (see e.g. the discussion in Katz and Shapiro). Total payment to the innovator v is then given by the following revenue function:

$$v = v(x, \ell)$$

where x is the aggregate supply of abatement or the market good in the downstream market. An obvious assumption is that $v(0, \ell) = v(x, 0) = 0$. It is also reasonable to assume that for a given ℓ, the use of the new technology in increasing in output or abatement, so that $v_x > 0$.

Since the profit of adapting the new technology may be decreasing in the number of firms adapting the new technology, there likely exist an optimal licence fee. Thus, we assume that $v_l > 0$ for small values of ℓ, but that v has a maximal level for any given x, so that $v_l < 0$ for sufficiently large values of ℓ. Finally, we make the additional plausible assumptions that $v_{xx} \geq 0$ and $v_{x\ell} \geq 0$, ensuring that private marginal costs of production or abatement are not declining in x and ℓ.

2.2 The downstream sector

The downstream sector consist of many small firms all producing the same good. In the case of a market good, x denotes industry supply, and in the case of environmental innovations, x denotes aggregate abatement. Further, abatement is defined as reduction in emissions from the emission level that would be chosen in the absence of any environmental regulation.

It is common to include technological change in the cost function by including the level of the level of knowledge as an argument in the cost function. Moreover, the meaning of technological improvement is normally quite straightforward: It is modelled as a downward shift in the cost function.[6] On the other hand, including knowledge as an argument in the cost function, presupposes free access to all new knowledge. Hence, we will instead use the cost function $C(x, \ell)$ where ℓ is explained above. We assume $C_x > 0$ and $C_{xx} > 0$.

The licence fee ℓ constitutes a pure transfer from the downstream sector to the innovator, and will in most cases lead to too little adoption of the new technology. Further, since a higher value of ℓ implies that the new technology is used to an even lesser extent, we assume $C_\ell \geq 0$. It also seems reasonable that $C_{x\ell} \geq 0$. It is not obvious what the sign of $C_{\ell\ell}$ should be. However, for

[6] See for instance Goulder and Mathai (2000).

$\ell > \bar{\ell}$ the new technology will not be used at all, and for values of ℓ beyond this threshold we have $C_\ell = 0$, suggesting $C_{\ell\ell} \leq 0$, which is henceforth assumed.

3 R&D incentives for a market good

Once the license fee ℓ is given, private marginal costs for the market good are $C_x(x,\ell) + v_x(x,\ell)$. Profit maximizing price takers equate this marginal cost with the output price, defining the supply function $x(p,\ell)$ by

$$C_x(x,\ell) + v_x(x,\ell) = p \tag{1}$$

Since $C_{xx} + v_{xx} > 0$, $x_\ell < 0$ provided $C_{x\ell} + v_{x\ell} > 0$. Moreover, $x_p > 0$ since $C_{xx} + v_{xx} > 0$.

The social and private benefit of the market good is denoted $B(x)$, with the standard properties $B' > 0$ and $B'' \leq 0$. The inverse demand function is hence given by

$$p = B'(x) \tag{2}$$

The market equilibrium is characterized by demand equal to supply, i.e. by $p = B'(x(p,\ell))$ where $x(p,\ell)$ is defined by (1). This gives an equilibrium price, and hence also an equilibrium output, for any given ℓ. We denote this equilibrium by $p^0(\ell)$ and $x^0(\ell)$. Since $C_{xx} + v_{xx} - B'' > 0$, $x^0(\ell)$ will be a strictly declining function provided $C_{x\ell} + v_{x\ell} > 0$. The curve $p^0(\ell)$ given by $p = B'(x^0(\ell))$ is hence upward sloping in the (p,ℓ) diagram in Figure 1 for $B'' < 0$.

The innovator will set ℓ taking (1) and (2) into consideration, i.e. so that $v(x^0(\ell),\ell)$ is maximized. This gives

$$v^0 = \max_\ell \left[v(x^0(\ell),\ell) \right] \tag{3}$$

The values along the iso-payoff curves for the innovator v', v^0 and v^I in the diagram are higher the further to the right we are in Figure 1, since

$\frac{dv}{dp} = v_x x_p > 0$.[7] The innovator's optimal choice of ℓ is at the point M in Figure 1. This is the point along the curve $p^0(\ell)$ that gives the innovator the highest payoff.

Denote the solution to (3) by ℓ^0. The use of the new technology in the case of a market good will be $x^0(\ell^0)$. From a social welfare point of view ℓ should be set equal to zero, and we should have $C_x(x, 0) = p = B'(x)$. This will yield $x^0(0)$ which is larger than $x^0(\ell^0)$ since x^0 is a strictly declining function. The difference reflects the efficiency loss from the innovator limiting the access to the new technology.

4 R&D incentives for abatement when the policy instrument is a carbon tax

The fundamental difference from the case of a market good is that now the regulator interferes with the demand for the new technology through its environmental policy. It is not obvious at what point in time the environmental policy is set. In the literature we have identified the following alternatives:

- Environmental policy is set before R&D is carried out
- Environmental policy is set after R&D is carried out, but before the innovator sets ℓ
- Environmental policy is set after R&D is carried out, but simultaneously with ℓ i.e. neither the innovator nor the regulator is able to commit to ℓ or policy
- Environmental policy is set after R&D is carried out, and after the innovator sets ℓ i.e. the innovator is able to commit to ℓ

In all cases we assume that the choices of the type of abatement technology and the amount of abatement carried by the polluting firms happens

[7] The iso-payoff curves are curves for constant $v(x(p, \ell), \ell))$. Se the Appendix for a derivation of their properties.

after environmental policy and ℓ is set.[8] Moreover, like most of the cited literature we do not consider the first case. R&D often takes a decade to complete, and it is difficult to imagine that governments are able to commit to an environmental policy more than 5-10 years into the future.

It is not easy to argue hard for any of the three other alternatives. We know that governments often change emission taxes from year to year, and at the same time we cannot see what is keeping the innovator from changing the licence fee accordingly. This suggests to model the setting of policy and the setting of the licence fee as a simultaneous game.

Laffont and Tirole (1996) propose that the governments can commit to policy by issuing buy options on emission permits. Laffont and Tirole (1996) therefore argue that governments can commit to policy, and that environmental policy is set before the innovator sets ℓ. On the other hand, in many countries, the government uses carbon taxes alongside emission permits, and do not commit to the size of the taxes (nor does most governments issue buy options).

How can the innovator commit to a certain licence fee? The innovator can try by issuing a Most-Favored-Customer clause, that is, guaranteeing that its current customers will be reimbursed if the licence fee is lowered in the future. As shown by Tirole (1988) this may work as a commitment device. Moreover, since the innovator knows when she is ready to launch her idea well in advance of the regulator, she could possibly preempt the regulator in this way.

In this paper we look at all three alternatives, and since R&D costs are sunk for all alternatives, social welfare is given by:

$$W = B(x) - C(x, \ell) \tag{4}$$

[8] Requate (2005) also includes a case in which the regulator sets environmental policy after the polluting firms has chosen technology, but before they have decided on the level of abatement.

where $B(x)$ now stands for benefits of abatement[9]. When setting environmental policy the government maximizes W with respect x, which again depends on the environmental policy instrument. In this section we focus on emission taxes; section 5 considers the case of quotas.

The polluting sector has abatement costs equal to $C(x,\ell)+v(x,\ell)$. Thus, once both p and ℓ are given, x is determined by setting marginal abatement costs equal to the emission tax rate. The supply function (1) defining $x(p,\ell)$ is thus valid also when x denotes abatement.

4.1 The tax is set after ℓ

If the price is set after the license fee ℓ and the regulator sets the tax p equal to the Pigouvian level B', we get exactly the same outcome as described in the previous section for a market good. If this were the case, the incentives for environmental R&D would thus be exactly the same as for a market good. However, this rule for setting the emission tax rate is generally not optimal: The government should choose p to maximize $B(x) - C(x,\ell)$, taking ℓ as given. This is achieved by equating the *social* marginal abatement cost with marginal benefits of abatement, i.e.

$$C_x(x,\ell) = B'(x) \tag{5}$$

which in combination with the supply function (1) gives

$$p = B'(x) + v_x(x,\ell) \tag{6}$$

defining $p^*(\ell)$ and $x^*(\ell) \equiv x(p^*(\ell),\ell)$ for any given ℓ. It follows that $p^*(\ell) > p^0(\ell)$, since $p^0(\ell)$ was defined by $p = B'(x)$ and $v_x(x,\ell) > 0$ (unless $\ell = 0$). Since $p^*(\ell) > p^0(\ell)$ and $x_p > 0$, it follows that $x^*(\ell) > x^0(\ell)$.

The reason for the government to set the emission tax rate higher than the Pigouvian rate is to encourage more abatement than what the Pigouvian rate gives: The pricing of the technology makes private marginal abatement costs

[9] If envrionemntal costs are $D(\bar{E}-x)$ we have $B(x) \equiv D(\bar{E}) - D(\bar{E}-x)$, implying $B(0) = 0$, $B' = D'$ and $B'' = -D''$.

higher than social marginal abatement costs, thus giving too little abatement if the tax rate is at the Pigouvian level.

The curve $p^*(\ell)$, drawn in Figure 2, is the regulator's response function for the case of environmental R&D: It tells us what the optimal carbon tax is for any given licence fee. Whatever ℓ is, the equilibrium abatement follows from $x(p^*(\ell), \ell) \equiv x^*(\ell)$. Notice that $p^*(\ell)$ must be drawn to the right of $p^0(\ell)$ since $p^*(\ell) > p^0(\ell)$.

The innovator will set ℓ taking the regulator's response function into consideration, i.e. so that $v(x^*(\ell), \ell)$ is maximized. This gives:

$$v^I = \max_\ell \left[v(x^*(\ell), \ell) \right] \tag{7}$$

where v^I denotes the equilibrium payoff to the innovator when the innovator sets its price before the government responds.

Denote the optimal ℓ in the abatement technology case ℓ^*. If $v^I > v^0$, incentives are higher for environmental R&D than for market goods R&D. Comparing (3) and (7) and using $x^*(\ell) > x^0(\ell)$ immediately results in the following proposition:

Proposition 1 *If environmental policy is set after the innovator sets the licence fee, incentives are higher for environmental R&D than for market goods R&D.*

The innovator's optimal choice of ℓ for this case is at the point I in Figure 2. This is the point along the curve $p^*(\ell)$ that gives the innovator the highest payoff. Since $p^*(\ell) > p^0(\ell)$ it follows that $v^I > v^0$.

4.2 The tax is set simultaneously with ℓ

When the innovator takes the carbon tax p as given, its response function follows from maximizing $v(x(p, \ell), \ell)$ with respect to ℓ. This gives the payoff

$$\tilde{v}(p) = \max_\ell \left[v(x(\ell, p), \ell) \right] \tag{8}$$

and the solution $\ell^*(p)$ to this maximization problem is the innovator's response function, illustrated in Figure 2. Any point on the curve $\ell^*(p)$ is given by the tangency point of an iso-payoff curve and the vertical line representing the given value of p. We have drawn the curve upward sloping: It seems reasonable to expect $\ell'(p) > 0$, i.e. that a higher demand gives the monopolist a higher optimal price. However, most of our results remain valid also if $\ell'(p) \leq 0$.

If the innovator chooses ℓ simultaneously with the regulator choosing p, the equilibrium must be characterized by both players being on their respective response functions. This equilibrium is illustrated as S in Figure 2. It is clear that the equilibrium tax is higher than the Pigouvian level also in the present case. However, it is not obvious that $v^S > v^0$, although this is the case the way we have drawn Figure 2.

For the special case of $B'' = 0$ (corresponding e.g. to a fixed international price in the case of a regular good), the curve $p^0(\ell)$ is vertical, and the point M will be at the intersection between $p^0(\ell)$ and $\ell(p)$. In this case we must therefore have $v^S > v^0$. Due to continuity we hence have the following result.

Proposition 2 *If environmental policy is set simultaneously with the innovator setting the licence fee, incentives are higher for environmental R&D than for R&D for market goods if B'' is sufficiently small .*

In the next section we give an example for which we may have both $v^S > v^0$ and $v^S < v^0$.

4.3 The tax is set prior to ℓ

If the tax is set prior to the license fee, the payoff to the innovator is as before given by (8). However, the tax will generally be different for this case than for the case when p and ℓ are set simultaneously. The regulator will set its tax taking the innovator's response function $\ell^*(p)$ into consideration.

In Figure 3 we have also included the iso-welfare curves W' and W^R for the regulator.[10] Since $C_l(x, \ell) > 0$, welfare is declining in ℓ for a given p. This means that the values along the iso-welfare curves for the regulator are higher the further down we are in Figure 3.

[10] See the Appendix for the derivation of the iso-welfare curves.

The regulator's optimal choice of ℓ for this case is at the point R in Figure 3. This is the point along the curve $\ell^*(p)$ that gives the regulator the highest welfare. Using v^R to denote the payoff to the innovator in this case, it is clear that we must have $v^R < v^S$ provided $\ell'(p) > 0$ (and $v^R \geq v^S$ if $\ell'(p) \leq 0$, henceforth this case is ignored). We have drawn the figure so $v^R < v^0 < v^S < v^I$. However, it is also possible for v^0 to be higher than both v^R and v^S or lower than both v^R and v^S.

From Proposition 2 we know that for the special case of $B'' = 0$, $v^S > v^0$. For this case it is clear from Figure 3 and the previous discussion that the sign of $\tilde{v}(p) - v^0$ must be equal to the sign of $p - B'$. In other words, whether incentives for R&D are larger or smaller for abatement than for market goods in this case thus depends on whether the optimal emission tax is higher than or lower than the Pigouvian level. To see what the size of $p - B'$ in the present case, we must consider the optimization problem of the government.

Once p is determined, the equilibrium values of ℓ and x follow, denote these by $\tilde{\ell}(p)$ and $\tilde{x}(p)$. Differentiating (4) gives:

$$\frac{dW}{dp} = \left[B'(x) - C_x(x,\ell)\right]\tilde{x}'(p) - C_l(x,\ell)\tilde{\ell}'(p)$$

Inserting the equilibrium condition (1) into this expression and setting $\frac{dW}{dp} = 0$ gives:

$$p = B' + v_x - \frac{\tilde{\ell}'(p)}{\tilde{x}'(p)} C_\ell(x,\ell)$$

The term v_x has the same interpretation as before: The government has an incentive to set the tax above the Pigouvian level in order to decrease the dead weight loss from the monopoly pricing of the new technology. If $\frac{\tilde{\ell}'(p)}{\tilde{x}'(p)} > 0$ and $C_\ell > 0$, the term $-\frac{\tilde{\ell}'(p)}{\tilde{x}'(p)} C_\ell(x,\ell)$ is negative, tending to make it optimal to set the emission tax below the Pigouvian level. In other words, by raising the tax above the Pigouvian level, the government also increases the efficiency loss from the suboptimal allocation of abatement between the old and new technology.

Proposition 3 *If environmental policy is set before the innovator sets the* *licence fee, the sign of $v^R - v^0$ is ambiguous.*

In the next section we provide an example in which both $v^R > v^0$ and $v^R < v^0$ is possible depending on the parameter values.

5 Example

5.1 The cost and revenue function

In line with Requate (2005) we look at an example in which not all firms benefit identically from the new technology. There exist a continuum of firms with unit emissions. The firms are ranked so that costs of abatement is increasing in the number of the firm x. Then, if a firm chooses the old abatement technology, it has abatement cost gx, while, if a firm buys the new abatement technology, it has abatement cost $\ell + \alpha gx$, where ℓ is a fixed licence fee and $\alpha \in \langle 0, 1\rangle$. Due to the fixed costs of the new technology, firms with higher numbers will choose the new technology. In particular, firms up to $\hat{x}$ will choose the old technology, where $\hat{x}$ is determined by $g\hat{x} = \alpha g\hat{x} + \ell$, implying $\hat{x} = \frac{\ell}{(1-\alpha)g}$. Payoff to innovator is thus given by:

$$v(x, \ell) = \ell\,[x - \hat{x}] = \ell\left[x - \frac{\ell}{(1-\alpha)\,g}\right] \tag{9}$$

And the cost function $c(x, \ell)$ is given by:

$$c(x, \ell) = \int_0^{\frac{\ell}{(1-\alpha)g}} gsds + \int_{\frac{\ell}{(1-\alpha)g}}^{x} \alpha gsds = \frac{\ell^2}{2\,(1-\alpha)\,g} + \frac{\alpha g x^2}{2} \tag{10}$$

As postulated above $c(x, \ell)$ is increasing in both arguments. Note also that private marginal abatement cost (MAC) $c_x + v_x$ is equal to $\alpha gx + \ell$. In the following we normalize such that $b = g = 1$.

5.2 Comparing the cases

The private sector equates private marginal cost with the market price (or the emission tax): $p = \alpha x + \ell$. Let marginal benefit of x be given by $B'(x) = 1 - \beta x(p)$. It is then possible to solve the model explicitly for each of the cases. In the Appendix we solve for the market goods case, and the two cases in which the government either sets p before or simultaneously with ℓ. Here we just report the results:

The revenue of the innovator in the market good case is given by:

$$v^0 = \frac{(1-\alpha)}{4\beta + 4\beta^2 + 4\alpha + 4\alpha\beta} \tag{11}$$

We then look at the ambiguous case in which the emission tax is set before licence. The revenue of the innovator is then given by:

$$v^R = \frac{\alpha(1-\alpha)(\alpha+1)^2}{(\beta + \alpha + 2\alpha\beta + 3\alpha^2 + \alpha^2\beta)^2} \tag{12}$$

The question is whether this revenue is lower than in the market good case. By comparing (12) with (11) from above we have that innovator revenue is higher in the market goods case if:

$$[\alpha - 1]\left[5\alpha^3 + 3\alpha^2 + 2\alpha^3\beta + 4\alpha^2\beta + 2\alpha\beta + \alpha^3\beta^2 + \alpha^2\beta^2 - \alpha\beta^2 - \beta^2\right] > 0$$

Clearly, for large β and small α, this could be the case i.e. both terms in brackets above are negative. On the other hand, for β equal to zero or close to zero, innovator revenue is higher in the environmental innovation case.

Finally, we look at the case in which the tax and the licence is set simultaneously. Innovator revenue is then given by:

$$v^S = \frac{\alpha(1-\alpha)}{(\alpha+1)^2(\beta+\alpha)^2}$$

Comparing v^S with v^0, we get that innovator revenue is higher in the market goods case if:

$$[\alpha - 1]\left[\alpha^3 + 3\alpha^2 + 2\alpha\beta(1-\alpha) + \alpha\beta^2 - \beta^2\right] > 0$$

and again we notice that for large β and small α, this could be the case i.e. both terms in brackets above are negative. On the other hand, for β equal to zero or close to zero, innovator revenue is higher in the environmental innovation case.

Assume for instance that $\alpha = 0.5$. Then $v^0 < v^R < v^S$ if $\beta = 1$, $v^R < v^0 < v^S$ if $\beta = 3$, while $v^R < v^S < v^0$ if $\beta = 4$.

6 R&D incentives for abatement with tradeable emission permits

So far the strategic variable of the regulator has been the price on emissions. Montero (2010) considers the case in which the amount of issued emission permits is the strategic variable, and in which the government is able to commit to a given amount of quotas before the innovator sets the licence fee. On the other hand, the model in Montero is less general than the one in this paper, so we think it is worthwhile to discuss the issue of quotas versus taxes in light of our model.

Quotas are set after the licence fee

Once the license is set, the socially optimal amount of abatement is given by (5), defining $x^*(\ell)$. The equilibrium payoff to the innovator is therefore like in the tax case given by (7). When the license is set before the environmental policy instrument, it therefore makes no difference whether an emission tax or quotas are used as the policy instrument. Proposition 1 remains valid also for the quota case.

6.1 Quotas and the license fee are set simultaneously

It is useful to start by deriving the response functions of the innovator and the government. For any value of x the innovator will chose ℓ to maximize $v(x, \ell)$, giving $\ell^*(x)$. This function is increasing in x provided $v_{x\ell} > 0$. It is drawn as the line $\ell^*(x)$ in Figure 4. The government wants to maximize $B(x) - C(x, \ell)$, giving the response function $x^*(\ell)$ defined by $B'(x) - C_x(x, \ell) = 0$. As shown in Figure 4 it is downward sloping provided $C_{x\ell} > 0$. Notice that for the special case of $C_{x\ell} = 0$ for all (x, ℓ), which is true in our example, $x^*(\ell)$ will be a vertical line. When x and ℓ are set simultaneously, we get the outcome S in Figure 4. What can we say about v^S(v at S) compared with v^0 (i.e. v at M)?

In Figure 4 we have also drawn the curve $x^0(\ell)$ which is given above from (1) and (2). This curve is drawn to the left of the curve $x^*(\ell)$ of the same reason as $p^0(\ell)$ is to the left of $p^*(\ell)$ in the figures above. That is, the government wants more use of the new technology than the market solution due to the efficiency loss from the licence fee. In the figure $v^S > v^0$. This will certainly be true if $C_{x\ell} = 0$ for all (x, ℓ), which is true in our example, implying that $x(\ell)$ is a vertical line. [11]However, $v^S < v^0$ is also possible, at least mathematically.[12]

6.2 Quotas are set before the licence fee

In Figure 4 we have also included the iso-welfare curve W^Q for the regulator. Since $C_l(x, \ell) > 0$, welfare is declining in ℓ for a given x. This means that the values along the iso-welfare curves for the regulator are higher the further down we are in Figure 4.

The government now gets to choose a point on $\ell^*(x)$, and it will choose the point Q in Figure 4. It must always be true that $v^Q \leq v^S$, with $<$ if $\ell(x)$ is upward sloping, i.e. if $v_{x\ell} > 0$. Since we have shown that $v^S < v^0$ is possible, $v^Q < v^0$ is therefore also possible. In the figure $v^Q > v^0$. One possibility of this occurring is the case in which $C_{x\ell} = v_{x\ell} = 0$ but $v_x > 0$. In this case $\ell(x)$ is horizontal while $x(\ell)$ will be vertical and to the right of

[11] We have also solved the example for the case of emission quotas. It can be obtained for the authors upon request.

[12] If e.g. $v_x = 0$ for all (x, ℓ), the curve $\ell^*(x)$ will be horizontal and the curve $x^*(\ell)$ will coincide with $x^0(\ell)$. If $C_{x\ell} > 0$ the curve $x^*(\ell) = x^0(\ell)$ will be downward sloping. With these curves it must be true that $v^S < v^0$. It is however not obvious that the combination of $v_x = 0$ and $C_{x\ell} > 0$ is particularly reasonable from an economic point of view.

$x^0(\ell)$. In this case Q and S will coincide, and $v^Q = v^S > v^0$. [13]

7 Discussion and conclusion

We have shown that the presentiment that incentives for environmental R&D are lower than incentives for market goods R&D is not generally true. When the innovator is able to commit to a licence fee before environmental policy is resolved, incentives are always higher for environmental R&D than for market goods R&D. Moreover, when the government is able to commit, but the innovator is not, or when neither the innovator nor the government is able to commit, the relative size of the incentives could go both ways.

Throughout the paper we have assumed that R&D takes place in separate R&D firms that sells its innovations to a competitive downstream sector producing either a market good or pollution abatement. If R&D instead took place in the competitive downstream sector and new knowledge became available to all firms in the sector free of charge, there is no difference between the incentives for market goods R&D and the incentives for environmental R&D. It is the innovator's ability to control the access to new knowledge, and the regulators's desire to use environmental policy to counteract the negative effect of this control, which creates the differences in the incentives between environmental R&D and market goods R&D.

Acemoglu et al. (2010) analyze another potential reason for possible differences in the incentives between environmental R&D and market goods R&D. In Acemoglu et al. (2010) there are two distinct bases of knowledge: One for brown energy, and one for green energy. It is assumed that knowledge spillovers are less important between the two bases than within the bases. The market for brown energy innovations is larger at the outset of the model. Hence, the green emerging field of technology development may have problems attracting researchers and research finance because doing research on existing technologies pay better. Furthermore, due to the assumption about knowledge spill-overs, green technologies may never take off even if emissions

[13] In our example with emission quotas we show that both $v^Q > v^0$ and $v^Q < v^0$ are possible. It can be obtained for the authors upon request.

are priced according to their marginal damages.

In our model there is only one polluting sector. However, for some environmental problems, like for instance climate change, many different sectors emit the same type of pollutant. Clearly, an innovation may only be relevant for one of the sectors. Given that environmental regulation is harmonized across sectors, this will presumably make it more difficult for the government to expropriate the innovation.

8 Appendix

8.1 The iso-payoff curves of the innovator

These curves are implicitly defined by:

$$v' = v(x(p,\ell),\ell)$$

where v' is some fixed level of the pay-off. By differentiating we obtain: $v_x x_p dp + (v_x x_\ell + v_\ell)d\ell = 0$, and hence, their curvature is described by:

$$\frac{d\ell}{dp} = \frac{-v_x x_p}{v_x x_\ell + v_\ell}$$

The numerator is negative or zero since $v_x, x_p \geq 0$. The denominator $v_x x_\ell + v_\ell$ is positive when $\ell < \ell^*$ and negative when $\ell > \ell^*$. Hence, for the sign of $\frac{d\ell}{dp}$ we have:

$$\begin{array}{ll} \frac{d\ell}{dp} < 0 & \text{for} \quad \ell < \ell^* \\ \frac{d\ell}{dp} > 0 & \text{for} \quad \ell > \ell^* \end{array}$$

Note also that since a higher p, likely yields a higher ℓ^*, the turning points of the iso-payoff curves in Figure 1 are drawn for higher ℓ^*, the higher the p. Moreover, since for a given ℓ, payoff is increasing p, pay-offs are increasing as we move to the right in the diagram ($\frac{\partial v}{\partial p} = v_x x_p \geq 0$).

8.2 The iso-welfare curves of the government

These curves are implicitly defined by:

$$w' = B(x(p,\ell)) - C(x(p,\ell),\ell)$$

where w' is some fixed level of the welfare. By differentiating we obtain: $(B' - C_x)x_p dp + [(B' - C_x)x_\ell - C_\ell]\, d\ell = 0$, and hence, their curvature is described by:

$$\frac{d\ell}{dp} = \frac{-(B' - C_x)x_p}{(B' - C_x)x_\ell - C_\ell}$$

Remember $x_p, C_\ell \geq 0$, while $x_\ell \leq 0$. The term $B' - C_x$ is maximized for some p given by $p^*(\ell)$. Thus, both the numerator and the denominator are negative when $p < p^*(\ell)$. When $p > p^*(\ell)$, the numerator turns positive. The sign of the denominator is equal to the sign of $\frac{\partial w}{\partial \ell}$. We assume $\frac{\partial w}{\partial \ell} < 0$, i.e. a lower price on the new technology, implies more use of the new technology which saves costs. Hence, for the sign of $\frac{d\ell}{dp}$ we have:

$$\begin{array}{lll} \frac{d\ell}{dp} > 0 & \text{for} & p < p^*(\ell) \\ \frac{d\ell}{dp} < 0 & \text{for} & p > p^*(\ell) \text{ and } \frac{\partial w}{\partial \ell} < 0 \end{array}$$

This is what we have drawn in Figure 3. Since we assume $\frac{\partial w}{\partial \ell} < 0$, welfare must be increasing as ℓ decreases. In other words, welfare must be decreasing as we move downwards in the diagram. Lastly, for ℓ above some threshold, no firm adapts the new technology and accordingly $C_\ell, x_\ell = 0$. The iso-welfare curves are then not defined.

8.3 Solving the example in section 5

8.3.1 The market goods case

The private sector equates private marginal cost with the market price: $p = \alpha g x + \ell$. Total supply x is then given by (for $g = 1$):

$$x = \frac{p - \ell}{\alpha g} \tag{13}$$

Let marginal benefit of x be given by $B'(x) = 1 - \beta x(p)$. In the market goods case we must have $p = 1 - \beta x$. By inserting for p in (13), and solving for x we obtain:

$$x = \frac{b - \ell}{\alpha g + \beta} \tag{14}$$

By inserting (14) into (9) we get the revenue function of the innovator as a function of ℓ only, $\ell \left[\frac{1-\ell}{\alpha+\beta} - \frac{\ell}{1-\alpha}\right]$, and by maximizing this expression wrt. ℓ we obtain the optimal ℓ:

$$\ell^0 = \frac{1-\alpha}{2(1+\beta)}$$

The revenue of the innovator in the market good case can then be calculated:

$$v^0 = \frac{1-\alpha}{4\beta + 4\beta^2 + 4g^2\alpha + 4g\alpha\beta} \tag{15}$$

8.3.2 Emission tax is set before licence

The private sector equates private MAC with the emission tax p which gives $x = \frac{p-\ell}{\alpha}$ as in (13) above. The number of firms choosing the new technology is $x - \hat{x} = \frac{p-\ell}{\alpha} - \frac{\ell}{1-\alpha}$. Hence, the revenue function of the innovator as a function of the emission tax (instead of x) is given by:

$$v(\ell, p) = \frac{p(1-\alpha)\ell - \ell^2}{\alpha(1-\alpha)} \tag{16}$$

The response function of the innovator follows from maximizing this for given p, which gives

$$\ell^*(p) = \frac{(1-\alpha)p}{2} \tag{17}$$

and note that the optimal ℓ^* is increasing in the emission tax. For the reduced form abatement function and the revenue function we further have: $x = \frac{(1+\alpha)p}{2\alpha}$, and $v^* = \frac{(1-\alpha)p^2}{4\alpha}$. Moreover, by inserting for x and ℓ^* into the cost function we obtain for the abatement costs as a function of p:

$$c(p) = \left(\frac{1+3\alpha}{8\alpha}\right)p^2$$

Now consider the problem of the government. The government maximizes the net benefit of abatement i.e. $B(x(p)) - c(p)$ with respect to p. As above let $B'(x) = 1 - \beta x(p)$. We then have for the optimal emission tax:

$$p^R = \frac{2\alpha(1+\alpha)}{\alpha + 3\alpha^2 + \beta(1+\alpha)^2}$$

and the revenue of the innovator can be calculated:

$$v^R = \frac{\alpha\,(1-\alpha)\,(\alpha+1)^2}{(\beta+\alpha+2\alpha\beta+3g\alpha^2+\alpha^2\beta)^2} \tag{18}$$

The question is whether this revenue is lower than in the market good case. By comparing (12) with (11) from above we have that innovator revenue is higher in the market goods case if:

$$[\alpha-1]\left[5\alpha^3+3\alpha^2+2\alpha^3\beta+4\alpha^2\beta+2\alpha\beta+\alpha^3\beta^2+\alpha^2\beta^2-\alpha\beta^2-\beta^2\right]>0$$

Clearly, for large β and small α, this could be the case i.e. both terms in brackets above are negative. On the other hand, for β equal to zero or close to zero, innovator revenue is higher in the environmental innovation case.

8.3.3 The tax and the licence is set simultaneously

The reaction function of the innovator is given by (17). The government maximizes the net benefit of abatement i.e. $B(x(\ell,p))-c(\ell,p)$ with respect to p. Thus, in order to derive the reaction function of the government, we need the cost function to be written as a function of ℓ and p. Using $x=\frac{p-\ell}{\alpha}$, we obtain $c(\ell,p)=\frac{\ell^2}{2(1-\alpha)}+\frac{(p-\ell)^2}{2\alpha}$. Hence., the reaction function of the government is given by:

$$p=\ell+\frac{\alpha}{\beta+\alpha} \tag{19}$$

This is an increasing function in ℓ. By solving (19) and (17) for p and ℓ we obtain:

$$\ell^S=\frac{\alpha(1-\alpha)}{(\alpha+1)\,(\beta+\alpha)},\; p^S=\frac{2\alpha}{\beta+\alpha+\alpha\beta+\alpha^2}$$

and inserting this back into (16) gives:

$$v^S=\frac{\alpha\,(1-\alpha)}{(\alpha+1)^2\,(\beta+\alpha)^2} \tag{20}$$

Comparing v^S with v^0, we get that innovator revenue is higher in the market goods case if:

$$[\alpha - 1]\left[\alpha^3 + 3\alpha^2 + 2\alpha\beta(1-\alpha) + \alpha\beta^2 - \beta^2\right] > 0$$

and again we notice that for large β and small α, this could be the case i.e. both terms in brackets above are negative. On the other hand, for β equal to zero or close to zero, innovator revenue is higher in the environmental innovation case.

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Figure 1

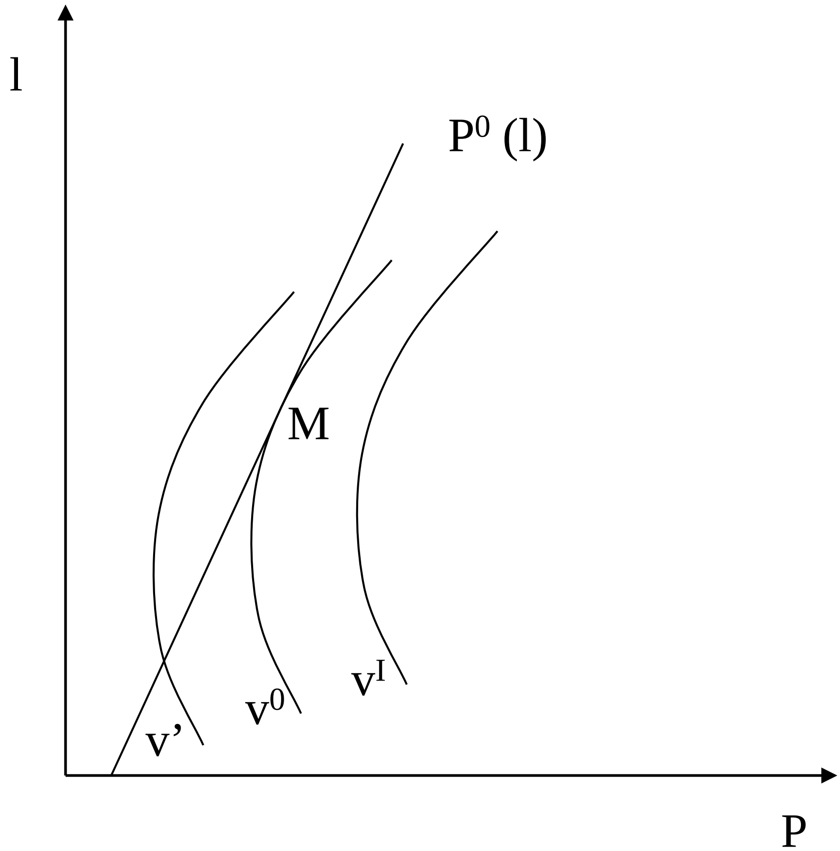

Figure 2

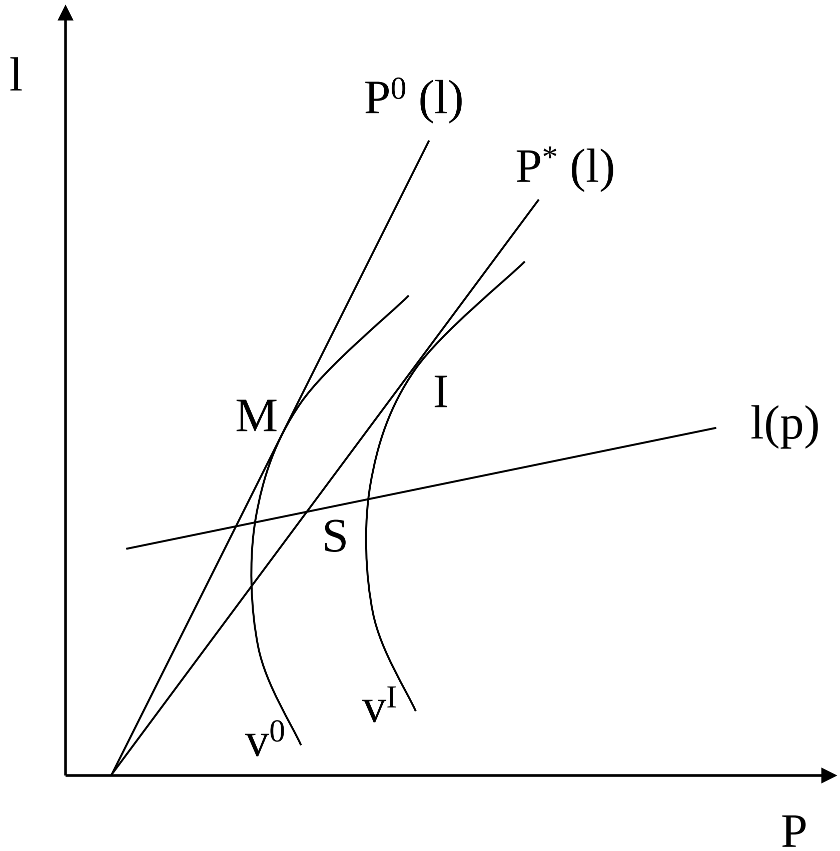

Figure 3

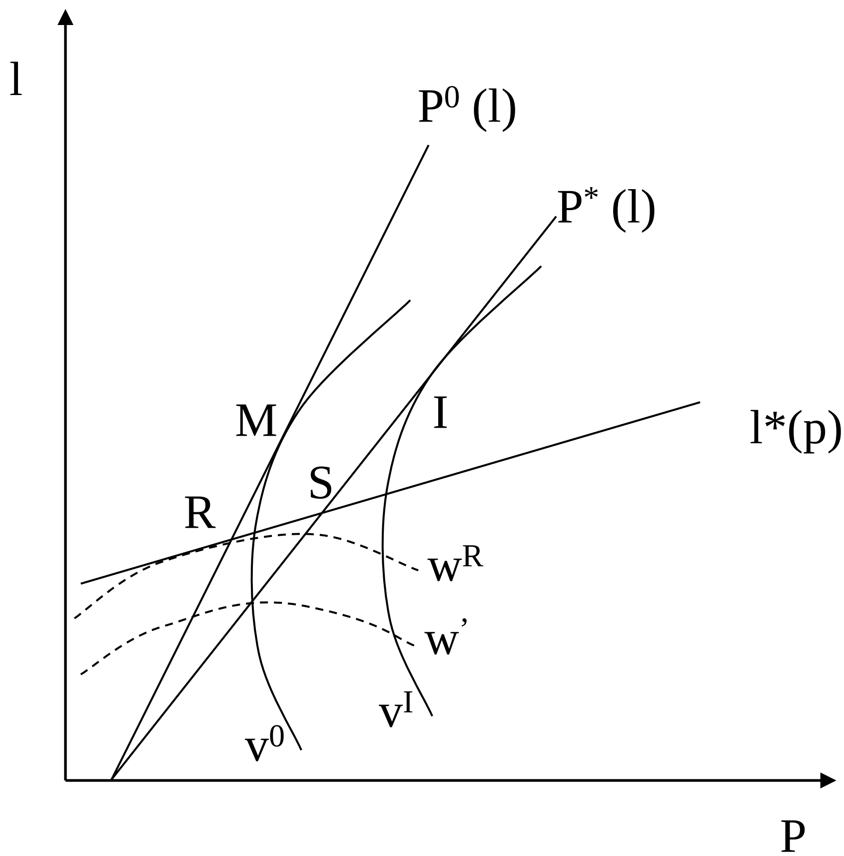

Figure 4