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Incentives for environmental R&D

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Incentives for environmental R&D*

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Abstract

Since governments influence the demand for a new abatement technology through their environmental policy, they may be able to expropriate innovations in new abatement technology ex post. Recent contributions in the environmental R&D literature seem to confirm this conjecture, and suggest that incentives for environmental R&D may be systematically lower than the incentives for market goods R&D. In this paper we compare the incentives for environmental R&D with the incentives for market goods R&D in a more general model of private 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 government sets its policy before or simultaneously with the innovator's choice of licence fee, incentives for environmental R&D may be higher or lower than for market goods R&D.

Keywords: R&D, environmental R&D, innovations, endogenous technological change

JEL classification: H23, O30, Q55, Q58

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1 Introduction

The recent literature on environmental R&D suggests that the incentives for environmental R&D may be distorted if governments are unable to commit to an environmental policy several years ahead.[1] By some this is also used as an argument for environmental R&D to take precedence over markets goods R&D in R&D subsidy programs. On the other hand, 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 of the incentives for R&D in a more general economic model of innovations. Finally, we analyze perfect price discrimination by the innovator, which to our knowledge has not been treated before in the context of environmental 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 to imperfect patent protection, the innovator may not be able to recover the initial R&D investment.[3] As far as we can see 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 should not lead to any systematic difference in the incentives for environmental R&D and for market goods R&D.

Our point of departure is another potential difference between the market goods case and the environmental technology case, namely the way in which

[1] See e.g. Laffont and Tirole (1996), Denicolo (1999), Montgomery and Smith (2007) and Montero (2011)

[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.

demand for the new innovation is determined. In the market good case demand for an innovation is given from the underlying preferences of consumers or technology of firms, and governments seldom interfere with demand even if they in theory could benefit from doing so.[4] In the environmental technology case, we have the opposite situation: Through its environmental policy the government must interfere with the demand for the new technology, and hence, non-interference is not an option. This makes it easier 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 its innovation, and the R&D investment may turn out not to 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.[5] In Laffont and Tirole the government expropriates 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 destroys the incentives for environmental R&D.

[4] One possible reason for why governments do not seek to influence demand for a market good innovation is discussed in the concluding section.

[5] 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), Denicolo (1999), Requate (2005), and Montero (2011).

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 most realistic case, as politicians seem to 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 (2011) build on Laffont and Tirole with respect to the sequence of decisions, but their results differ in a number of ways. For instance, in Montero (2011) 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 as 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 Montero (2011) all polluting firms have the same benefit from the new technology, Requate (2005) includes heterogenous firms. In general this makes it much harder for the government to expropriate the innovation. Moreover, Requate (2005) also analyzes different sequences of the decisions by the government and the innovator. However, he does not consider the simultaneous move 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, which either produces a market good or pollutes and abates, is competitive. Further, 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 sell their innovations in technology markets.[6] 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 of the incentives could go both ways. The results depend on several factors, including whether the innovator is able to price discriminate between different buyers of the new technology.

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 good. In Sections 4 through 6 it is assumed that an innovation reduces the abatement cost of polluting firms. In these sections we compare the incentives for environmental R&D and other R&D. In sections 4 and 5 it is assumed that the policy instrument is a carbon tax, while we in Section 6 briefly discuss the case of quotas. Finally, in section 7 we consider the case in which the innovator is able to capture all of the benefits to the downstream sector of the new technology. Section 8 concludes.

2 The model

2.1 The innovation sector

Our formal model has a similar setup as in Laffont and Tirole (1996), Denicolo (1999), Requate (2005), and Montero (2011), with only one innovating firm. With more R&D, the new technology is either better (i.e. lower costs)

[6] 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).

as in e.g. Montero (2011), or the probability of success (i.e. of obtaining the new technology) is higher, as in e.g. Laffont and Tirole (1996). We consider the post-innovation situation in which a successful innovation has given some specific new knowledge that can reduce costs. 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.

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 her innovation by the competitive sector. The users of the new technology must pay a licence fee to the innovator per unit of some variable that is positively related to aggregate output or abatement. An obvious case would be the one considered by Katz and Shapiro (1986), where each downstream firm pays a fixed licence fee in order to use the new technology. However, our model also includes the case in which the licence payment depends on the use of the new technology by each firm (see e.g. the discussion in Katz and Shapiro). In any case, total payment to the innovator v is given by a revenue function that depends on a price parameter ℓ and is increasing in aggregate output or abatement:

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

where x is the aggregate output of a market good or total abatement by polluting firms in the downstream market. Note that x is *total abatement* i.e. removal of polluting emissions by both the new and the old technology.

In our formal model the innovator thus only has a one-piece tariff. In section 7 we argue that expanding this to e.g. a two-part tariff would not necessarily change any results, as long as the innovator cannot obtain revenue without creating some distortions in the downstream market for producing a market good or reducing emissions.

An obvious assumption about the revenue function $v = v(x, \ell)$ is that that a zero price of whatever the licence is linked to gives zero revenue, and also that revenue is zero if output or total abatement is zero; i.e. $v(0, \ell) = v(x, 0) = 0$. It is also reasonable to assume that for a given value of ℓ, the use of the new technology in increasing in output or abatement, so that $v_x > 0$. We also 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 (for sufficiently high values of ℓ producers will prefer the old, free technology).

We only give a formal analysis of the post-innovation situation. However, we assume that the higher the equilibrium revenue is to the innovator in this post-innovation phase, the larger are the incentives for R&D in the pre-innovation phase. Hence, the larger is the equilibrium value of v, the better is the new technology, and/or the higher is the probability of obtaining the new technology.

2.2 The downstream sector

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

Once the new technology is developed, the cost function is $C(x, 0)$ if the technology is used in a socially optimal way. However, with a fee on the use of the technology, the technology will typically be less than optimally used (Laffont and Tirole; Montero), and the cost function is instead $C(x, \ell)$, which hence usually will be higher than $C(x, 0)$. We make the standard assumptions that $C_x > 0$ 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 $C_\ell \geq 0$. Finally, we make the additional plausible assumptions that $C_{xx} + v_{xx} > 0$ and $C_{x\ell} + v_{x\ell} > 0$, i.e.

that private marginal costs of production or abatement are increasing in x and ℓ.

3 R&D incentives for a market good

Once the licence 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 $C_{xx}+v_{xx}>0$ and $C_{x\ell}+v_{x\ell}>0$, it follows that $x_\ell<0$ and $x_p>0$.

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 $p=B'(x\left(p,\ell\right))$ 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 $C_{xx}+v_{xx}-B''>0$ and $C_{x\ell}+v_{x\ell}>0$, $x^0(\ell)$ will be a strictly declining function. 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

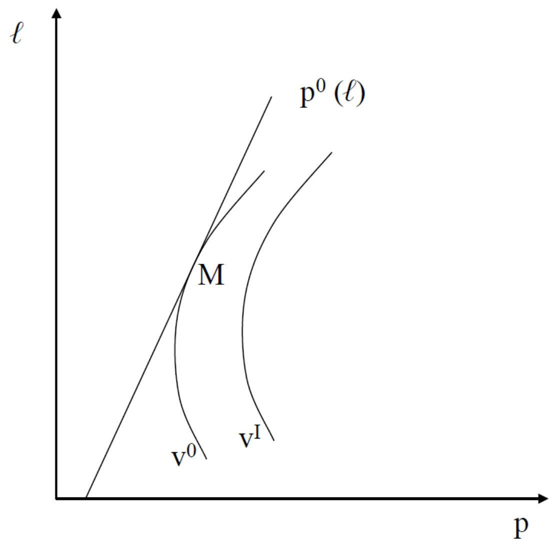
$$v^0=\max_{\ell}\left[v(x^0(\ell),\ell)\right] \tag{3}$$

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

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

Figure 1. This is the point along the curve $p^0(\ell)$ that gives the innovator the highest payoff.

Figure 1



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 we should have $C_x(x, \ell) = p = B'(x)$, given the social cost function $C(x, \ell)$. This will yield $x^0(0)$ which is larger than $x^0(\ell^0)$ since $x^0(\ell)$ is a strictly declining function. The difference reflects the efficiency loss caused by the innovator's pricing of her technology.

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

The difference from the case of a market good is that now the regulator, through its choice of environmental policy, affects demand for the new technology. It is not obvious at what point in time the environmental policy is set. We have identified the following alternatives:

derivation of their properties.

- 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.

As far as we know the third case is not analyzed in the literature before. 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 after environmental policy and ℓ is set.[8] Moreover, like most of the cited literature we do not consider the first case. The time span from initiating R&D till the resulting innovation is no longer marketable is in many cases considerably more than a decade. It is difficult to imagine that governments are able to commit to an environmental policy so far into the future.

It is not easy to argue strongly 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 determination of the environmental policy and the licence fee as a simultaneous move 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

[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.

do not commit to the size of the taxes (nor do 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 her 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:

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

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 6 briefly discusses 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 emission tax p is set after the licence fee ℓ and the regulator sets this tax equal to the Pigovian level B', we get exactly the same outcome as described in the previous section for a market good. 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

[9] If E denotes emissions without any abatement and environmental costs are $D(E - x)$, we have $B(x) \equiv D(E) - D(E - x)$, implying $B(0) = 0$, $B' = D'$ and $B'' = -D''$.

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

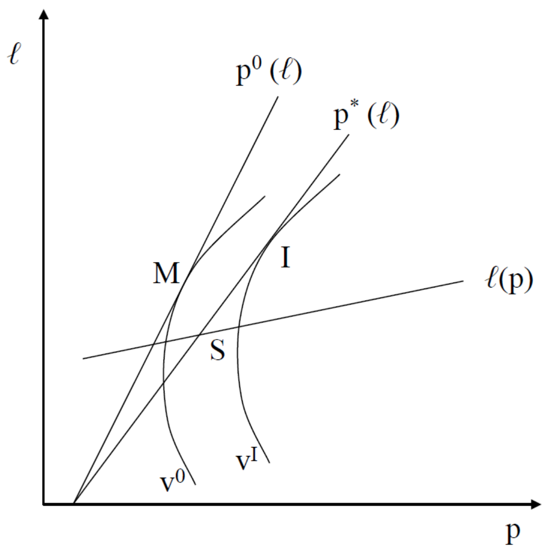
$$p = B'(x) + v_x(x,\ell) \tag{6}$$

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

The reason for the government to set the emission tax rate higher than the Pigovian rate is to encourage more abatement than what the Pigovian rate gives: The pricing of the technology makes private marginal abatement costs higher than social marginal abatement costs, thus giving too little abatement if the tax rate is at the Pigovian 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 $p^*(\ell) > p^0(\ell)$ for $\ell > 0$.

Figure 2



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 her 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, her 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 Pigovian 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 private good), the curve $p^0(\ell)$ is vertical, and the point M will be at the intersection between $p^0(\ell)$ and $\ell(p)$. Hence, since $p^*(\ell) > p^0(\ell)$, we must have $v^S > v^0$ with $B'' = 0$. Due to continuity we then 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 market goods R&D if B'' is sufficiently close to zero.*

When B'' becomes more negative, a small change in ℓ will lead to a large change in the emission tax p. Thus, the induced demand for the new innovation becomes more elastic in ℓ, and this makes it harder for the innovator to extract monopoly profit in the environmental R&D case. In section 5 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

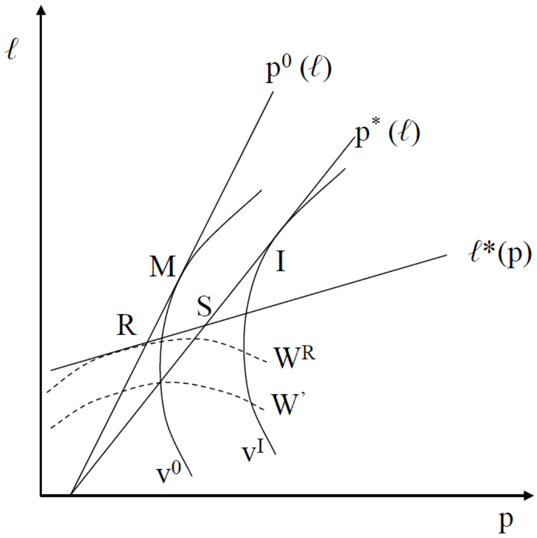
If the tax is set prior to the licence fee, the payoff to the innovator is as before given by (8). For the limiting case of $C_\ell = 0$, the size of ℓ does not have any direct effect on social welfare $(B(x) - C(x, \ell))$. The regulator will in this case therefore choose its tax in the same way as for the case when it was set simultaneously with ℓ, since the regulator has no incentive to try to influence ℓ. Hence, we get the same outcome S as in the case of p and ℓ being set simultaneously.

More generally, for $C_\ell > 0$, the tax will be different for the present 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 included the iso-welfare curves W' and W^R for the regulator. These curves must be horizontal at the point where they cross $p^*(\ell)$. Further, since $C_\ell(x, \ell) > 0$, 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]

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

Figure 3



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.

Remember that when $B'' = 0$, the curve $p^0(\ell)$ is vertical. If the tagency point between the iso-welfare curve and the $\ell(p)$ curve is to the right of $p^0(\ell)$, we must have $p > B'$and $v^R > v^0$. If the tagency point is to the left of $p^0(\ell)$, we have the opposite result. Thus, the sign of $v^R - v^0$ 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 Pigovian 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:

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

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

$$p = B' + v_x - \frac{\tilde{\ell}'(p)}{\tilde{x}'(p)} C_\ell(x,\ell) \tag{9}$$

The term v_x has the same interpretation as before: The government has an incentive to set the tax above the Pigovian 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 Pigovian level. In other words, by raising the tax above the Pigovian 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. For the case of $B'' = 0$, the sign of $v^R - v^0$ is equal to the sign of $p - B'$.*

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 consider an example in which the benefits from the new technology vary across firms. For the case of a market good there is a continuum of firms with unit production capacity. The firms are ranked so that costs of production are increasing in the number of the firm

x. Similarly, for the the case of abatement there is a continuum of firms with unit emissions, and firms are ranked so that costs of abatement are increasing in the number of the firm x.

If a firm chooses the old technology, it has production or abatement cost gx, while, if a firm buys the new technology, it has production or abatement cost $\ell + \alpha g x$, where ℓ is a fixed licence fee and $\alpha \in (0,1)$. Due to the fixed costs of the new technology, firms with higher numbers will choose the new technology (if they produce/abate). 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 $\hat{x} = \frac{\ell}{(1-\alpha)g}$.

The payoff to innovator is thus given by:

$$v(x,\ell) = \ell\,[x - \hat{x}] = \ell\left[x - \frac{\ell}{(1-\alpha)\,g}\right] \tag{10}$$

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

$$c(x,\ell) = \int_{0}^{\frac{\ell}{(1-\alpha)g}} gsds + \int_{\frac{\ell}{(1-\alpha)g}}^{x} \alpha gsds = \frac{\ell^2}{2\,(1-\alpha)\,g} + \frac{\alpha g x^2}{2} \tag{11}$$

As postulated above $c(x,\ell)$ is increasing in both arguments. Note also that private marginal production or abatement cost $c_x + v_x$ is equal to $\alpha g x + \ell$. 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:

$$v^0 = \frac{(1-\alpha)}{4\beta + 4\beta^2 + 4\alpha + 4\alpha\beta} \tag{12}$$

Turning to the case of abatement, we first look at the case in which the emission tax is set before the licence. The revenue of the innovator is then given by:

$$v^R = \frac{\alpha(1-\alpha)(\alpha+1)^2}{(\beta + \alpha + 2\alpha\beta + 3\alpha^2 + \alpha^2\beta)^2} \tag{13}$$

The question is whether this revenue is lower than in the market good case. By comparing (13) with (12) we find that $v^0 > v^R$ if and only 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, the innovator's revenue for the case in which the tax and the licence are set simultaneously. Innovator revenue is given by:

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

Comparing v^S with v^0, we find that $v^0 > v^S$ if and only 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 Quotas versus taxes

So far the strategic variable of the regulator has been the price on emissions. In this section we briefly discuss the case in which the amount of issued emission permits is the strategic variable.

Consider first the case in which the amount of emission permits is determmined after the licence fee ℓ is set. Once the licence is set, the socially optimal amount of abatement is given by (5), defining $x^*(\ell)$. The equilibrium payoff to the innovator is therefore the same as in the tax case given by (7). When the licence 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.

The equivalence between the quota case and the tax case no longer holds if the policy instrument is set prior to or simultaneously with the license. In a supplement to this paper (available upon requst) we show that we get exactly the same ambiguity in the quota case as we found for the tax case.

A comparison between quotas and taxes is only meaningful if the government can commit to using one of the instruments. If not, the government will choose the policy instrument that is best ex post. In the remainder of this section we show that the government will always prefer taxes to quotas (or be indifferent as a limiting case).

Assume that the government sets a quota either prior to or simultaneously with the license. Let the optimal quota be x^0. The best response of the innovator is to choose ℓ so that $v(x^0, \ell)$ is maximized. The optimal ℓ, denoted ℓ^Q, is given by

$$v_\ell(x^0, \ell^Q) = 0 \tag{14}$$

Now consider a tax as an alternative to this quota. One possibility would be to set the tax at a level p^0 making the equilibrium abatement be x^0. In this case the optimal optimal ℓ, denoted ℓ^T, is given by

$$v_x(x(p^0, \ell^T), \ell^Q)x_\ell + v_\ell(x(p^0, \ell^T), \ell^T) = 0 \tag{15}$$

where $x^0 = x(p^0, \ell^T)$.

Since $v_x > 0$ and $x_\ell < 0$, it follows that

$$v_\ell(x^0, \ell^T) > 0$$

Comparing (14) with (15) it follows from the second order condition $v_{\ell\ell} < 0$ that $\ell^T < \ell^Q$. But since $C_\ell \geq 0$ this must imply that social welfare is higher with the tax than with the quota:

$$W^T - W^Q = \left[B(x^0) - C(x^0, \ell^T)\right] - \left[B(x^0) - C(x^0, \ell^Q)\right] \geq 0$$

This inequality is true when the quota is optimally chosen while the tax is chosen so that abatement is the same as in the quota case. With an optimally chosen tax welfare must be even higher. Hence, we obtain the following proposition:

Proposition 4 *If the government cannot commit to the choice of instrument before the innovation happens, the government will choose taxes as the policy instrument.*

As noted by other authors (e.g. Montero, 2011) quotas make the demand for the new innovation more inelastic. This makes it easier for the innovator to exploit her monopoly position, which in turn is the opposite of what the government wants.

7 The innovator can capture all of the benefits from her innovation

So far, we have assumed that the innovator only has a one-piece tariff. Expanding this to e.g. a two-part tariff would not necessarily change any results, as long as the innovator cannot obtain revenue without creating distortions in the downstream market for producing a market good or reducing emissions.

There are two distortions that are driving the results obtained so far. First, the pricing of the new technology implies that it is used less widely than what is optimal (for any output or abatement level), so that social costs are higher than with an optimal use of the technology. In our model this implies that $C(x, \ell) > C(x, 0)$.

The second distortion is that the pricing of the technology makes private marginal production or marginal abatement costs higher than the social marginal costs i.e. $C_x(x, \ell) + v_x(x, \ell) > C_x(x, \ell)$. This distorts the choice of the output or abatement level. Without this distortion, the curve $p^*(\ell)$ in Figures 2 and 3 would coincide with the curve $p^0(\ell)$.

Even if the pricing of the new technology is more complex than the one-dimensional price assumed in this paper, it is difficult to imagine that these two distortions can be completely eliminated. Nevertheless, it is useful to consider the extreme case in which the innovator has so much information and ability to discriminate between different users of her technology that she can obtain all of the downstream sector's gross benefits of using the new technology. The rest of this section is therefore devoted to a relatively brief discussion of this case.

Clearly, it is in the innovator's interest that the cost of the downstream sector is as low as possible, thus making the revenue that the innovator can obtain as large as possible. The first distortion mentioned above is thus eliminated, implying that the cost of the downstream sector will be $C(x, 0)$. However, as we shall see below it is not obvious that the innovator will wish to eliminate the second distortion mentioned above: By pricing her technology in a manner that makes private marginal costs exceed social marginal costs, the innovator can in some cases increase the output price/emission tax so that gross benefits of the downstream sector are increased.

7.1 Regulation with an emission tax

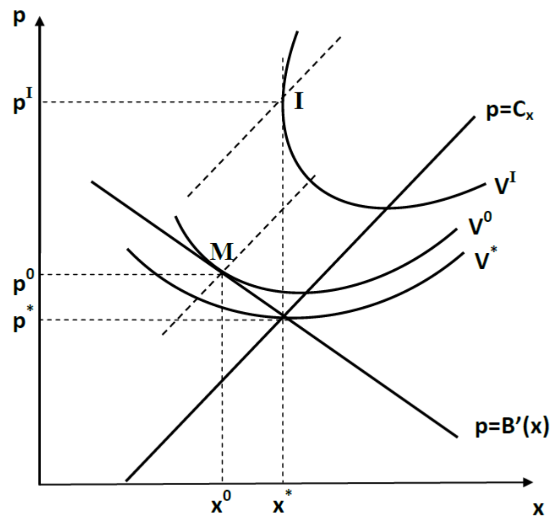
Before any payment to the innovator, the payoff to the downstream sector of adopting the new technology in a socially optimal way is

$$V(p,x) = [px - C(x,0)] - \pi(p) \tag{16}$$

where $\pi(p)$ is the profit if only the old technology is used.

The envelope theorem gives $\pi'(p) = x^{old}(p)$, the latter being the supply function if only the old technology is used. Moreover, let $x(p)$ be defined by $C_x(x,0) = p$. The supply function $x(p)$ is thus the output or abatement level that maximizes $V(p,x)$ for a given value of p. We assume that $x(p) > x^{old}(p)$. In other words, for a given price or emission tax, the optimal output or abatement level is higher when the new technology is used than if only the old technology is used. Both $x(p)$ and $x^{old}(p)$ are drawn in Figure 4 as upward-sloping supply curves.

Figure 4



We proceed to consider the iso-payoff curves of the downstream sector (i.e. curves for constant V). Using the notation above, the slope of the iso-payoff curves is given by:

$$\frac{dp}{dx} = \frac{C_x - p}{x - x^{old}(p)}$$

Three such iso-payoff curve is drawn in Figure 4, where the curves are downward-sloping between $x^{old}(p)$ and $x(p)$, since in this region $C_x - p < 0$ and $x - x^{old}(p) > 0$. The curves are horizontal where they cross $x(p)$ and vertical where they cross $x^{old}(p)$.

We now assume that the innovator is able to appropriate all of the profit $V(p, x)$ due to her sophisticated pricing of the new technology. Consider first the game in which the innovator takes p as given when setting her price parameters. This will be the case when x is abatement and an environmental tax is set either simultaneously with or prior to the the innovators price schedule. Through her pricing, the innovator is able to determine x.[11] Clearly, the best the innovator can do is then to choose x to maximize $V(p, x)$, giving $x = x(p)$. The supply function $x(p)$ is thus identical to the best-response function of the innovator. This implies that the innovator charges a zero abatement dependent fee such that $C_x = p$.

Social welfare is maximized for $B'(x) = C_x(x, 0)$. Since $C_x(x, 0) = p$ whatever p the government chooses, this optimum is obtained by the government setting p so that $B'(x) = p$, i.e. at p^* in Figure 4. The curve $B'(x)$ is also drawn in Figure 4 as a downward-sloping demand curve. The point (p^*, x^*) constitutes the Nash-equilibrium in the simultaneous move game i.e. the innovator decides her pricing policy and the government sets the emission tax, simultaneously. Moreover, it is also the solution to the game in which the government is able to commit to an emission tax before the innovator resolves her pricing policy. The government then picks the welfare maximizing point on $x(p)$ which is (p^*, x^*).

Consider next the case of a market good. The equilibrium must still satisfy $B'(x) = p$. However, since p is no longer chosen by the government, the innovators choice of x need not be on the best response curve of the innovator. The innovator chooses x^0 such that her payoff is maximized, and her highest V is then obtained at the point M in Figure 4. She can obtain this point by setting her price parameters so that the downstream sector will

[11] She can for instance charge a fee ℓ per unit of abatement such that marginal cost of the downstream industry is $C_x + \ell$.

choose x^0. From Figure 4 we note that $p^0 > C_x(x^0, 0)$, and thus, the pricing policy must involve a positive abatement dependent fee. The intuition is that the innovator uses her pricing policy to manipulate the downstream sector to behave as a monopoly thereby increasing revenues. Clearly, the payoff to the innovator in this case (V^0 in Figure 4) is higher than the payoff for the abatement case when p was set prior to or simultaneously with the pricing of the technology (V^* in Figure 4).

Finally, consider the abatement case in which the regulator chooses policy after the innovator has set her price parameters. Social welfare is as above maximized for $B'(x) = C_x(x, 0)$, i.e. $x = x^*$. Knowing that p will be determined so this is satisfied, the innovator can choose her price scheme so she can obtain the value of p that maximizes V. This is at the point I in Figure 4, giving the innovator the payoff V^I, satisfying $V^I > V^0 > V^*$. Again we must have $p^I > C_x(x^I, 0)$ i.e. the innovator charges a positive abatement dependent fee.[12]

The results for the case of an emission tax are summarized in the following proposition:

Proposition 5 *If the emission tax is set after the innovator chooses her price parameters, the innovator's revenue is higher for the case of environmental R&D than for market goods R&D. If the emission tax is set simultaneously with or before the innovator's choice of her price parameters, the innovator's revenue is lower for the case of environmental R&D than for market goods R&D.*

In the Appendix we have an example that solves for the case in which the innovator is able to capture all of the benefits from her innovation.

7.2 Regulation with quotas

When the regulator uses quotas as the regulatory instrument, the regulator simply chooses x^* given by $B'(x) = C_x(x, 0)$ as long as abatement costs

[12] See also the example given in the Appendix.

are given by $C(x, 0)$. The quota price p will depend on the supply curve of abatement. The innovator sets her price parameters so that this supply curve intersects $x = x^*$ at the point I in Figure 4, implying that the innovator achieves the payoff V^I. Hence, we have

Proposition 6 *If quotas are used as the policy instrument, the innovator's revenue is higher for the case of environmental R&D than for other R&D.*

8 Discussion and conclusion

Our point of departure has been that there is a difference between a market good innovation and a pollution abatement innovation with respect to the government's response to the innovation after the innovation has happened. In the former case the government seldom seeks to influence demand for the innovation, while in the latter case the government determines demand through the choice of environmental policy. Clearly, this difference would disappear if the government in both cases had access to a product specific subsidy, for instance differentiated VAT, which could be used to ensure optimal use of the innovation. One reason why the government may not want to use such a subsidy is that it would entail additional administrative costs which may exceed the expected benefits of its use. These costs may include the political costs of terminating the use of the subsidy when the innovation is overtaken by a new and better innovation.

Adjusting the stringency of environmental policy likely does not entail the same administrative costs. Hence, given that the innovation is already there, the government may try to limit the innovator's ability to extract monopoly profit by adjusting environmental policy in order to ensure a more widespread use of the innovation. This may in turn distort the private incentives for environmental R&D. The literature has so far indicated that this is the case, however, the literature has not systematically compared the incentives for environmental R&D with the incentives for market goods R&D.

By using a general model and analyzing a broad collection of cases, we conclude 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. This result holds independent of the type of environmental policy instrument being used. Further, 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. This result is independent of the type of environmental policy instrument being used.

Only in the special case in which the innovator is able to capture *all* private surplus from the innovation, we get results that confirms the presentiment that incentives for environmental R&D are lower than incentives for market goods R&D. When the regulator uses an emission tax and the innovator cannot commit to a licence fee before environmental policy is resolved, incentives are unambiguously higher for market goods R&D than for environmental R&D. With perfect price discrimination, the innovator uses her pricing strategy to induce the downstream sector to behave in a monopolistic way thereby increasing this sector's gross surplus. In the environmental R&D case this is not possible if environmental policy is determined simultaneously with or before the innovator's price scheme. On the other hand, the presentiment is no longer true if the government uses quotas or if the innovator can commit to a pricing strategy before policy is set.

By some authors lower private incentives for environmental R&D has been used as an argument for environmental R&D to take precedence over markets goods R&D in R&D subsidy programs[13]. There may exist good reasons for giving priority to environmental R&D in R&D subsidy budgets, however, the argument based on there being a systematic difference in the incentives for R&D favoring market goods R&D should be used with greater

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

care.

There are also other reasons why it may prove undesirable for the regulator to expropriate an abatement technology innovation. 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. If the innovation is only relevant for one of the sectors and environmental regulation is harmonized across sectors, the regulator may not be able to expropriate the innovation.

Throughout the paper we have assumed that R&D takes place in a separate R&D firm 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.

9 Appendix

9.1 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:

$$\frac{d\ell}{dp} < 0 \quad \text{for} \quad \ell < \ell^*$$
$$\frac{d\ell}{dp} > 0 \quad \text{for} \quad \ell > \ell^*$$

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, payoffs are increasing as we move to the right in the diagram ($\frac{\partial v}{\partial p} = v_x x_p \geq 0$).

9.2 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.

9.3 Solving the example in section 5

9.3.1 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 $g = 1$):

$$x = \frac{p - \ell}{\alpha g} \tag{17}$$

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 (17), and solving for x we obtain:

$$x = \frac{b - \ell}{\alpha g + \beta} \tag{18}$$

By inserting (18) into (10) 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:

$$v^0=\frac{1-\alpha}{4\beta+4\beta^2+4g^2\alpha+4g\alpha\beta} \tag{19}$$

9.3.2 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 (17) 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:

$$v(\ell,p)=\frac{p(1-\alpha)\ell-\ell^2}{\alpha(1-\alpha)} \tag{20}$$

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

$$\ell^*(p)=\frac{(1-\alpha)p}{2} \tag{21}$$

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:

$$v^R = \frac{\alpha\,(1-\alpha)\,(\alpha+1)^2}{\left(\beta + \alpha + 2\alpha\beta + 3g\alpha^2 + \alpha^2\beta\right)^2} \tag{22}$$

The question is whether this revenue is lower than in the market good case. By comparing (13) with (12) 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.

9.3.3 The tax and the licence is set simultaneously

The reaction function of the innovator is given by (21). 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:

$$p = \ell + \frac{\alpha}{\beta + \alpha} \tag{23}$$

This is an increasing function in ℓ. By solving (23) and (21) 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 (20) gives:

$$v^S = \frac{\alpha\left(1-\alpha\right)}{\left(\alpha+1\right)^2\left(\beta+\alpha\right)^2} \tag{24}$$

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.

9.4 Example Section 7

To better understand the results for the case in which the innovator is able to appropriate the whole social surplus it may be useful to consider an example. Let the downstream sector consist of a fixed number of firms, each of which is assumed to benefit from the new technology, so that all output/abatement in equilibrium is with the use of the new technology. However, as in Requate (2005), firms are assumed to differ in the size of these benefits.

The innovator's pricing scheme is a price ℓ per unit of x, and in addition a fixed fee f_i for firm i. This fixed fee is set so that firm i is indifferent between using the new and the old technology, and is then assumed to use the new technology. The innovator's revenue is hence

$$V = \Sigma_i f_i + \ell x$$

The innovator captures all of the downstream sector's benefits of the new technology by setting each f_i as explained above, implying that

$$\Sigma_i f_i = \max_x \left[px - C(x,0) - \ell x\right] - \pi^{old}(p)$$

where $px - C(x,0) - \ell x$ is the aggregate profit of the downstream sector if it chooses the new technology and $\pi(p)$ as above is the aggregate profit of the downstream sector if it chooses the old technology. The downstream sector's choice of x must satisfy $C_x(x,0) + \ell = p$, giving $x = s(p - \ell)$ where $s' = C_{xx}^{-1} > 0$.

From these equations it follows that

$$V(p,\ell) = \max_x [px - C(x,0) - \ell x] - \pi(p) + \ell s(p - \ell)$$

and using the envelope theorem we find

$$\begin{aligned} V_p &= s(p-\ell) - x^{old}(p) + \ell s'(p-\ell) \\ V_\ell &= -\ell s'(p-\ell) \end{aligned}$$

For any given value of p, the best the innovator can do is to set $\ell = 0$.

Whatever ℓ is, the downstream sector's output or abatement choice implies that

$$C_x(s(p-\ell),0) + \ell = p \tag{25}$$

Moreover, whatever ℓ is, (25) implies that the government achieves $B'(x) = C_x(x,0)$ by setting p so that

$$B'\left(s\left(p-\ell\right)\right) + \ell = p \tag{26}$$

When p is determined prior to or simultaneously with ℓ and f, we know that $\ell = 0$, so (25) and (26) give p^F as defined above. On the other hand, when p is determined after ℓ and f, the innovator knows from (25) and (26) that $p - \ell$ is independent of ℓ, so that the maximal value of V is given by $V_p + V_\ell = 0$, implying $s(p-\ell) = x^{old}(p)$. In Figure 4 this means that the supply curve $s(p-\ell)$ intersects with $x = x^*$ at the point I.

For the case of a market good, we have

$$B'\left(s\left(p-\ell\right)\right) = p \tag{27}$$

instead of (26). Together with (25) this gives p as an increasing function of ℓ (but now with $\frac{dp}{d\ell} < 1$), so that also in this case it is optimal for the innovator to set $\ell > 0$. The optimal ℓ makes the supply curve $s(p - \ell)$ intersect with the demand curve $B'(x)$ at the point M in Figure x3.

The interpretation is that the innovator uses her market power to restrict output in the downstream sector, thus increasing gross profits there. Had the downstream sector been a monopolist, it would itself restrict output in this manner, and there would be no need for the innovator to set $\ell > 0$.

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