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## Incentives for Environmental R&D

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# Incentives for Environmental R&D

## Abstract

Since governments can 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. This suggests that 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 more public support than other R&D. 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 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.

JEL-Code: H230, O300, Q550, Q580.

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

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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.<sup>1</sup> 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. 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.<sup>2</sup> Second, due to imperfect patent protection, the innovator may not be able to recover the initial R&D investment.<sup>3</sup> 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

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<sup>1</sup>See for example Montgomery and Smith (2007).

<sup>2</sup>See for instance Jones and Williams (2000).

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

consumers or technology of firms, and governments normally do not interfere with demand. In the environmental technology case, we have the opposite situation: Through its environmental policy the government cannot 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 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.<sup>4</sup> 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.

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

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<sup>4</sup>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 (2010).

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) 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 (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 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 (2010) all polluting firms have the same benefit from the new technology, Requate (2005) includes heterogeneous 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 look at 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 that 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.<sup>5</sup> Each R&D firm is assumed to be so large that it is not a price taker in the market

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<sup>5</sup>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).

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. 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 consider 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 (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). 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 its 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  $\ell$  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.

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 abatement is zero; i.e.  $v(0, \ell) = v(x, 0) = 0$ . It is also reasonable to assume that for a given value of  $\ell$ , the use of the new technology is increasing in output or abatement, so that  $v_x > 0$ . We also assume that  $v_\ell > 0$  for small values of  $\ell$ , but that  $v$  has a maximal level for any given  $x$ , so that  $v_\ell < 0$  for sufficiently large values of  $\ell$  (for sufficiently high values of  $\ell$  producers will prefer the old, free technology). 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  $\ell$ .

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  $\ell$  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  $\ell$  implies that the new technology is used to an even lesser extent, we assume  $C_\ell \geq 0$ . It also seems reasonable that  $C_{x\ell} \geq 0$ , assumed henceforth. It is not obvious what the sign of  $C_{\ell\ell}$  should be. However, for values of  $\ell$  beyond some threshold the new technology will not be used at all, so that  $C_\ell = 0$  for such high values of  $\ell$ , suggesting  $C_{\ell\ell} \leq 0$ , which is henceforth assumed.

### 3 R&D incentives for a market good

Once the licence fee  $\ell$  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

$$C_x(x, \ell) + v_x(x, \ell) = p \quad (1)$$

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

$$p = B'(x) \quad (2)$$

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  $\ell$ . 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  $(p, \ell)$  diagram in Figure 1 for  $B'' < 0$ .

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

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

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  $\frac{dv}{dp} = v_x x_p > 0$ .<sup>6</sup> The innovator's optimal choice of  $\ell$  is at the point M in Figure 1. This is the point along the curve  $p^0(\ell)$  that gives the innovator the

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<sup>6</sup>The iso-payoff curves are curves for constant  $v(x(p, \ell), \ell)$ . See the Appendix for a derivation of their properties.

highest payoff.

Denote the solution to (3) by  $\ell^0$ . 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  $\ell$  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  $\ell$ .
- Environmental policy is set after R&D is carried out, but simultaneously with  $\ell$ ; i.e. neither the innovator nor the regulator is able to commit to  $\ell$  or policy.
- Environmental policy is set after R&D is carried out, and after the innovator sets  $\ell$ ; i.e. the innovator is able to commit to  $\ell$ .

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  $\ell$  is set.<sup>7</sup> Moreover, like most of the cited

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<sup>7</sup>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.

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 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  $\ell$ . 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:

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

where  $B(x)$  now stands for benefits of abatement<sup>8</sup>. 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

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<sup>8</sup>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  $B'' = -D''$ .

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  $\ell$  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 $\ell$

If the emission tax  $p$  is set after the licence fee  $\ell$  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  $\ell$  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  $\ell$ . 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 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  $\ell$  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  $\ell$  taking the regulator's response function into consideration, i.e. so that  $v(x^*(\ell), \ell)$  is maximized. This gives:

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

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

Denote the optimal  $\ell$  in the abatement technology case  $\ell^*$ . 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  $\ell$  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 $\ell$

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

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

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  $\ell$  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 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 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 $\ell$

If the tax is set prior to the licence 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  $\ell$  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.<sup>9</sup> Since  $C_l(x, \ell) > 0$ , welfare is declining in  $\ell$  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.

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<sup>9</sup>See the Appendix for the derivation of the iso-welfare curves.

The regulator's optimal choice of  $\ell$  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 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  $\ell$  and  $x$  follow, denote these by  $\tilde{\ell}(p)$  and  $\tilde{x}(p)$ . Differentiating (4) gives:

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

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

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

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  $\ell + \alpha gx$ , where  $\ell$  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:

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

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

$$c(x, \ell) = \int_0^{\frac{\ell}{(1-\alpha)g}} g s ds + \int_{\frac{\ell}{(1-\alpha)g}}^x \alpha g s ds = \frac{\ell^2}{2(1-\alpha)g} + \frac{\alpha g x^2}{2} \quad (11)$$

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  $\ell$ . Here we just report the results:

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

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

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:

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

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

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

Clearly, for large  $\beta$  and small  $\alpha$ , this could be the case i.e. both terms in brackets above are negative. On the other hand, for  $\beta$  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

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

and again we notice that for large  $\beta$  and small  $\alpha$ , this could be the case i.e. both terms in brackets above are negative. On the other hand, for  $\beta$  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 trade-able 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. Since the model in Montero is less general than the one in this paper, we believe it is worthwhile to discuss the issue of quotas versus taxes in light of our model.

## 6.1 Quotas are set after the licence fee

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.

## 6.2 Quotas and the licence 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  $\ell$  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 values along the iso-payoff curves for the innovator  $v^0$  and  $v^S$  in the diagram are higher the further to the right we are in Figure 4, since  $v_x(x, \ell) > 0$ .

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  $(x, \ell)$ , which is true in the example in section 5,  $x^*(\ell)$  will be a vertical line. When  $x$  and  $\ell$  are set simultaneously, we get the outcome S in Figure 4.

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.

What can we say about  $v^S$  ( $v$  at S) compared with  $v^0$  (i.e.  $v$  at M)? In the figure  $v^S > v^0$ . This will certainly be true if  $C_{x\ell} = 0$  for all  $(x, \ell)$ , which is true in the example in section 5, implying that  $x(\ell)$  is a vertical line.<sup>10</sup>

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<sup>10</sup>We have also solved the example in section 5 for the case of emission quotas. It can be obtained for the authors upon request.

However,  $v^S < v^0$  is also possible.<sup>11</sup>

### 6.3 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  $\ell$  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  $v^S < v^0$  is possible (see footnote 11),  $v^Q < v^0$  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  $x^0(\ell)$ . In this case Q and S will coincide, and  $v^Q = v^S > v^0$ .<sup>12</sup>

## 7 The innovator can capture all of the benefits from its 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 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  $C(x, \ell) > C(x, 0)$ . Without this distortion, the government would not

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<sup>11</sup>We have constructed an example, available upon request, for which both  $v^S < v^0$  and  $v^S > v^0$  are possible.

<sup>12</sup>In the example in section 5 with emission quotas we show that both  $v^Q > v^0$  and  $v^Q < v^0$  are possible. It can be obtained from the authors upon request.

have any interest in the size of  $\ell$  per se, and if it were to set its environmental policy before  $\ell$  it would simply choose  $p$  (for the tax case) or  $x$  (for the quota case) on its response function as explained after (6). (Notice that (9) is identical to (6) for  $C_\ell = 0$ ). Thus, R would coincide with S in Figure 3, and Q would coincide with S in Figure 4.

The second distortion is that the pricing of the technology makes private marginal production or abatement costs higher than the social marginal costs. 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 image 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 its technology that it 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 its 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 profit to the downstream sector of adopting the new technology in a socially optimal way is

$$V = [px - C(x, 0)] - \pi(p) \quad (14)$$

where  $\pi(p)$  is the profit if only the old technology is used. Assume that the innovator due to sophisticated pricing of its technology is able to appropriate all of this profit. Moreover, assume that the innovator through its pricing also is able to determine  $x$  (an example of how this may be done is given below).

Consider first the simplest case in which  $p$  is given when the innovator sets its price parameters. This will be the case when  $x$  is abatement and an environmental tax is set simultaneously with or prior to the the innovators price schedule. Clearly, the best the innovator can do is to choose  $x$  to maximize  $V$ , giving

$$C_x(x, 0) = p \quad (15)$$

Social welfare is maximized for  $B'(x) = C_x(x, 0)$ ; given (15) this is obtained by the government setting  $p$  so that the equilibrium outcome satisfies

$$B'(x) = p \quad (16)$$

Let  $(p^F, x^F)$  – F for first-best – denote the outcome given by (15) and (16).

Consider next the case of a market good. In this case the equilibrium will satisfy  $B'(x) = p$  no matter what the innovator does. Hence, it is possible for the innovator to choose  $(p^F, x^F)$ , giving it the same value of  $V$  as in the case above. However, usually the innovator can do better. Inserting  $B'(x) = p$  into  $V$  and differentiating w.r.t.  $x$  gives, using  $\pi'(p) = x^{old}(p) = x^{old}(B'(x))$  (in obvious notation) from the envelope theorem:

$$V'(x) = [B'(x) - C_x(x, 0)] + [x - x^{old}(B'(x))] B''(x) \quad (17)$$

Assume that  $V(x)$  is concave and that  $x^F = x(p^F) > x^{old}(p^F)$ ; the latter inequality holding provided social marginal costs with the new technology are

lower than marginal costs with the old technology. It then follows from (17) that  $V'(x^F) < 0$ , so that the value of  $x$  maximizing  $V(x)$  is lower than  $x^F$ . Defining  $x^M$  – M for market – by  $V'(x^M) = 0$ , we hence have  $x^M < x^F$  and  $p^M > p^F$  (the last inequality from (16) and  $B'' < 0$ ). Notice that  $B'(x^M) > C_x(x^M, 0)$  implies (from (17) and  $V'(x^M) = 0$ ) that  $x^M > x^{old}(p^M)$ .

Finally, consider the abatement case in which the regulator chooses its policy after the innovator has set its price parameters. As in the analysis in section 4.1, the optimal  $x$  is given by  $B'(x) = C_x(x, 0)$ , i.e.  $x = x^F$ . Knowing that  $p$  will be determined so this is satisfied, the innovator can choose its price scheme so that it can obtain the value of  $p$  that maximizes  $V$ . Since  $x$  is given ( $= x^F$ ), this maximization problem is solved for  $p^I$  defined by (using  $\pi'(p) = x^{old}(p)$ )

$$x^{old}(p^I) = x^F \quad (18)$$

We know from above that  $x^F > x^M > x^{old}(p^M)$ . Since  $x^{old}(p)$  is increasing in  $p$  it follows from (18) that  $p^I > p^M$ . If the innovator instead had chosen its price scheme so the equilibrium tax was  $p^M$ , its revenue would have been  $[p^M x^F - C(x^F, 0)] - \pi(p^M) > [p^M x^M - C(x^M, 0)] - \pi(p^M)$ <sup>13</sup>. The r.h.s. is the revenue to the innovator for the case of a market good. Since the innovator chooses  $p^I$  instead of  $p^M$ , this gives it an even higher revenue. We can thus conclude that when the tax is set after the pricing of the innovation, this gives the innovator a higher revenue and hence higher R&D incentives than in the corresponding case of a market good.

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

**Proposition 4** *If the emission tax is set after the innovator chooses its price parameters, the innovator's revenue is higher for the case of environmental R&D than for other R&D. If the emission tax is simultaneously with or before*

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<sup>13</sup>Proof of the inequality: By definition  $p^F = C_x(x^F, 0)$ . Moreover,  $p^M > p^F$ . It follows that  $p^M > C_x(x^F, 0) > C_x(x, 0)$  for all  $x < x^F$ , implying the inequality.



*the innovator's choice of its price parameters, the innovator's revenue is lower for the case of environmental R&D than for other R&D.*

## 7.2 Regulation with quotas

When the regulator uses quotas as the regulatory instrument, it simply chooses  $x^F$  given by (16) as long as abatement costs are given by  $C(x, 0)$ . The quota price  $p$  is determined passively in the market by (15), giving  $p^F$ . This holds no matter what the decision sequence is. The revenue to the innovator is hence in all cases equal to (in obvious notation)  $[p^F x^F - C(x^F, 0)] - \pi(p^F) = [p^F x^F - C(x^F, 0)] - [p^F x^F - C^{old}(x^F)] = C^{old}(x^F) - C(x^F, 0)$ , which from the analysis above is lower than the revenue in the corresponding case of a market good. Hence, we have

**Proposition 5** *If quotas are used as the policy instrument, the innovator's revenue is lower for the case of environmental R&D than for other R&D.*

## 7.3 Example

To understand the results for the tax case it may be useful to consider a very simple 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  $\ell$  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

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

The innovator captures all of the downstream sector's benefits of the new

technology by setting each  $f_i$  as explained above, implying that

$$\Sigma_i f_i = \max_x [px - C(x, 0) - \ell x] - \pi(p)$$

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  $\ell$  is, the downstream sector's output or abatement choice implies that

$$C_x(s(p - \ell), 0) + \ell = p \tag{19}$$

Moreover, whatever  $\ell$  is, (19) implies that the government achieves  $B'(x) = C_x(x, 0)$  by setting  $p$  so that

$$B'(s(p - \ell)) + \ell = p \tag{20}$$

When  $p$  is determined prior to or simultaneously with  $\ell$  and  $f$ , we know that  $\ell = 0$ , so (19) and (20) give  $p^F$  as defined above. On the other hand, when  $p$  is determined after  $\ell$  and  $f$ , the innovator knows from (19) and (20) that  $p - \ell$  is independent of  $\ell$ , so that the maximal value of  $V$  is given by  $V_p - V_\ell = 0$ , implying  $s(p - \ell) = x^{old}(p)$ .

For the case of a market good, we have

$$B'(s(p - \ell)) = p \tag{21}$$

instead of (20). Together with (19) this gives  $p$  as an increasing function of  $\ell$  (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 interpretation is that the innovator uses its 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  $\ell > 0$ .

## 8 Discussion and conclusion

As mentioned in the introduction there are many reasons why the incentives for R&D may be distorted such that the market outcome is socially inefficient. However, to our knowledge, empirical research has so far not been able to show that there is a systematic difference in the magnitude of these market failures between environmental R&D and market goods R&D.

In this paper we have investigated to what extent the time inconsistency problem distort the private incentives for environmental R&D, and could serve as an argument for increasing the share of environmental R&D in public R&D budgets. We find 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 also holds independent of the type of environmental policy instrument being used. Only in the case when the innovator is able to capture *all* private surplus from the

innovation 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 its 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.

Since the perfect price discrimination case seems unrealistic, we conclude that neither the market failure argument nor the time inconsistency argument provide a convincing justification for policies directed particularly towards environmental R&D.

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:

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

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

### 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:

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

This is what we have drawn in Figure 3. Since we assume  $\frac{\partial W}{\partial \ell} < 0$ , welfare must be increasing as  $\ell$  decreases. In other words, welfare must be decreasing as we move downwards in the diagram. Lastly, for  $\ell$  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  $g = 1$ ):

$$x = \frac{p - \ell}{\alpha g} \tag{22}$$

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 (22), and solving for  $x$  we obtain:

$$x = \frac{b - \ell}{\alpha g + \beta} \tag{23}$$

By inserting (23) into (10) we get the revenue function of the innovator as

a function of  $\ell$  only,  $\ell \left[ \frac{1-\ell}{\alpha+\beta} - \frac{\ell}{1-\alpha} \right]$ , and by maximizing this expression wrt.  $\ell$  we obtain the optimal  $\ell$ :

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

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

$$v^0 = \frac{1-\alpha}{4\beta + 4\beta^2 + 4g^2\alpha + 4g\alpha\beta} \quad (24)$$

### 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 (22) 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:

$$v(\ell, p) = \frac{p(1-\alpha)\ell - \ell^2}{\alpha(1-\alpha)} \quad (25)$$

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

$$\ell^*(p) = \frac{(1-\alpha)p}{2} \quad (26)$$

and note that the optimal  $\ell^*$  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  $\ell^*$  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:

$$v^R = \frac{\alpha(1-\alpha)(\alpha+1)^2}{(\beta + \alpha + 2\alpha\beta + 3g\alpha^2 + \alpha^2\beta)^2} \quad (27)$$

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:

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

Clearly, for large  $\beta$  and small  $\alpha$ , this could be the case i.e. both terms in brackets above are negative. On the other hand, for  $\beta$  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 (26). 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  $\ell$  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:

$$p = \ell + \frac{\alpha}{\beta + \alpha} \quad (28)$$

This is an increasing function in  $\ell$ . By solving (28) and (26) for  $p$  and  $\ell$  we obtain:

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



and inserting this back into (25) gives:

$$v^S = \frac{\alpha(1-\alpha)}{(\alpha+1)^2(\beta+\alpha)^2} \quad (29)$$

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

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

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

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Figure 1

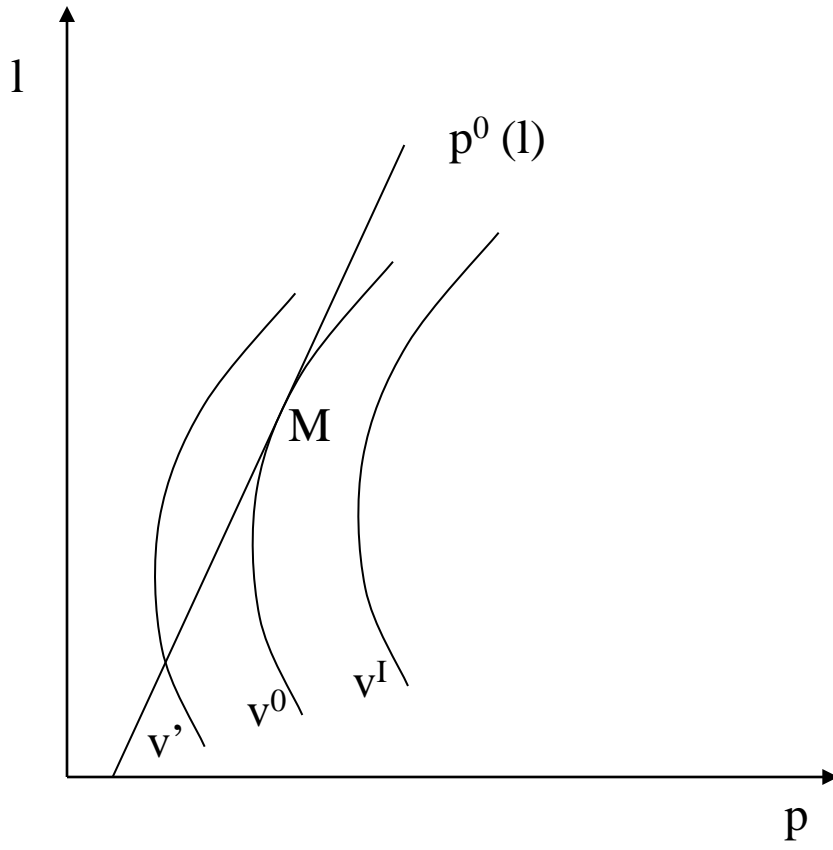


Figure 2

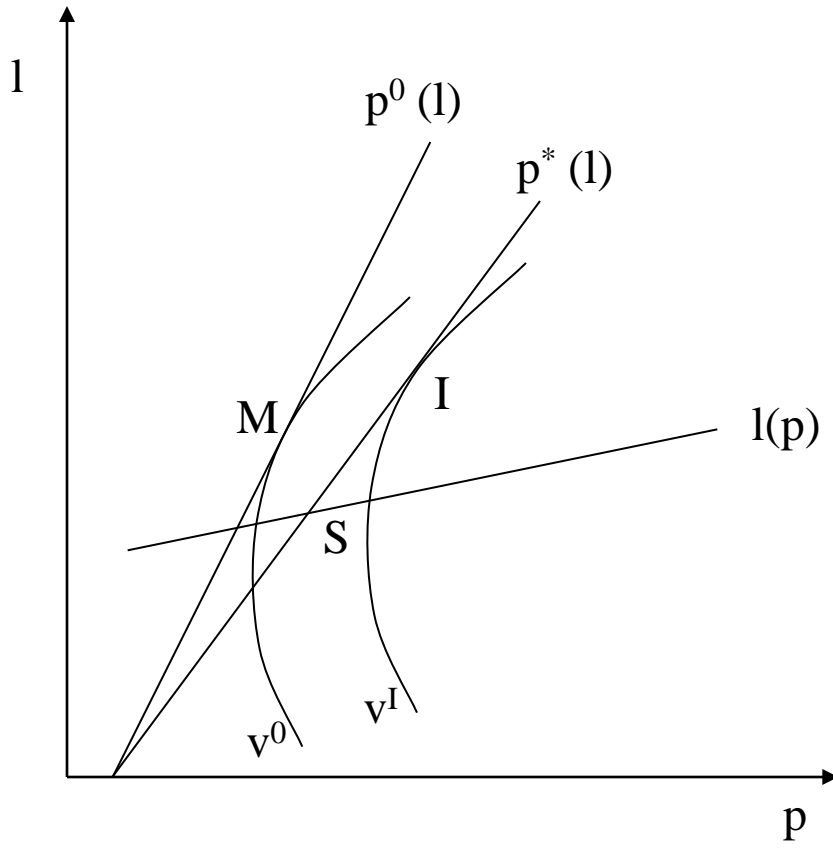


Figure 3

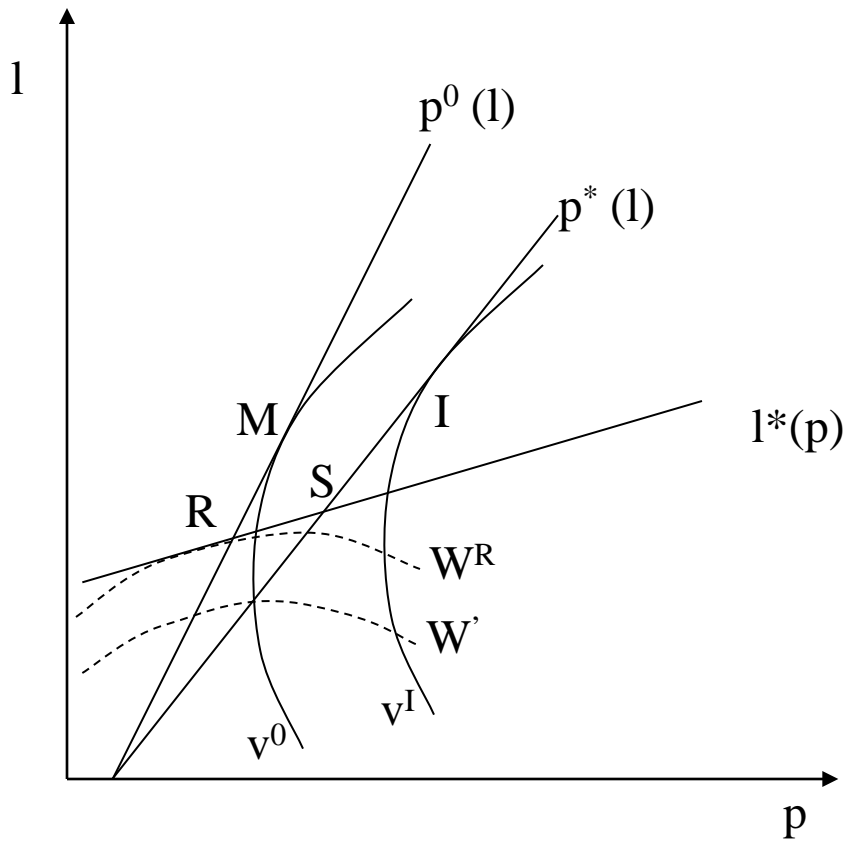


Figure 4

