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# MEMORANDUM

No 12/2010

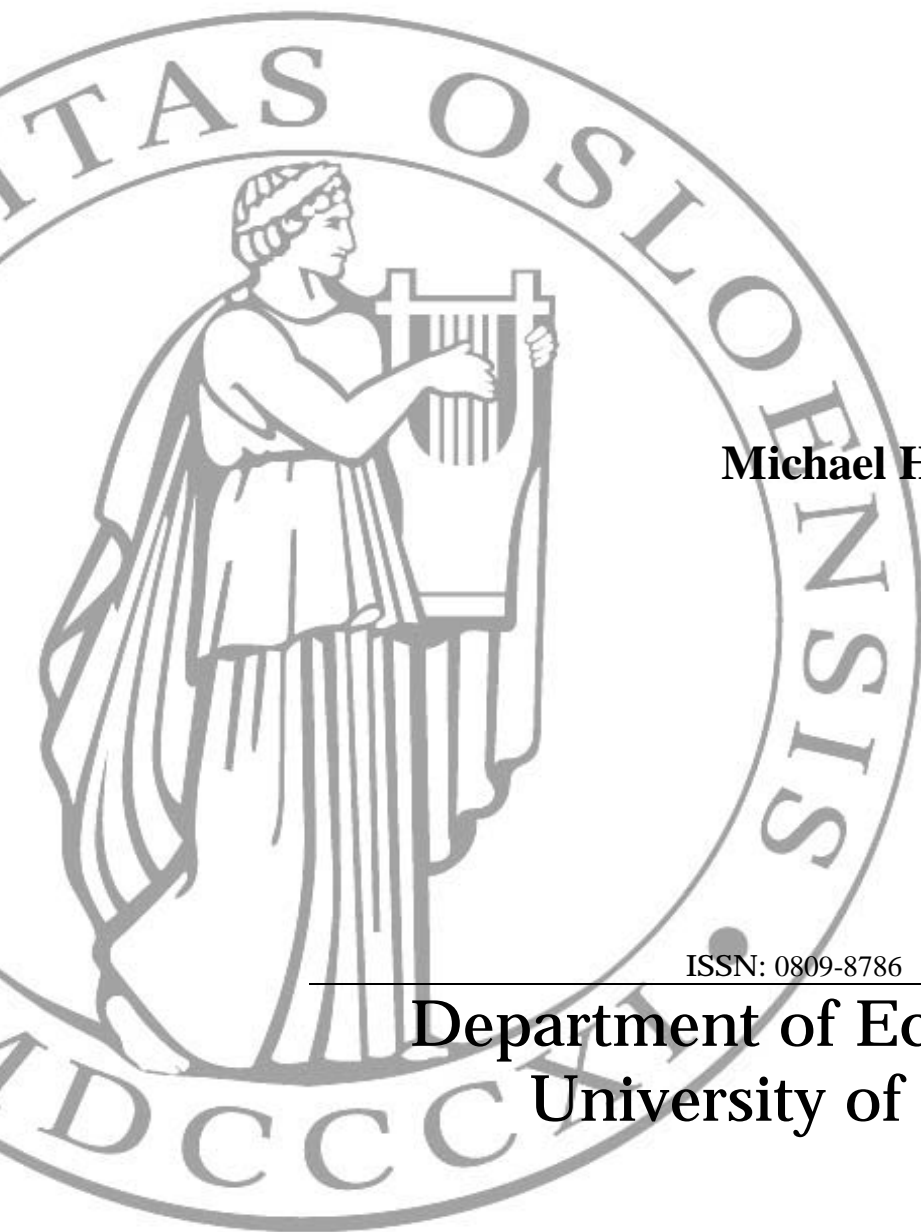
**Environmental R&D**

**Michael Hoel**

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# Environmental R&D\*

Michael Hoel<sup>†</sup>

July 23, 2010

## Abstract

The topic of this note is issues related to R&D expenditures leading to improved technologies for reducing environmentally harmful emissions. The focus is on the following questions: Will a market economy where environmental policies are restricted to taxes or quotas give the socially efficient outcome for such R&D? Does the answer to this question depend on whether one uses taxes or quotas to regulate emissions? Are market failures associated with environmental innovations different than for innovations elsewhere in the economy?

**Keywords:** environmental policy, R&D, endogenous technological development

**JEL classification:** O3, Q5, Q55

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\*This note is meant as a supplement to other literature for students at the master and phd level studying these issues. I am grateful for many useful comments from Rolf Golombek and Mads Greaker.

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## Foreword

This note is meant as a supplementary text to various journal articles treating topics related to the title of the note. The title "Environmental R&D" refers to issues related to R&D expenditures leading to improved technologies for reducing environmentally harmful emissions. The target audience for the note is master and phd students in environmental economics.

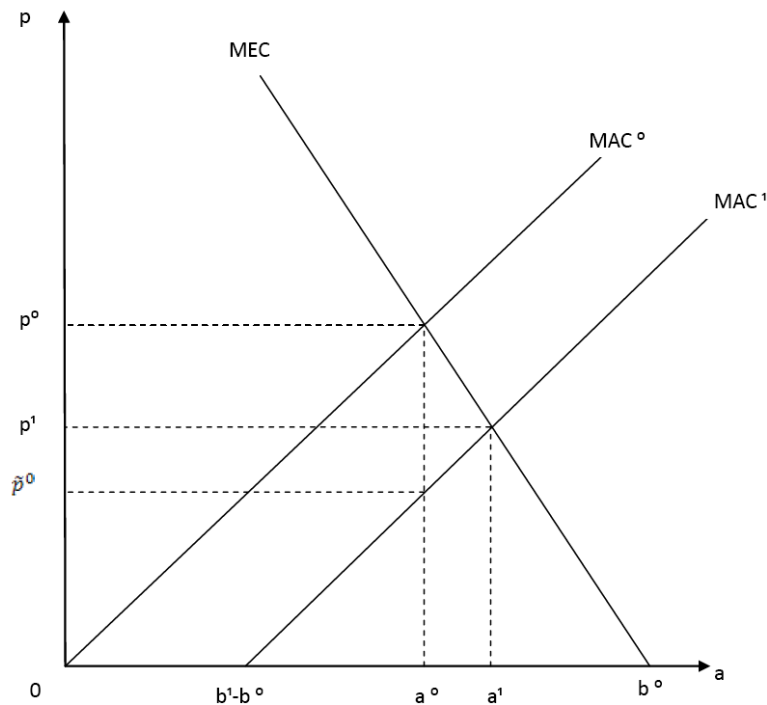
The note does not treat nearly all issues related to endogenous technological development related to the environment. Also for the issues treated in the note, specialized articles in many cases give a fuller treatment. For overviews over the quite large literature on endogenous technological development related to the environment, see, e.g., Jaffe et al. (2002), Löschel (2002), and Requate (2005a).

## 1 Introduction

Consider a "standard" description of optimal environmental policy as described in figure 1. Starting with a particular technology, the marginal abatement cost function is given by  $MAC^0$ . Environmental costs are assumed to be increasing and strictly convex in emissions, so that the marginal environmental costs  $MEC$  are higher the higher are emissions, i.e., the lower is the abatement level. Optimal abatement is given by  $a^0$  in figure 1. As is well known from the literature on environmental economics, this optimum can be achieved by setting quotas at the level  $a^0$  or by setting an appropriate emission tax— $p^0$  in figure 1.

Assume now that the abatement technology is improved, so that the new marginal abatement cost curve is  $MAC^1$ ; a more detailed discussion of the difference between the abatement costs for the two technologies is given in sections 2 and 3. Clearly, the new optimum is  $a^1$ , which may be achieved by setting quotas at this level or by setting a tax equal to  $p^1$ .

This note is concerned with endogenous technological development. A distinction is often made between knowledge derived from experience (so-called 'learning by doing', or LbD) and knowledge based explicitly on research



**Figure 1**

and development (R&D), although the distinction in practice is not so clear. The present note only considers R&D based technological development.

When technology improvements are caused by R&D expenditures, there are several important issues:

1. what is the socially efficient amount of R&D?
2. will a market economy where environmental policies are restricted to taxes or quotas give the socially efficient outcome?
3. does the answer to question 2 depend on whether one uses taxes or quotas to regulate emissions?
4. if the answer to question 2 is negative, what supplementary policy can be used to improve social efficiency?
5. if there are market failures associated with innovations, are these different for environmental innovations than for innovations elsewhere in

the economy?

The main focus of this note is on questions 2 and 5. Regarding issue 2, the conclusion is that there are good reasons to expect market failures related to R&D aimed at reducing abatement costs. However, the answer to question 5 is not so obvious: For some types of technological improvements, there is in principle little difference between environmental R&D and R&D in other areas in the economy (section 5) . However, for R&D leading to major innovations there may be some important differences (section 6).

The rest of the note is organized as follows. Sections 2 and 3 introduce concepts used throughout the note, and explain in more detail what kind of technological advances are being considered. The socially optimal amount of R&D is derived in section 4. Section 5 gives an analysis of the case in which each innovation is small, so that it makes sense to assume that innovators and all other economic agents are price takers. For this case, market failures associated with environmental R&D are very similar to market failures associated with R&D elsewhere in the economy. Section 6 discusses the case of large innovations, implying that the innovator is no longer a price taker. For this case there may be important differences between environmental R&D and R&D elsewhere in the economy.

## **2 Emissions, abatement and technology**

Abatement is usually defined with a reference to the emission level that would be chosen in the absence of any environmental regulation. This emission level is often called the Business as Usual (BaU) level. Abatement is thus defined as the difference between BaU emissions and actual emissions. When discussing technological changes, care must be taken about exactly what is meant by abatement. The reason for this is that the BaU emission level itself may depend on technology: A technological improvement may reduce emissions even if there is no environmental regulation. Throughout this note, abatement is defined as the difference between BaU emissions *under the original technology* and actual emissions.

To formalize the points above, let abatement costs be denoted by  $C(a, y)$ , where  $a$  is abatement and  $y$  is some measure of the technology level, with  $y = 0$  initially (i.e. with no R&D). This abatement cost function is derived from a function giving social benefits  $B$  as a function of emissions  $e$  and the technology level  $y$ , i.e.  $B(e, y)$ . This function is assumed to be concave, increasing in  $e$  up to a level  $b(y)$ , and increasing in  $y$ . An obvious interpretation of this benefit function is that emissions are proportional to some input entering a production function (e.g. carbon energy), with a cost (or international price) per unit of the input equal to  $q$ . If the production function is  $\Phi(e, y)$ , value added is  $B(e, y) = \Phi(e, y) - qe$ , and social benefits are simply defined as value added. Without any concern for the environment, the optimal choice of the input  $e$  is given so value added is maximized, i.e., by  $\Phi_e(e, y) = q$ , or  $B_e(e, y) = 0$ . Keeping  $q$  constant, this defines the BaU level as  $e = b(y)$ .

As stated above, abatement is in this note defined as the difference between BaU emissions under the original technology and actual emissions. With the notation above, this gives  $a = b(0) - e$ . An abatement level equal to  $b(0)$  gives zero emissions, this is the point  $b^0$  in figure 1.

Abatement costs are defined so that minimizing costs is equivalent to maximizing social benefits. This property holds for  $C(a, y) = B^* - B(b(0) - a, y) = B^* - B(e, y)$ , where the constant term  $B^*$  is arbitrary. With this definition, the level of the cost is arbitrary, but changes in the abatement cost level due to changes in  $a$  or  $y$  are of economic interest. The abatement cost function  $C(a, y)$  is defined only for  $a \in [b(0) - b(y), b(0)]$ , corresponding to emissions levels between zero and the BaU level for the given technology level.

In figure 1,  $b^0$  is the BaU emission level for the initial technology. The technological change from 0 to 1 is in figure 1 assumed to reduce emissions from  $b^0$  to  $b^1$  even without any environmental regulation (zero emission tax), giving abatement  $b^0 - b^1$  without costs (ignoring the sunk R&D costs) and abatement costs given by the marginal abatement cost function  $MAC^1$  for abatement beyond  $b^0 - b^1$ . Marginal abatement costs are given by  $C_a(a, y) = B_e(b(0) - a, y)$ . Notice that for  $y = a = 0$  we have  $C_a = 0$ , as drawn in figure



1.<sup>1</sup>

While an improvement in technology increases total benefits ( $B_y > 0$ ) and thus lowers total costs ( $C_y < 0$ ), it is not obvious that *marginal* abatement costs decline for all abatement levels, as assumed in figure 1. Marginal abatement costs decline if  $C_{ay} < 0$ . From the definition of  $C$  this is equivalent to  $B_{ey} < 0$ . Throughout sections 4-7 it is assumed that  $C_{ay} < 0$ . However, the next section shows that it is not obvious that  $C_{ay} = B_{ey} < 0$ .

### 3 Types of technological improvement

The present section gives a discussion of several types of technological improvements related to carbon emissions, and discusses the assumption that marginal abatement costs go down as technology improves.<sup>2</sup> There are (at least) three types of improvements in technology that may reduce abatement costs for carbon emissions:

- increased energy efficiency
- reduced costs of non-carbon energy
- reduced costs of carbon capture and storage (CCS).

#### 3.1 Increased energy efficiency

Increased energy efficiency is sometimes vaguely described as the possibility of producing the same output with lower energy input. However, if increased energy efficiency can only be achieved by using more of other inputs, e.g., capital, this is simply a substitution effect. Increased energy efficiency can be defined as the possibility of producing the same output with lower energy input without increasing the use of other factors of production. An obvious way of modelling this is to include the technology variable as one of the inputs in the production function in the manner we did in  $\Phi(e, y)$  above, see, e.g.,

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<sup>1</sup>In Figure 1 it is also assumed the the *MEC* function intersects the  $x$ -axis at  $b^0$ , i.e. at zero emissions. This need not be the case: It would intersect to the left if environmental costs were zero for small emission levels and be vertical at  $b^0$  if marginal costs are strictly positive as emissions increase from zero.

<sup>2</sup>This section is a rewritten version of parts of Golombek and Hoel (2009).

Popp (2004, 2006). The assumption  $C_{ay} = B_{ey} = \Phi_{ey} < 0$  means that an increase in the input “technology level” reduces the marginal productivity of carbon energy ( $\Phi_e$ ). A special case of the general production function  $\Phi(e, y)$  is the case where increased energy efficiency is modelled as carbon energy augmenting technological improvement through a variable  $a(y)$  that is increasing in  $y$ :  $\Phi(e, y) = \phi(a(y)e)$ . For this case it is straightforward to show that  $C_{ay} = B_{ey} = \Phi_{ey} < 0$  if and only if the price elasticity of carbon energy with respect to its price (measured positively) is less than one. Most empirical studies of energy demand find price elasticities lower than one<sup>3</sup>, suggesting that  $C_{ay} = B_{ey} = \Phi_{ey} < 0$  for technological improvements that increase energy efficiency. Notice that if  $\Phi_{ey} < 0$  for all emission levels, BaU emissions will decline as  $y$  increases.

### 3.2 Reduced costs of non-carbon energy

Non-carbon energy—for example, hydropower, nuclear, solar, wind, and bio-energy—are imperfect substitutes for carbon energy. Adding non-carbon energy  $r$  with a unit cost  $s(y)$  to the production function introduced previously,  $B(e, y)$  may now be defined by

$$B(e, y) = \max_r [\phi(e, r) - qe - s(y)r]$$

The envelope theorem gives

$$B_e(e, y) = \phi_e(e, r(s(y))) - q$$

Technological improvements that lower the costs of non-carbon energy ( $s' < 0$ ) will increase the use of this type of energy ( $r' < 0$ ). From the equation above we have  $B_{ey} = \phi_{er}r's'$  which thus is negative if and only if  $\phi_{er} < 0$ . If the production function  $\phi$  is a CES function, a *necessary* condition for  $\phi_{er} < 0$  to hold is that the elasticity of substitution is larger than one.<sup>4</sup>

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<sup>3</sup>See, e.g., Kilian (2008).

<sup>4</sup>More precisely: If  $\phi$  is a CES function with an elasticity of substitution equal to  $\sigma$  and a scale elasticity equal to  $\varepsilon$ ,  $\phi_{er} < 0$  if and only if  $\sigma > \frac{1}{1-\varepsilon}$ .

### 3.3 Reduced costs of carbon capture and storage

Carbon capture and storage (CCS) will always have some costs, and will thus not be used if there are no restrictions on emissions. A lower CCS cost will therefore not have any effect on BaU emissions. On the other hand, if there is a sufficiently high carbon tax on emissions, CCS will be used, and under reasonable conditions reduced cost of CCS will increase its use. This case may be described as follows, where total use of carbon energy is  $e + x$ , and  $x$  denotes the use of CCS. The cost of CCS is given by  $g(x, y)$ . The benefit function is now given by

$$B(e, y) = \max_x [\phi(e + x) - q(e + x) - g(x, y)]$$

defining  $x$  as a function of  $y$ . The envelope theorem gives

$$B_e(e, y) = \phi'(e + x(y)) - q$$

implying  $B_{ey} = \phi'' x'(y)$ . Since  $\phi'' < 0$ ,  $B_{ey} < 0$  provided  $x'(y) > 0$ , i.e. provided lower costs of CCS give increased use of CCS.

## 4 The socially optimal level of R&D

Denote environmental damage costs by  $D(e)$ , assumed increasing and strictly convex. The value of abatement is defined as  $V(a) = V^* - D(b(0) - a) = V^* - D(e)$ , where the constant term  $V^*$  is arbitrary. With this definition, the absolute value of abatement is arbitrary<sup>5</sup>, but the change in this level due to changes in  $a$ , i.e., the marginal value of abatement  $V'(a)$ , is an economically meaningful variable. The function  $V'(a)$  corresponds to the curve *MEC* in figure 1.

The optimal level of R&D depends on the relationship between R&D expenditures  $x$  and the technology level  $y$ . To simplify, the time lag between  $x$  and  $y$  is ignored, as are various types of uncertainty. It is assumed that  $y$

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<sup>5</sup> $V(0) = 0$  if  $V^* = D(b^0)$

is proportional to  $x$ , i.e.,  $y = gx$  where  $g$  is a positive constant.

The social optimum gives the values of abatement and R&D expenditures (and hence also emissions and the technology level) that maximize social welfare, i.e., that maximize  $V(a) - C(a, gx) - x$ . This gives (inserting  $y = gx$ )

$$C_a(a, y) = V'(a) \tag{1}$$

$$-C_y(a, y) = \frac{1}{g} \equiv f \tag{2}$$

Equation (1) is the standard requirement that marginal costs of abatement should equal the marginal environmental cost, that is, the Pigovian level. Equation (2) also has a straightforward interpretation: Since  $g$  measures the technology level per unit of R&D expenditures,  $g^{-1} \equiv f$  measures R&D expenditures per unit of technology, so  $f$  is the unit cost of the technology level. Equation (2) therefore simply states that the marginal benefit of improved technology (in terms of lower abatement costs) should be equal to the marginal costs of improving the technology.

## 5 Many small innovations

This section considers the case in which the technology improvement from  $y = 0$  to some positive value of  $y$  is caused by the sum of a large number of innovations. The R&D decisions are made before the abatement decisions, but obviously the expected abatement decisions influence the R&D decisions. The assumption that R&D expenditures are determined before abatement reflects the fact that it takes more time to change the technology level than abatement.

### 5.1 Optimal post-innovation environmental policy

In this section it is assumed that government policy (taxes or quotas) is set optimally once innovations have occurred. Sub-section 5.2 briefly considers alternative assumptions about policy. A thorough discussion of alternative

assumptions about how and when the environmental policy is determined is given by Requate (2005b).

Each innovation is assumed to be so small that the innovator correctly understands that the emission price (tax or quota price) is practically independent of the innovator's own innovation. Each innovator understands that due to the sum of all innovations the emission price will decline from its pre-innovation level  $p^0$  to a lower post-innovation level  $p^1$ , see figure 1. However, each innovator knows that this will be the case independent of the innovator's own choice of R&D.

The innovators are assumed to be identical to the polluting firms, and the number of these firms is so large that each of them is a price taker. At the aggregate level, the relationship between R&D and technology is given by the "production function"  $y = gx$ . Starting at some R&D level  $x$  a small increase  $\Delta x$  gives an increase in  $y$  equal to  $g\Delta x$ , so that the social benefits of  $\Delta x$  are  $-C_y g \Delta x$  (equal to the cost reduction  $\Delta x$  gives). However, looked upon from the individual innovator the payoff from an R&D expenditure  $\Delta x$  may be lower than  $-C_y g \Delta x$ : Due to limited intellectual property rights, only part of the social benefits  $-C_y g \Delta x$  are captured by the innovation firm. This is modeled as the total benefits  $-C_y g \Delta x$  being equal to  $k(-C_y g \Delta x) + (1 - k)(-C_y g \Delta x)$ , with the first term representing the private payoff to an R&D expenditure of  $\Delta x$ . For  $k < 1$  the part  $(1 - k)(-C_y g \Delta x)$  represents the benefits of the innovation that go to other firms than the innovator. According to Popp (2006), various studies suggest that imperfections in the markets for innovations imply that the social returns to R&D are about four times higher than the private returns, implying  $k = 1/4$  in the above framework.

If the price of emissions at the abatement stage is  $p$ , minimized costs of abatement and emission taxes or quota purchases is

$$H(y, p) = \min_a [C(a, y) + p(b(0) - a)]$$

implying that

$$C_a(a, y) = p \tag{3}$$

This gives  $a$  as an increasing function of  $p$  and  $y$ .

At the R&D stage, firms want to minimize  $H(y, p) + x$ , taking into account that  $\frac{\partial y}{\partial x} = kg$ . This gives  $H_y kg + 1 = 0$ . Since the envelope theorem implies  $H_y = C_y(a, y)$ , it follows that

$$-kC_y = \frac{1}{g} \equiv f \tag{4}$$

Comparing (4) with (2), we see that the market equilibrium gives the same rule for R&D expenditures as the social optimum if  $k = 1$ . If the emission price is set at its Pigovian level ( $p = V'(a)$ ), the market outcome therefore coincides with the social optimum. This is true irrespective of whether emissions are regulated by taxes or by quotas, as long as the regulation gives  $p = V'(a)$ .

As mentioned above,  $k < 1$  is probably a better description of reality than  $k = 1$ . For  $k < 1$  it can be shown that even if  $p = V'(a)$ , the market outcome gives too little R&D, and also too little abatement (the latter result follows from figure 1 if  $y$  is lower than its socially optimal level).

## 5.2 Commitment to environmental policy prior to innovation

So far, the environmental policy has been assumed to be set optimally given whatever innovations have occurred. In some of the literature various alternatives to this assumption are considered. For instance, Downing and White (1986) consider the case in which the environmental policy is set optimally prior to innovations, i.e. a tax equal to  $p^0$  in figure 1 for the tax case or a quota equal to  $a^0$  for the quota case. Clearly, if innovations give  $y > 0$ , the outcome of such policies cannot give the social optimum. An issue sometimes addressed in the literature is a comparison of tax regulation and quota regulation. In particular, a question raised is which form of regulation gives the largest incentives for R&D. The answer to this follows immediately from

the analysis above: From the market equilibrium conditions (3) and (4), it is straightforward to verify that  $x$  is larger the higher is  $p$ . Since  $p = p^0$  in the tax case and  $p = \tilde{p}^0 < p^0$  in the quota case (see figure 1), it follows that R&D is larger under tax regulation than under quota regulation.

Consider next an alternative assumption about environmental regulation: The government commits to the tax or quota that maximizes social surplus  $V(a) - C(a, gx) - x$  with the market equilibrium condition (4) as a constraint. If  $k = 1$  it follows from the preceding analysis that the regulation should give (1), and the first-best outcome is achieved. The interesting case is when  $k < 1$ . The second-best optimal regulation with quotas is found by maximizing  $V(a) - C(a, gx) - x$  with respect to  $a$  subject to (4), i.e. subject to  $kC_y(a, y) + f = 0$ . Optimization gives

$$V'(a) - C_a(a, y) = -\frac{(1-k)fC_yC_{ay}}{kC_{yy}} \quad (5)$$

which is negative if  $k < 1$ . Together with (4), (5) determines  $a$  and  $y$ , and hence also  $x$ .

Notice that (5) implies that quotas should be set so that marginal abatement costs exceed marginal environmental costs (for  $k < 1$ ). The quota price associated with this second-best regulation follows from (3). Exactly the same outcome would be achieved by setting a tax equal to this equilibrium emission price.

### 5.3 Innovations outside the emission sector

So far, it has been implicitly assumed that the firms that do R&D are the same as the firms that cause pollution and engage in emission abatement. A better description of reality might be to assume that innovations take place in specialized firms who sell or license their innovations to the polluting firms: According to Requate (2005b), 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). The articles by Parry (1995), Biglaiser and Horowitz (1995), Laffont and Tirole (1996),

Denicolo (1999), Requate (2005b), and Montero (2010) assume that R&D is done by one or several R&D firms that differ from the polluting firms.

Assume first that the sector containing these R&D firms has the production function  $y = gx$  like before, and that firms in this sector are price takers in the market for their output, which is "knowledge"  $y$  sold to the polluting firms for a price  $\ell$  per unit of  $y$ . We can think of each unit of  $y$  being a particular technology making abatement less costly, so that the aggregate abatement cost function is  $C(a, y)$  as before. In a competitive equilibrium with constant unit costs, the price will be equal to the unit cost, i.e.,  $\ell = f \equiv g^{-1}$ . Restricting ourselves to the case of  $k = 1$  (no technology spillovers across polluting firms), the demand for abatement cost reducing technologies by the price taking polluting sector will be determined by the cost minimum condition  $-C_y(a, y) = f$ . The efficient outcome is thus achieved, since the supply and demand conditions give (2).

Golombek et al. (2010) assume that each unit of  $y$ , i.e., each abatement cost reducing technology, is produced by one firm, and that this firm has a fixed cost  $f$  of its R&D. Assuming free entry into the R&D sector, the equilibrium is as before characterized by zero profits, i.e.,  $\ell = f$ . Combining this with the the demand for the abatement cost reducing technologies, we get

$$-C_y = f \tag{6}$$

If  $f$  is the social marginal cost per unit of  $y$ , it is straightforward to verify that this condition is also the condition for the socially optimal amount of  $y$ . However, this result will no longer hold if  $f$ , regarded as given by each R&D firm, in reality depends on the aggregate number of R&D firms, so that  $f = f(y)$ . What might the reasons be for  $f$  depending on  $y$ ? One reason why  $f$  might be *increasing* in  $y$  is that the cost of developing an idea differs across ideas, with the least expensive ideas being developed first—firms are "fishing out" the best ideas. Hence, the fixed cost of firms is increasing in the number of ideas being developed in a period, and therefore increasing in the number of firms. Moreover, there is chance of duplication in the R&D sector,



which will strengthen the argument of  $f'(y) > 0$ , since it is reasonable to expect the probability of duplication to be increasing in the number of R&D firms. A firm discovering that a competitor has already invented the idea the firm is working on has to start from scratch, and therefore the average effort required for each firm to develop a unique technology concept is increasing in the number of firms. Notice that duplication may be accidental (companies simultaneously discovering the same type of improvement), or intentional, as for example in patent races (see Jones and Williams, 2000).

There may also be factors tending to make  $f$  be *decreasing* in  $y$ . One reason given, often in a dynamic context, is that new knowledge builds on existing knowledge. With the present static framework this could be modeled as  $f'(y) < 0$ : The more knowledge creation elsewhere in the economy, the easier it is for a single R&D firm to develop a new technology.

If  $f'(y) \neq 0$ , the total cost of R&D is  $f(y)y$ , and the marginal cost is  $f(y) + yf'(y)$ . In the social optimum it is this marginal cost that must be equal to  $-C_y$ . The market equilibrium condition (6) therefore gives too little R&D if  $f' < 0$  and too much R&D if  $f' > 0$ .

## 5.4 Implications for R&D policy

The analysis above demonstrated that a market economy may give the wrong amount of R&D, even if emissions are regulated optimally (i.e. giving an emission price equal to the Pigovian level  $V'(a)$ ). In the formal analysis, this would be the case if  $k < 1$ , or, with the model used in the end of section 5.3, if  $f'(y) \neq 0$ . Theoretically, it is possible for the market both to give too much or too little R&D. However, most of the empirically oriented literature on these issues suggests that the market outcome typically will have less R&D than what is socially optimal (see Jones and Williams, 2000).

If the market outcome gives too little R&D, this is a justification for using policy instruments to directly affect R&D. However, exactly the same arguments can be used for *all* types of R&D, not only environmental R&D. To see this, use the model above, but let  $a$  now stand for the production of an ordinary good, such as bicycles, laptops or LCD TVs. The function  $V'(a)$

is simply the inverse demand function for this good, and  $p$  is the price of the good. The market equilibrium is as described in figure 1, with lower price and larger quantity the better the technology is (i.e., the lower is the marginal cost curve). Just like for abatement, the market outcome will give too little R&D in this sector of the economy if  $k < 1$  (or  $f' < 0$ ). While the analysis of this section justifies policies directed toward R&D to correct for this market failure, it does not give any justification for treating environmental R&D differently from any other R&D (unless there is reason to believe that the market failures are stronger for environmental R&D than for other R&D).

## 6 Large innovations

As in section 5.4, it is assumed throughout the present section that the R&D sector is independent of the polluting sector. The polluting sector is modeled as in the previous sections. However, in the present section it is assumed that each R&D firm is so large that it is not a price taker in the market for its innovations. The formal model has a similar setup as in Laffont and Tirole (1996), Denicolo (1999), Requate (2005b), and Montero (2010), with only one innovating firm. Moreover, in most of the analysis it is assumed that the R&D activity may affect the optimal environmental policy (i.e., the emission price or the emission quota) once the innovation has occurred. Section 6.4 briefly considers the case where the innovation has no affect on the optimal environmental policy.

### 6.1 A major cost reducing innovation for a regular good

It is useful to first consider a regular good (bicycle, laptop, LCD TV, etc.). Prior to any innovation the marginal cost of producing the good in quantity  $a$  is  $C'(a)$ , and the inverse demand function is  $V'(a)$ . Prior to the innovation, the competitive equilibrium is given by  $Q$  in figure 2.

Assume that there is a potential innovation which, if successful, brings

costs of producing the good to zero.<sup>6</sup> The probability of succeeding with the development of the new technology is  $\pi(x)$  with  $\pi' > 0$ , i.e., increasing in the R&D effort. To find the social optimum in this case, define the social surplus excluding R&D expenditures for the two technologies:

$$\begin{aligned} W^0 &= \max_a [V(a) - C(a)] \\ W^1 &= \max_a V(a) \end{aligned}$$

Since the new technology is better than the initial technology,  $W^1$  must be higher than  $W^0$ . More precisely,  $W^1 - W^0$  is equal to the triangle  $OQb^0$  in figure 2.

Expected net social surplus (including R&D expenditures) is

$$EW = \pi(x) [W^1 - W^0] - x$$

and the value of  $x$  that maximizes this expression is given by

$$\pi'(x) [W^1 - W^0] = 1 \tag{7}$$

If a private innovator succeeds, it can license its technology to the producing firms for a price  $p$  per unit output using this technology. Producers will then no longer have marginal costs  $C'(a)$ , but a new marginal cost function  $\tilde{C}'(a)$ . This new marginal cost function coincides with the original one up to  $a^0(p)$ , defined by  $C'(a^0) = p$ , and is horizontal and equal to  $p$  to the right of  $a^0(p)$ . The new market equilibrium is at  $\tilde{Q}$  in figure 2. The profit to the innovator is  $p[a(p) - a^0(p)]$ , where  $a(p)$  is defined by  $V'(a) = p$ . If the innovator succeeds, it will charge the price  $p^*$  that maximizes  $p[a(p) - a^0(p)]$ , giving the profit  $p^*[a(p^*) - a^0(p^*)]$  (equal to  $p^*(a^* - a^0)$  in figure 2). The optimal amount of effort for the innovator is the value of  $x$  that maximizes  $\pi(x) \{p^*[a(p^*) - a^0(p^*)]\} - x$ , giving

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<sup>6</sup>This is the same assumption as in Laffont and Tirole (1996). The analysis and results would be qualitatively the same if it instead was assumed that the post-innovation cost was  $c$  per unit with  $c > 0$ .

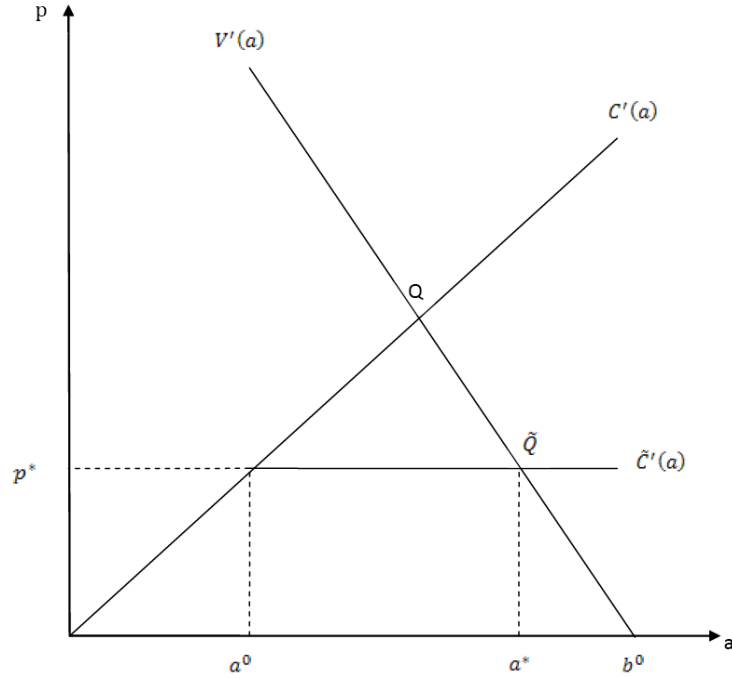


Figure 2

$$\pi'(x)p^* [(a(p^*) - a^0(p^*))] = 1 \quad (8)$$

From figure 2 it is clear that  $p^* (a^* - a^0) < W^1 - W^0$ , the latter being equal to the area  $OQb^0$ . By comparing (8) with (7) it is therefore follows that there is less R&D under the market outcome than what is socially efficient.

In addition to giving too little R&D, the market gives an inefficient use of the innovation when successful: The efficient outcome is to have a total output of the good equal to  $b^0$ , with all of the production using the new technology (implying zero costs). The market outcome has too little production ( $a^*$  instead of  $b^0$ ), and some of this production ( $a^0$ ) is with the old, costly technology.

## 6.2 A major abatement cost reducing innovation with an emission tax

The analysis above revealed that a market economy gives too little R&D for the type of innovations considered. Is this market failure similar for environmental R&D? This question is addressed below, assuming first that environmental regulation takes the form of an emission tax.

Assume first that the government commits to a specific tax in the event of an innovation. This tax could be equal to  $p^*$  in figure 2, i.e., equal to the value of  $p$  that maximizes  $p[a(p) - a^0(p)]$ . Ignoring first the possibility of buying the technology from the R&D firm, the polluting firms would with this tax abate  $a^0(p^*)$  and pay the emission tax for their remaining  $b^0 - a^0$  emissions. But if the innovator sold its technology at a price marginally below  $p^*$  (per unit abatement the technology is used for), it would be better for the polluting firms to buy this technology for abating  $b^0 - a^0$  (in addition to abating  $a^0$  with the old technology) rather than paying an emission tax for  $b^0 - a^0$  emissions. With a tax equal to  $p^*$ , the innovator can thus charge a price of  $p^*$  (or marginally below  $p^*$ ) and receive a profit equal to (almost)  $p^*(b^0 - a^0)$ . Since  $b^0 > a^* = a(p^*)$  (see figure 2), the profit to the innovator is higher than it was for an ordinary good (which was  $p^*(a^* - a^0)$ ). With  $a^*$  replaced by  $b^0$  in (8) we therefore also get more R&D than in the corresponding situation for an ordinary market good.

Notice that  $p^*$  is only one of many possible tax rates. For an emission tax  $\theta < p^*$ , the best the innovator can do is to charge a price marginally below  $\theta$ . Moreover, it is readily verified that  $p[a(p) - b^0]$  is increasing in  $p$  also for values of  $\theta$  higher than  $p^*$  up to a limit  $\hat{p}$  defined by the solution to maximizing  $p[a(p) - b^0]$ . For an arbitrary emission tax  $\theta$ , the price charged by the innovator will hence be equal to  $\text{Min}\{\theta, \hat{p}\}$ . Increasing the emission tax from  $p^*$  to a higher value will therefore increase the profit to the innovator, and thus increase R&D. However, the higher the tax is (up to  $\hat{p}$ ), the larger is  $a^0$ , i.e. the more costly is the abatement.

We can thus conclude that *if* the government can commit to a specific post-innovation tax rate, it is possible to make the incentives for R&D *higher*

than they were for the corresponding situation for an ordinary market good. Unfortunately, commitment of this type is quite unrealistic. First, although there is only one type of innovation in our simple model, there is in reality a large range of possible type of innovations. It is difficult to see how one could make a commitment for all types of outcomes of the process of innovation.

Even if our model is taken literally and the complication of many types of innovations is ignored, commitment is difficult to imagine. The payoff to an innovator will typically last for many years—perhaps several decades—after the R&D has been initiated. It is in practise impossible for a government to commit to a tax policy that far into the future.

Instead of assuming commitment to a particular emission tax, it seems reasonable to expect the government to freely set the emission tax in order to maximize social welfare once the innovation has taken place. With a zero post-innovation abatement cost, the best post-innovation tax is arbitrarily close to zero: With this tax the best response from the innovator is to charge a price marginally below the tax, and thus achieve a non-zero profit. With this price the polluting sector will buy the technology and use it for all its abatement (except  $a^0(\varepsilon)$  if  $\varepsilon$  is the price charged for the new technology). The first-best social optimum with zero emissions and all abatement being done with the new, zero-cost technology is thus achieved.

The problem with this tax policy is of course that the profit to the innovator will be only marginally above zero. Hence, there will be no incentive to undertake any R&D. It follows that with an emission tax that the government has the discretion to set at any time, there will be no incentives for environmental R&D.

The above feature differs from the case of R&D directed toward ordinary market goods. For such goods the market would typically give positive R&D, although less than the socially optimal level. However, if sector specific policies were permitted in the case of ordinary market goods, there would be no difference between R&D related to such goods and environmental R&D: For the case of market goods, the first-best post-innovation outcome could be achieved by setting a maximal price for the good marginally above zero. The best response from the innovator would be to charge a price for its

technology marginally below the maximal price, so that producers of the good would purchase the license for the new technology. If such a policy was expected by the potential innovator, it would eliminate all incentives for R&D, since a successful innovation in this case would give the innovator a profit only marginally above zero.

### 6.3 A major abatement cost reducing innovation with emission quotas

Emission quotas give a maximal limit on emissions, which is equivalent to a minimum amount of abatement. From the definition  $a = b(0) - e$  of abatement,  $e \leq \bar{e}$  is equivalent to  $a \geq b^0 - \bar{e}$ . If the minimum abatement requirement is set to  $a^* = a(p^*)$  in figure 2 (i.e.  $e \leq b^0 - a^*$ ), the demand function facing the innovator is  $a^* - a^0(p)$ . This is a steeper demand function than it faced for an ordinary market good, which was  $a(p) - a^0(p)$ . This means that the innovator can increase its profits above  $p^* [a^* - a^0(p)]$  by charging a price for the use of its innovation above  $p^*$ . In other words, by setting an emission quota equal to  $b^0 - a^*$ , i.e., a minimum abatement requirement equal to  $a^*$ , the government can make the incentives for R&D, and thus the level of R&D, higher than for an ordinary market good. Moreover, the lower the emission quota, the higher is the profit of the innovator, and the higher is R&D. However, since a lower emission quota gives a higher price for the new technology, abatement with the old, costly technology will be higher the lower is the emission quota.

Like for the tax case, it seems unlikely that the government can commit to a specified quota. If emission quotas instead are chosen optimally once the innovation has occurred, the government will chose  $a$  to maximize  $V(a) - C(a^0(p(a)))$ , where  $p(a)$  is the price the innovator will charge when emissions are limited to  $b^0 - a$ .<sup>7</sup> This optimum will give the innovator a positive profit, and thus also larger R&D than the tax case gave (which was zero).

With the type of innovation considered in this section, it thus follows that *if* the government can commit to the regulatory regime (taxes or quotas),

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<sup>7</sup>Formally,  $p(a)$  is the solution to  $\max_p [p(a - a^0(p))]$ .

quotas are preferable from the perspective of giving incentives to R&D.

## 6.4 Innovations when there are many sources of emissions

Perhaps the most drastic assumption in this section is that all emissions could be eliminated at a constant cost with the new technology.<sup>8</sup> For CO<sub>2</sub> emissions, there is a wide range of sources. One could imagine a major innovation replacing previous abatement options with a low-cost new option for a particular source (for instance a new low-cost source of electricity, a new type of engine for some type of transportation, or a new low-cost type of CCS). However, it is difficult to imagine any single innovation replacing the original aggregate abatement cost function with a new low cost abatement function for the whole economy. It is therefore of interest to briefly consider how some of the results are changed if the replacement of an abatement cost function  $C'(a)$  with a zero-cost new option only applies to a particular sector of the economy, responsible for only part of the economy-wide emissions.

A main conclusion from section 6.2 was that the post-innovation optimal policy would be to set the emission tax marginally above zero. This remains true if the government has the option of setting different emission taxes for different sectors of the economy.<sup>9</sup> There may, however, be legal or other reasons forcing the government to have a common emission tax throughout the economy. If this is the case, and if there are considerable emissions in other sectors of the economy than the sector under consideration, the optimal tax must be a compromise between what is desirable for the sector under consideration and the rest of the economy. If the sector under consideration is of some size, it therefore seems likely that the post-innovation optimal emission tax is lower than what was optimal prior to the innovation. However, unless the sector under consideration is very large, the optimal emission tax will not drop to zero as a response to the innovation. This means that

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<sup>8</sup>In the formal analysis this cost was zero, but the important assumption was that it was constant.

<sup>9</sup>Sector specific emission taxes are in many ways similar to sector specific price regulations as discussed in the end of section 6.2.



there will be incentives for R&D and thus positive R&D. Moreover, it was demonstrated in section 6.2 that with a positive tax the incentives for R&D could be higher for environmental R&D than for R&D in sectors producing ordinary market goods. For innovations only covering emissions for part of the economy, it is hence no longer obvious that there are lower incentives for environmental R&D than for other R&D.

## 7 Concluding remarks

The analyses in the preceding sections has shown that there very well may be market failures related to environmental R&D. This suggests a role for policies directed directly towards such R&D. However, it is not obvious that the market failures related to environmental R&D are qualitatively different from the market failures associated with other R&D. For R&D giving "small innovations" , in the sense that the optimal emission price is unaffected by any single innovation, there is no indication that the incentives for environmental R&D is less than the incentives for other types of R&D. For such types of R&D it therefore seems difficult to justify policies other than general policies affecting all types of R&D, provided the environmental policy gives a correct price signal through an emission tax or a quota price. However, section 6 demonstrated that there may be good reasons for having specific policies directed towards R&D that potentially can lead to a single innovation that is so large that the optimal post-innovation emission price is affected.

Given that there are market failures related to environmental R&D, it is of interest to compare tax regulation with quota regulation, and see which gives an R&D level closest to the socially efficient level. There is no unambiguous result from such a comparison. The performance of taxes versus quotas depends both on the type of innovation (small or large) and on to what extent policy makers can commit to a particular policy.

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