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# Innovation prizes for environmental R&D

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Abstract in Norwegian:

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# Innovasjonspriser for miljøvennlig FoU

Rolf Golombek, Mads Greaker og Michael Hoel

Innovasjonspriser er et virkemiddel der aktøren mottar penger fra regulator hvis hun lykkes med å utvikle en ny teknologi som oppfyller visse tekniske kriterier. Innovatøren investerer i forskning for å utvikle en ny teknologi når hun er klar over at hvis hun lykkes, så vil hun motta en innovasjonspris.

Vi viser at innovasjonspriser er et effektivt FoU virkemiddel. Videre diskuterer vi om innovasjonspriser rettet mot utvikling av miljøvennlig energi skal være høyere enn innovasjonspriser rettet mot utvikling av mer effektiv teknologi for produksjon av ordinære markedsgoder (ingen eksterne effekter). Et hovedresultat er at dersom etterspørselskurven etter et markedsgode, alternativt kurven for marginal gevinst av økt rensing, er brattere enn grensekostnaden til den opprinnelige teknologien, bør innovasjonsprisen for miljøvennlig energi være større enn innovasjonsprisen for et markedsgode. I spesialtilfellet med en gitt markedspris, alternativt en gitt marginal gevinst av økt rensing, skal innovasjonsprisen for et markedsgode være størst.

# Innovation prizes for environmental R&D*

Rolf Golombek[†], Mads Greaker[‡] and Michael Hoel[§]

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**Abstract**

The government influences demand for new abatement technologies through its environmental policy. If the government uses innovation prizes to provide the socially correct incentives for a monopoly innovator to invest in R&D, the innovation prize for environmental R&D will therefore in general differ from the innovation prize for market goods R&D. We show that if the slope of the demand curve/marginal benefit of abatement curve is sufficiently large relative to the slope of the marginal cost curve, then the innovation prize for environmental R&D should be greater than the innovation prize for market goods R&D. We also demonstrate that if the government can use a tax rebate to promote diffusion of the innovation, the innovation prize for environmental R&D should always be greater than the innovation prize for market goods R&D.

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

***JEL classification: H23, O30, Q55, Q58***

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# 1 Introduction

It is well known that an innovator may not be able to capture the full social benefit of her innovation. In the innovation literature this is referred to as the *appropriability problem*, see Arrow (1962), and it provides a rationalization for the government to support private research and development (R&D) by policy measures.

Typically, the government aims at supporting all kinds of private R&D - innovations in standard market goods as well as environmentally friendly innovations - equally. However, a few papers suggest that the appropriability problem might be larger for environmental R&D than for regular market goods R&D. One example is Laffont and Tirole (1996). They study a game where an innovation in a pollution abatement technology makes the government respond by setting a very low emission tax rate, thereby undermining the demand for the new product. The innovator is therefore forced to set a low price on the new technology in order to attract customers. Thus, in equilibrium the government expropriates the value of the patent and hence amplifies the appropriability problem.

Gerlagh et al. (2014) and Acemoglu et al. (2012) argue that the magnitude of other R&D market failures, for example, the "standing-on-shoulders" effect (positive learing externality) and the patent system, are larger for environmental R&D than for market goods R&D. If this is correct, it rationalizes that the appropriability problem is larger for environmental R&D than for regular market goods R&D. Also Montgomery and Smith (2007) argue that the incentives for environmental R&D are weaker than the incentives for market goods R&D, and they therefore suggest that in distributing R&D subsidies priority should be given to environmental R&D. In the present paper we follow up on these studies by examining whether the appropriability problem is larger for environmentally friendly innovations than for innovations in technologies designed to produce standard market goods (i.e., no externalities).

There is a number of policy instrument that may trigger more R&D and thus solve the appropriability problem; some examples are research subsidies, tax rebates and patents. In the present paper we will focus on an alternative R&D instrument, namely an innovation prize; the innovator receives an amount of money if she successfully innovates. Brennan, Macauley and Whitefoot (2012) provide an informal discussion of innovation prizes. They categorize innovation prizes along several dimensions, and suggest different criteria that may be used to assess who should receive the prize, for example, the first one to come up with a solution that meets a set of criteria, or the best solution relative to some criteria at a specific future point in time. They argue that the government should introduce innovation prizes for environmental R&D as this instrument may serve as a payment pre-commitment. Also Newell and Wilson (2005) argue to use innovation prizes as an environmental R&D policy tool.

One aim of the present paper is to formalize an examination of innovation prizes and to study the efficiency properties of an innovation prize both for environmental R&D (henceforth referred to as E) and market goods R&D (henceforth referred to as M). To analyze the incentives to invest in R&D we use a model of the innovation process inspired by Requate (2005). In the first stage a monopoly innovator invests in R&D, which determines the probability to successfully innovate. The innovator takes into account that she will receive an innovation prize if she develops a new technology. For innovations aiming at developing an abatement technology (environmental R&D), the government sets an emission tax in the second stage of the game in order to obtain the efficient level of abatement (whereas for a market good innovation there is no second stage). In the third stage the monopoly innovator sets a license fee that competitive downstream firms have to pay in order to use the innovation. Finally, firms in the downstream industry decide whether to rent the new technology or continue with the old, less efficient, technology.

We find that an innovation prize can induce an efficient amount of R&D (Proposition 1). Without a prize, the revenue of the innovator equals the licence income, which in general differs from the social value of the innovation. If, hypothetically, the net income of the innovator is equal to the social value of the innovation, the innovator will choose the efficient amount of R&D. Therefore, the innovation prize should ensure that the sum of the prize and the licence income is equal to the social value of the innovation.

In our model the social value of an additional unit of a standard market goods is simply captured by the demand curve, whereas with environmental R&D the social value of improved environment is measured by the marginal benefit of abatement curve. For market goods R&D, the downstream firms have one marginal cost curve prior to the innovation and another marginal cost curve after the innovation (if the innovation materializes). Similarly, for environmental R&D the downstream firms have one marginal cost of abatement curve prior to the innovation and another marginal cost of abatement curve after the innovation (if it materializes). In comparing the optimal innovation prize for environmental R&D to the optimal innovation prize for R&D directed at an ordinary market good, we assume that the two innovations have the same potential to increase welfare. This is handled by imposing that i) the demand curve is identical to the marginal benefit of abatement curve, ii) the marginal cost curves prior to innovation are identical, and iii) the marginal cost curves after an innovation are also identical, that is, the shifts in the marginal costs curve due to the innovation are identical.

We find that if the common slope of the demand curve/marginal benefit of abatement curve relative to the common slope of the marginal cost curves (prior to an innovation) exceeds 0.75, then the innovation prize for environmental R&D should be greater than the innovation prize for market goods R&D (Proposition 2). In the special case of a given world market price/a given social cost of carbon, the innovation prize for market goods R&D should exceed the innovation prize for environmental R&D. We also find that with a profit-maximizing monopolistic innovator, the increase in social value following from the innovation is greatest with environmental R&D (Proposition 3).

We demonstrate that the efficient level of R&D can be reached also by offering subsidies that cover a share of the R&D expenses. Moreover, it is cheaper for the government to use an R&D subsidy than an innovation prize (Proposition 8). On the other hand, if the government does not know how radical the innovation will be ex ante, then for environmental R&D expected welfare is higher with an innovation prize than with an R&D subsidy (Proposition 9).

Our paper is linked to different strands of the environmental economics literature. First, a key topic in our paper is whether the government can reach the first-best outcome: With a profit-maximizing monopoly innovator, the government is able to reach an efficient level of R&D investment by offering an innovation prize. However, the first-best social outcome is not attained: In our model there is a difference between the first-best post-innovation outcome and the equilibrium with a profit-maximizing innovator because the innovator charges a licence fee for the new technology: Because it is socially optimal that all downstream producers convert to the new technology once it is developed, implementation of the first-best outcome requires no licence fee. In contrast, a profit-maximizing monopoly innovator will charge a fee to let downstream producers use the new and more efficient technology, thereby lowering the number of producers switching to the superior technology.

To reach the first-best social outcome an innovation prize has to be combined with another type of a policy instrument, for example, a tax rebate to all firms that adopt the new technology. With an innovation prize and a tax rebate, the innovation prize for environmental R&D should be greater than the innovation prize for market goods R&D (Proposition 9): By construction the two innovations increase social welfare by the same amount, but the appropriability problem is larger for environmental innovations due to the strategic interaction between the government and the innovator.

The (in)ability to reach the first-best social outcome has been studied in a number of papers in the environmental R&D literature. For example, Requate (2005) shows that social welfare can be increased if the government could pre-commit to an emission tax that would be implemented if the innovation occurs. Another example is the pioneering paper by Downing and White (1986) on the ratchet effect; if a polluting firm discovers a more environmentally friendly process, then the government may tighten the regulation of the firm. Consequently, the 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 other environmental policy instruments than emission taxes, the ratchet effect may lead to too little innovation.

Second, while the old literature like Downing and White (1986) assumed that a polluting firm could also innovate, more recent contributions distinguish between the R&D sector, which develops a new abatement technology, and the regulated polluting sector, which may install the new abatement technology. Both Laffont and Tirole (1996) and Requate (2005) separate the innovator from the polluting sector, as we do. Still, these papers, as well as papers building on Laffont and Tirole (1996), for example, Denicolo (1999) and Montero (2011), do not include a systematic comparison of environmental R&D with market goods R&D. This is in contrast to our study.

Third, while Laffont and Tirole (1996) and Montero (2011) assume that all polluting firms obtain the same benefit from the new technology, Requate (2005) examines heterogeneous firms. In the Requate paper heterogeneous firms make it harder for the government to reduce the deadweight loss from the monopolistic pricing of the innovation. We consider both the case in which the benefit from the innovation differs across firms (Sections 2-4) and the case of identical benefit of the innovation (Section 5.1). In the latter case we show that if limit pricing of the new technology is optimal for the innovator, then there is no appropriability probem with market good R&D whereas there is a too strong incentive for environmental R&D (Proposition 5). In Section 5.1 we also demonstrate that when all users have the same value of the innovation, and it is optimal with an interior solution for the licence fee in the the environmental R&D case, and the slope of the demand curve/marginal benefit of abatement curve relative to the slope of the marginal cost function is sufficiently large, then the optimal innovation prize with environmental R&D should be higher than the optimal innovation prize for market goods R&D (Proposition 6).

Finally, our paper adds to the growing literature on policy measures (other than subsidies, tax rebates and patents) that provide incentives for more R&D. For example, patent buy-outs are analyzed theoretically by Wright (1983), and more lately by Weyl and Tirole (2012) and Chari, Golosov and Tsyvinski (2012). The latter papers advocate partial patent buy-outs due to asymmetric information between the regulator and the innovator. Also Newell and Wilson (2005) discuss the problem of getting the prize right for a patent buy out. They argue that a buy-out may be too costly for governments. Kremer (2001a; 2001b) discusses another instrument - advanced market commitment - where the government commits to purchase a given quantity that meets pre-specified criteria, thereby providing incentives to develop new products.

The effect of a monetary award on innovation has been studied by Brunner, Lerner and Nicholas (2011). They find positive effects of money prizes on innovations in the British agricultural sector. Interestingly, their results suggest that the honor of winning a prize has a separate effect; medals boost the effects of a money prize.[1] Neckerman et al. (2014) find that labor market awards may trigger substantially more effort from the employees than their expected value would suggest. Recently, the EU announced under its Horizon 2020 program innovation prizes up to € 3 millions to whoever can most effectively meet a defined challenge within the following areas: Antibiotics, transmission barriers, city air improvement, spectrum sharing, and food scanners. Our contribution to this literature is to provide an analytical examination of innovation prizes.

[1] Another example of an innovation prize is from the 18th century: rulers in England, the Netherlands and Spain offered large amounts of money to the one who could construct an instrument that determined the position of a ship in open sea, see Jones (2002).

The rest of the paper is laid out as follows. In Section 2 we study the decisions of an innovator who aims at developing a more efficient technology that produces a standard market good. We show how the government can design an innovation prize in order to solve the appropriability problem. In Section 3 we study innovation in abatement technology, and we compare the two innovation prizes in Section 4. Here we discuss under what conditions the environmental innovation prize should be higher than the market good innovation prize. In Section 5 we discuss modifications and extensions of the basic model. Whereas we in Sections 2-4 assume that downstream firms differ with respect to the cost advantage of using the new technology, in Section 5.1 we examine the case where this cost advantage does not differ between firms. Also R&D subsidies, asymmetric information, and an innovation prize combined with a tax rebate are analyzed in Section 5.

Throughout the paper we assume that the emission tax is set before the innovator sets her license fee, that is, the government moves first. Although other decision sequences are possible - the tax might be determined simultaneously with the licence fee or the tax might be set after the licence fee - the government move first game is the one mostly studied in the literature, see, for example, Laffont and Tirole (1996). This sequence may reflect that it is easier for the government to commit, for example, through passing a law or repeately announce a policy, than for the innovator to commit. In Section 6 the two alternative sequences are commented on - they are analyzed in a supplementary paper. Section 6 also comments on the case of the government using quotas, not an environmental tax, as the environmental policy instrument. One reason to mainly focus on an environmental tax, as we do in the present paper, is that Requate (2005) has shown that for the type of model we use, it is optimal for the government to implement an environmental tax as the policy instrument.

## 2 Innovations reducing the cost of a market good

We consider an innovation project which has the potential of reducing the cost of a production process. The innovator can through her choice of R&D investment level affect the probability to innovate. If the innovator has success, that is, innovates, she receives an innovation prize from the government and rents out her new technolog to firms producing a standard market good. Firms can either pay a licence fee to the innovator and get access to the new and superior technology, or continue production with the old technology.

In our model an innovation lowers the cost of producing an ordinary market good. We assume that the potential cost reduction is known and exogenous, which can be interpreted as follows: the government specifies some technical criteria that must be met in order to receive the innovation prize. If these criteria are fulfilled, a specific cost-reduction follows.

We assume that the sequence of moves in this multi-stage game between an innovator and the regulator is as follows: I) The government announces an innovation price, II) The innovator invests in R&D, III) If the innovator succeeds (innovates), she sets a price on the innovation (the licence fee), and downstream firms decide whether to pay the licence fee and adopt the new cost-reducing technology or cotinue with the old, high cost, technology.

### 2.1 The appropriability problem with a market good

The social and private value of an innovation is illustrated in Figure 1. The curve $OMC$ is the $O$ld $M$arginal $C$ost curve, i.e., marginal cost prior to a successful innovation. In the Figure and in our formal analysis, this curve is assumed linear. It is also assumed that it starts at zero; this is, however, only for analytical convenience. One (but not the only) interpretation of the curve $OMC$ is that there is a continuum of firms with unit production capacity. The output $x$ is hence equal to the number of firms, and firms are ranked so that costs of production are increasing in the number of firms $x$.

[Figure 1]

The (inverse) demand curve is also assumed to be linear: $1 - \beta x$, where we have chosen the units of value so that the constant term (choke price) is one. The pre-innovation equilibrium is at the point $B$ in Figure 1.

We assume that a successful innovation shifts the marginal cost curve downwards in a proportion $1 - \alpha$; i.e., if the original marginal cost curve is $\gamma x$, the new marginal cost curve is $\alpha\gamma x$, where $\alpha$ is exogenous and lies between 0 and 1. This *N*ew *S*ocial *M*arginal *C*ost curve is denoted *NSMC* in Figure 1.

A first-best post-innovation outcome would be the equilibrium point *D.* If this were achieved, the social value of the innovation would clearly be the sum of reduced costs and increased consumer benefit, given by the area *OBD* in Figure 1. Henceforth we denote this area by $V^*$ and refer to it as the maximum social value of the innovation. In the first-best post-innovation outcome, total production is equal to $x^*$, and all firms use the new technology.

The first-best outcome $D$ would be achieved if the private marginal cost of the downstream producers was equal to the social marginal cost. However, if the innovator charges a license that depends on the production volume, this will not be the case. We shall assume that the downstream producers can choose between the old technology and the new technology, with the latter requiring a license fee $\ell$ per unit of output to the proprietary firm.

If a firm indexed $i$ chooses the old technology, it has production cost $\gamma i$, while if a firm rents the new technology, it has production cost $\ell + \alpha\gamma i$. Note that all firms would benefit from the new technology, but due to the fixed cost of the new technology, only firms with higher numbers will choose the new technology (provided they produce). In particular, firms with index up to $\hat{x}^M$ ($M$ - market good) in Figure 1 will choose the old technology, where

$\hat{x}^M$ is determined by $\gamma\hat{x}^M = \alpha\gamma\hat{x} + \ell^M$, implying

$$\hat{x}^M = \frac{\ell^M}{\gamma(1-\alpha)}. \tag{1}$$

It follows that the $N$ew $P$rivate $M$arginal $C$ost curve ($NPMC$) in Figure 1 is the line going through $OAC$ with the distance $AF$ being equal to the licence fee $\ell$ (endogenously determined, see below); the first $\hat{x}^M$ firms do not use the new technology because the license fee is too high. Total production $\bar{x}^M$ is determined in a competitive equilibrium such that the $N$ew $P$rivate $M$arginal $C$ost is equal to demand. The first $\hat{x}^M$ units will be produced by the old technology (as prior to the innovation), whereas the remaining units ( $\bar{x}^M-$ $\hat{x}^M$) will be produced by the new technology. The increase in social benefit caused by the innovation when the innovator is a monopolist, henceforth denoted $V^M$ ($M$ for market good), is therefore equal to the area $FABCE$.

Notice that $V^M < V^*$ for two reasons. First, the positive license fee implies that the first $\hat{x}^M$ producers will not use the new technology although it is socially optimal to do so; the social marginal cost of using the technology is zero once the technology is developed. This loss is represented by $OAF$ in Figure 1. Second, the positive license fee implies that downstream producers will choose the output level $\bar{x}^M$, while the socially optimal output level is $x^*$. This loss is given by $ECD$ in Figure 1. The sum of these two losses is identical to the difference between $V^*$ and $V^M$, which in Figure 1 is the difference between $OBD$ and $FABCE$.

It is clear from the discussion above that the payoff to the innovator is[2]:

$$v^M = \max_{\ell^M} \left\{ \ell^M \left[ x^M - \frac{\ell^M}{\gamma(1-\alpha)} \right] \right\}. \tag{2}$$

This payoff is given by the area $FACE$ in Figure 1, where the length of $AF$ is the solution to (2) when the endogenous determination of $x$ is taken into account.

[2]For $x < \hat{x}$, no firms buy the new technology, hence $v = 0$.

In Appendix 1 we show how to calculate $V^M$ and $v^M$ taking account of the endogenous determination of $\ell$:

$$V^M = \frac{3(1-\alpha)}{8\gamma(\alpha + \frac{\beta}{\gamma})(1 + \frac{\beta}{\gamma})} \tag{3}$$

$$v^M = \frac{(1-\alpha)}{4\gamma(\alpha + \frac{\beta}{\gamma})(1 + \frac{\beta}{\gamma})}. \tag{4}$$

Clearly, $V^M > v^M$ for all $\alpha, \beta$ and $\gamma$. Thus, the innovator is not able to appropriate the whole social surplus from the innovation. As will be shown below, R&D will therefore be lower than what is socially optimal. We now turn to how to design a policy measure that provides the correct R&D incentives for the innovator. In the next subsection we focus on an innovation prize. Alternative and supplementary instruments are discussed in Section 5.

## 2.2 Innovation prize with a market good

Let the private cost of R&D be given by $k$. Following Laffont and Tirole (1996), we assume that by investing $k$ the innovator succeeds with probability $z(k)$, where $z(0) = 0$, $z(k) < 1$, $z' > 0$, $z'' < 0$ and $z'(0) = \infty$. If the innovator succeeds, marginal cost will be reduced by a factor $1 - \alpha$. We assume that the parameter $\alpha$ is exogenous and that the innovator knows $\alpha$ before she chooses how much to invest in R&D. Thus, without public support to R&D, the innovator solves:

$$\max_k \left\{ z(k)v^M - k \right\}, \tag{5}$$

where $v^M$ is the patent income of the innovator. Hence, the innovator will choose the R&D level $k^M$ that is the solution of the following first-order condtion:

$$z'(k^M)v^M = 1. \tag{6}$$

The properties of $z(k)$ ensures that $k^M$ is uniquely defined and strictly increasing in $v^M$.

From a social point of view, the optimal level of R&D is the solution of

$$\max_k \left\{ z(k)V^M - k \right\} \tag{7}$$

where $V^M$ is the increase in social benefit caused by the innovation. This gives the first-order condition:

$$z'(k)V^M = 1. \tag{8}$$

One way to correct for the market failure of $v^M < V^M$ is to introduce an innovation prize $P^M$. From (6) and (8) we see that if the innovator receives an innovation prize $P^M = V^M - v^M$ in addition to the patent revenue $v^M$, that is, she obtains in total $V^M$, the amount of R&D undertaken will be identical to what is socially optimal. Hence, we have the following proposition:

**Proposition 1** *An innovation prize $P^M = V^M - v^M$ removes the appropriability problem for a market good.*

From Proposition 1 and (3) and (4) we find that the innovation prize is given by

$$P^M = V^M - v^M = \frac{(1-\alpha)}{8\gamma(\alpha + \frac{\beta}{\gamma})(1 + \frac{\beta}{\gamma})}, \tag{9}$$

which is equal to the area $ABC$ in Figure 1. Clearly, $P^M$ is positive for all parameter values, implying that without an innovation prize (or any other policy support) R&D will be lower than what is socially optimal.

A more radical innovation (lower $\alpha$) will shift the $NSMC$ curve in Figure 1 downwards. This tends to increase the social value of the innovation, $V^M$ (the area $FABCE$ in Figure 1). Also the $NPMC$ curve will shift downwards, but less than the $NSMC$ curve because the license fee will increase; the innovator will exploit the higher cost saving of using the new technology. With our parameterization, the down-stream producer beeing indifferent between the old and the new technology, $\hat{x}^M$, will not change; for this producer the gain from lower cost of the new technology is exactly offsett by a higher license fee. However, the shift in the $NSMC$ cuve will increase the number of operating firms ($\bar{x}^M$). Therefore, the number of firms using the new technology ($\bar{x}^M - \hat{x}^M$) increases, and because also the licence fee increases (see above), the patent income $v^M$ ($FACE$ in Figure 1) will increase. The optimal prize $P^M$ inceases ($ABC$ in Figure 1) to compensate for the higher license fee.

# 3 Innovations reducing abatement costs

We now turn to the case of environmental R&D. We assume that there is a group of firms, each having installed an abatement technology. Initially, a firm can either use this high-cost abatement technology, or emit environmentally harmful emissions. In the latter case, the firm pays an environmental tax to the government.

There is an innovator who invests in R&D in order to develop a more cost-efficient abatement technology. If the innovator has success, she rents out the new technology at a price - the licence fee. Firms can either abate, using the old, hig-cost technology or the new technology, or pay an environmental tax to the government.

The sequence of moves is as follows: I) The government announces an innovation prize, II) The innovator invests in R&D, III) If the innovator develops a more efficient technology, the regulator resets its emission tax (prior to the game, there is an emission tax that ensures the optimal pre-innovation abatement level), IV) The innovator sets a price on the innovation, and V) polluting firms decide whether to emitt or abate, and, if they abate, whether to adopt the new pollution abatement technology or use the old, high-cost, technology.

## 3.1 The appropriability problem with an abatement technology

We assume that the abatement cost function has exactly the same properties as the cost function in the previous section. Therefore, we may interpret the linear pre-innovation marginal cost function $OMC$ in a similar manner as we did before: There is a continuum of firms, each having one unit of emissions, and firm $i$ either abates all its emissions at cost $\gamma i$ or has no abatement. As before, a successful innovation reduces abatement costs for firm $i$ from $i\gamma$ to $\alpha\gamma i$ . If firm $i$ rents the new technology for the fee $\ell$, its private abatement cost is changed from $\gamma i$ to $\alpha\gamma i + \ell$. As in Section 2.1, the firm $\hat{x}^E$ ($E$-environmental R&D) is indifferent between the two technologies.

There is also a function measuring the marginal benefit of increased abatement, which is assumed to be exactly the same as the demand function in the market good case. Prior to an innovation, an optimal environmental policy will give the equilibrium point $B$ in Figure 2. Moreover, a first-best post-innovation outcome would be the equilibrium point $D$. If this were achieved, the social value of the innovation would be the sum of reduced social abatement costs and reduced environmental costs, given by the area $OBD$ in Figure 2 (denoted $V^*$ as before).

[Figure 2]

Abatement is determined by private marginal abatement costs being equal to the emission tax $t$, i.e., $\alpha\gamma\bar{x}^E + \ell^E = t$. The government chooses the emission tax to maximize social benefits minus social costs, and it takes into consideration that this tax affects both the license fee $\ell$ and total abatement $x$, i.e.,

$$\max_t \left\{ B(x^E(t)) - C(x^E(t), \ell^E(t) \right\} \tag{10}$$

where $B(x^E)$ is the quadratic benefit function corresponding to the linear marginal benefit function $1 - \beta x^E$. Further, $C(x^E(t), \ell^E(t))$ is the aggregate social abatement cost function, which covers costs for those firms using the old technology ($x^E \leq \hat{x}^E$), that is, $OMC$ is their marginal cost curve, as well as costs for firms using the new technology, that is, $NPMC$ is their marginal cost curve.

The problem (10) is solved in Appendix 2. Here, we find how the licence fee is related to the emission tax ($\ell^E(t) = \frac{(1-\alpha)t}{2}$) and also how total abatement is related to the emission tax ($\bar{x}^E(t) = \frac{t(1+\alpha)}{2\alpha\gamma}$). These expressions show that a higher tax will increase both the licence fee and total abatement.

In choosing the emission tax $t$ the government maximizes total welfare, which means that the government minimizes the deadweight losses $OAF$ and $ECD$ in Figure 2. A higher tax increases total abatement, which will reduce the deadweight loss $ECD$. More abatement means that the number of firms renting the new technology will increase, which the innovator will exploit by setting a higher licence fee. This generates a derived effect: a higher licence fee tends to increase the number of firms sticking to the old technology. More firms using the old technology suggests that the deadweight loss $OAF$ increases. The optimal tax has to balance the two deadweight losses.

In Appendix 2 we derive the increase in social benefit caused by the innovation when the innovator is a monopolist (and the users of the innovation abate emissions), $V^E$, and the income to the innovator, $v^E$:

$$V^E = \frac{(1-\alpha)(1+2\alpha)}{2\gamma\left(1+\frac{\beta}{\gamma}\right)(3\alpha^2+\alpha+\alpha^2\frac{\beta}{\gamma}+2\alpha\frac{\beta}{\gamma}+\frac{\beta}{\gamma})} \tag{11}$$

$$v^E = \frac{\alpha(1-\alpha)(1+\alpha)^2}{\gamma\left(3\alpha^2+\alpha+\alpha^2\frac{\beta}{\gamma}+2\alpha\frac{\beta}{\gamma}+\frac{\beta}{\gamma}\right)^2}. \tag{12}$$

$$t = \frac{2\alpha(1+\alpha)}{\alpha(1+3\alpha)+\frac{\beta}{\gamma}(1+\alpha)^2}. \tag{13}$$

## 3.2 Innovation prize with an abatement technology

From (11) and (12) we see that in general $V^E$ differs from $v^E$. If $v^E < V^E$, too little R&D will be undertaken by the innovator, whereas investment in R&D will be too large if $v^E > V^E$. Assuming, as in Section 2, that by investing $k$ the innovator succeeds with probability $z(k)$, an innovation prize $P^E = V^E - v^E$ will ensure that the innovator gets the correct incentives to invest in R&D:

$$P^E = V^E - v^E = \frac{(1-\alpha)\left(4\alpha^3 + \alpha^2 - \alpha + \alpha^2\frac{\beta}{\gamma} + 2\alpha\frac{\beta}{\gamma} + \frac{\beta}{\gamma}\right)}{2\gamma\left(1+\frac{\beta}{\gamma}\right)\left(3\alpha^2 + \alpha + \alpha^2\frac{\beta}{\gamma} + 2\alpha\frac{\beta}{\gamma} + \frac{\beta}{\gamma}\right)^2}. \tag{14}$$

From (11) we find that $\frac{dV^E}{d\alpha} < 0$; a lower cost reduction following from the innovation (a higher $\alpha$) will of course lower the social value of the innovation. The effect of a shift in $\alpha$ on the income of the innovator ($v^E$) turns out to be

involved, and therefore also a shift in $\alpha$ on the research price ($P^E = V^E - v^E$) is ambiguous: The graph in Figure 3 shows all combinations of $\alpha$ and $\theta = \frac{\beta}{\gamma}$ for which $\frac{dP^E}{d\alpha} = 0$. This curve is single peaked and $\frac{dP^E}{d\alpha} > 0$ below the graph ($\frac{dP^E}{d\alpha} < 0$ above the graph).[3] The complexity of $\frac{dP^E}{d\alpha}$ may indicate that a comparison of $P^E$ and $P^M$, both of which depend on $\alpha$, may not be straigth forward. We now turn to comparing the two types of innovation.

[Figure 3]

[3]The sign of $\frac{dP^E}{d\alpha}$, as well as the sign of all other expressions of interest, are independent of $\beta$ and $\gamma$ for a given value of $\theta = \frac{\beta}{\gamma}$. In our calculations, we have therefore set $\gamma = 1$.

## 4 Comparing the two types of innovation

In this Section we compare the two innovation prizes ($P^M$ and $P^E$), the two social values of innovations ($V^M$ and $V^E$) and the two licence revenues ($v^M$ and $v^E$) under the normalization $\gamma = 1$ (see footnote 4).

First, we solve the equation $P^M = P^E$ wrt. $\alpha$ (requiring $\theta = \frac{\beta}{\gamma} \geq 0$):

$$\theta = \alpha \frac{-3\alpha^2 + 2\sqrt{4\alpha^4 + 10\alpha^3 + 17\alpha^2 + 14\alpha + 4} + 1}{\alpha^3 + 5\alpha^2 + 7\alpha + 3} = f(\alpha). \qquad (15)$$

By substituting $\theta = f(\alpha)$ into the relation $P^M = P^E$ and then differentiate wrt. $\alpha$, we find that $f'(\alpha) > 0$, that is, a higher $\alpha$ (a lower cost reduction following from the innovation) requires a higher $\theta$ (the slope of the demand curve/marginal benefit of abatement curve relative to the slope of the marginal cost curves) to retain the equality $P^M = P^E$. Hence, the curve $P^M = P^E$ is upward sloping, see Figure 4. By simply inserting a combination of $\alpha$ and $\theta$ that is not on the curve $P^M = P^E$, we find that $P^E > P^M$ above the curve (and thus $P^E < P^M$ below the curve).

[Figure 4]

As seen from Figure 4, as $\alpha$ approaches 1, $\theta$ has to approach a value somewhat above 0.7 in order to ensure that $P^M = P^E$. This asymptotic value is simply $f(1) = 0.75$. Hence, for $\theta \geq 0.75$ we are above the curve $P^M = P^E$, and here $P^E > P^M$.

In the special case of $\theta = 0$ (due to $\beta = 0$), $P^E < P^M$. With market goods R&D, $\beta = 0$ means that the world market price is given, whereas with environmental R&D, $\beta = 0$ means that the marginal benefit of abatement is given. For the climate issue, $\beta = 0$ means that the social cost of carbon is given, which seems reasonable for a small country, at least for a single sector in a small country.

For the intermediate cases $0 < \theta < 0.75$ the ranking of $P^M$ and $P^E$ also depends on $\alpha$. From Figure 4 we see that for a given value of $\theta$, $P^E > P^M$ requires that $\alpha < \alpha_\theta$ where ( $\alpha_\theta, \theta$) is a point on the curve $P^M = P^E$ and $\alpha_\theta$

is increasing in $\theta$ due to the cruve $P^M = P^E$ being upward sloping.

**Proposition 2** *If the slope of the demand curve/marginal benefit of abatement curve relative to the slope of the marginal cost curve ($\theta$) exceeds 0.75, then the innovation prize for environmental R&D ($P^E$) should be greater than the innovation prize for market goods R&D ($P^M$). In the special case of a given world market price/a given marginal benefit of abatement ($\beta = 0$), the innovation prize for market goods R&D ($P^M$) should exceed the innovation prize for environmental R&D ($P^E$).*

We now take a closer look at the components of the research prizes. For the increase in social surplus caused by the innovation, we find that

$$V^E - V^M = \frac{(\alpha-1)^2(3\alpha\theta+\alpha+\theta)}{8(1+\theta)(\alpha+\theta)(3\alpha^2+\alpha+\alpha^2\theta+2\alpha\theta+\theta)} > 0.$$

This result reflects that the government uses the emission tax to move the social value of the environmental innovation, $V^E$, closer to the maximum social value, $V^*$. With market goods R&D, no similar instrument is (per assumption) available, which reflects that there is no externality for the ordinary market good. Therefore, we always have $V^E > V^M$:

**Proposition 3** *The increase in social surplus due to an innovation is higher with environmental R&D than with market goods R&D ($V^E > V^M$).*

Figure 5 shows combinations of $\alpha$ and $\theta$ for which $v^M = v^E$. As seen from the Figure, this is an upward sloping curve where $v^M > v^E$ above the curve ($v^M < v^E$ below the curve). Note that in contrast to Figure 4, there is no $\theta$ in Figure 5 for which the ranking of $v^M$ and $v^E$ is independent of $\alpha$. For the special case $\beta = 0$ we have

$$v^E - v^M \mid_{\beta=0} = \frac{(\alpha-1)^2(5\alpha+3)}{4\alpha(3\alpha+1)^2} > 0,$$

that is, $v^E > v^M$ when $\beta = 0$.

[Figure 5]

**Proposition 4** *In the special case of a given world market price/a given social cost of carbon* ($\beta = 0$)*, the licence income* ($v$)*, the licence fee* ($\ell$) *and the firm beeing indifferent between the old and new technology* ($\hat{x}$) *is highest under environmental R&D.*

# 5 Modifications and extensions

In this Section we analyze different modifications and extensions of the basic model. Whereas in Sections 2-4 the benefit of the innovation differed between users of the new technology, in Section 5.1 we consider the case of an identical benefit of the innovation. In Section 5.2 we analyse the model when the government uses an R&D subsidy, not an innovation prize, to reach the efficient level of R&D. Whereas the discussion in Sections 2-5.2 is based on the government knowing the cost reduction if the innovator succeeds in developing a new technology, in Section 5.3 we discuss the case of the government not knowing the cost reduction ex ante. In Section 5.4 we consider the case that the government has an additonal policy instrument; firms renting the new technology receive a tax rebate that covers part of, or all of, the licence fee. Finally, in Section 5.5 we study the case when the government uses a product specific subsidy to stimulate demand for the market good. This instrument (along with the innovation prize) may be introduced to counteract the market power of the monopoly innovator.

## 5.1 Innovations affecting all users identically

So far we have assumed that the innovation lowers the slope of the marginal cost curve, but leaves the intercept with the vertical axis unaffected. This assumption implies that downstream firms differ in how useful the innovation is for them. In particular, there are some firms that would hardly get their costs reduced by using the new technology. Therefore, the innovator would always price the innovation so that some firms would not purchase the right to use it.

If we instead had assumed that not only the slope of the marginal cost curve was affected but also the intercept with the vertical axis, it is not obvious that the innovator's optimal license fee will exclude some potential users. If the value of the innovation is sufficiently homogeneous across potential users, it may be optimal to set a license fee that makes all potential users buy the right to use the innovation. To focus on this possibility, we briefly discuss the limiting case of all users having exactly the same value of the innovation. In our model this means that the original marginal cost curve, $OMC$ in Figure 4, shifts downwards with a constant horizontal shift $EA$.

[Figure 6]

Consider first an innovation that reduces the costs of producing an ordinary market good. A first-best post-innovation outcome would be the equilibrium point $C$. If this were achieved, the maximum social value of the innovation, $V^*$, would clearly be the sum of reduced costs and increased consumer benefit (the area $EABC$ in Figure 6). As before, the first-best outcome $C$ would be achieved if the private marginal cost of the downstream producers was equal to the social marginal cost. However, also in this case the innovator will charge a license fee that depends on the production volume, so the private marginal cost curve will not coincide with the $NSMC$-curve.

The license fee can obviously not exceed $EA$ in Figure 6, otherwise no-one would want to rent the technology. The optimal licence fee will either be equal to (or marginally below) $EA$, or lower.[4] To formalize, let $\sigma + \gamma x$ be marginal cost prior to the innovation ($\sigma$ is equal to $OA$ in Figure 6). Further, let $\sigma - \delta + \ell + \gamma x$ be the new private marginal cost after a successful

[4] Henceforth, we assume that if the licence fee is equal to the gain of using the new technology ($EA$), all agents will switch to the new technology.

innovation where $\delta$ is the cost reduction due to the innovation ($\delta$ is equal to $EA$ in Figure 6). In Appendix 3 we show that in the market good case it is optimal with limit pricing ($\ell = \delta$) if $\delta \leq 1 - \sigma$, whereas it is optimal with limit pricing in the environmental case if $\delta \leq \frac{\gamma}{\beta}(1 - \sigma)$.

Assume first that it is optimal with limit pricing in both cases. Consider first the market good case. Because the new private marginal cost will be identical to the *OMC*-curve, the equilibrium output will be unaffected by the innovation, that is, the equilibrium output is still $x^0$ in Figure 6. The social value of the innovation is therefore equal to the reduction in social costs, that is, the area *EABD* in Figure 6. But this is exactly the same as the value to the innovator. Hence $v^M = V^M$, and therefore $P^M = 0$; there is no appropriability problem.

Consider next the case of an environmental innovation. Because the innovation will be used by all downstream polluting firms no matter what the emission tax is (as long as it is positive), the regulator's only consideration when setting the tax rate is how much abatement that will be achieved. The socially optimal abatement level is $x^*$, which will be achieved by setting the tax rate equal to $t^*$ in Figure 6. With this tax rate, the maximum social value of the innovation is obtained, i.e., $V^E = V^*$, which corresponds to the area *EABC* in Figure 6. The revenue to the innovator is given by the area *EAFC*, which is *larger* than the area *EABC*. Therefore, $v^E > V^E$. Hence, for environmental R&D the R&D effort $k$ chosen by the innovator will be *higher* than what is socially optimal.

If $\frac{\beta}{\gamma} < 1$ it is possible to have $(1 - \sigma) < \delta \leq \frac{\gamma}{\beta}(1 - \sigma)$, that is, there is limit pricing in the environmental case ($P^E < 0$) but not in the market good case. For the market good case we then have the situation described in Figure 7, where the endogenously determined licence fee is equal to $EF$. The social value of the innovation $V^M$ is given by $EABCD$, while the innovator's income $v^M$ is given by $EFCD$. It is clear that $v^M < V^M$, implying $P^M > 0$. The size of $P^M$ is given by the area $FABC$.

[Figure 7]

Proposition 5 sums up the results for the case of limit pricing in the environmental good case:

**Proposition 5** *Assume all users have the same value of the innovation. If limit pricing is the optimal strategy for the innovator in the enviroronmental good case ($\delta \leq \frac{\gamma}{\beta}(1-\sigma)$), then the prize $P^E$ should be negative. The prize $P^M$ should be zero if there is limit pricing also in the market good case ($\delta \leq 1-\sigma$), otherwise $P^M > 0$. Hence, for these cases the optimal innovation prize with environmental R&D ($P^E$) is lower than the optimal innovation prize with market goods R&D ($P^M$).*

If $\frac{\beta}{\gamma} > 1$ it is possible to have $\frac{\gamma}{\beta}(1-\sigma) < \delta \leq 1-\sigma$, that is, there is limit pricing in the market good case ($P^M = 0$) but not in the environmental case. In Appendix 3 we show that if $\gamma$ is sufficiently small, that is, $\frac{\beta}{\gamma}$ is sufficiently large, we have $P^E > 0$, so that $P^E > P^M$ for this case.

With an interior solution for the license fee also in the market case (i.e., $\delta > 1-\sigma$), it is clear from our discussion of Figure 7 that $P^M = V^M - v^M < V^M$. Moreover, we have $V^E > V^M$ because the first-best amount of abatement ($x^*$) will be achieved in the environmental case while the output will only be $\bar{x}$ in the marked good case. In Appendix 3 we show that $v^E$ approaches zero as $\frac{\beta}{\gamma}$ approaches infinity. Hence $P^E$ approaches $V^E$ as $\frac{\beta}{\gamma}$ approaches infinity. From the inequalities above it follows that $P^E > P^M$ when $\frac{\beta}{\gamma}$ is sufficiently large.

Proposition 6 sums up the discussion above:

**Proposition 6** *If all users have the same value of the innovation, and it is optimal with an interior solution for the licence fee in the the environmental R&D case ($\frac{\gamma}{\beta}(1-\sigma) < \delta$), and the slope of the demand curve/marginal benefit of abatement curve relative to the slope of the marginal cost function ($\beta/\gamma$) is sufficiently large, then the optimal innovation prize with environmental R&D ($P^E$) is higher than the optimal innovation prize with market goods R&D ($P^M$).*

## 5.2 R&D subsidy

Governments more often subsidize research inputs than research output. In our model it is easy to see that the government can also use an R&D subsidy $s$ to induce the efficient amount of R&D. In this case the innovator pays $(1-s)k$, while the government pays $sk$ of the R&D costs. Thus, when setting $k$ the innovator solves:

$$\max_{z} \{z(k)v - (1-s)k\}.$$

The optimal $k$ is given from:

$$z'(k)v = 1 - s. \tag{16}$$

The government wants $z'(k)V = 1$, see (8). Hence, the optimal subsidy rate is given by:

$$s = \frac{V - v}{V} = \frac{P}{V}. \tag{17}$$

For a market good innovation, it follows from (3) and (9) that the optimal subsidy rate is:

$$s^M = \frac{1}{3}. \tag{18}$$

This exact number follows from the linearity of the demand curve/marginal benefit of abatement curve and the linearity of the marginal cost curve. Nevertheless, it is interesting that the subsidy is independent of both $\alpha$ (how much the innovation lowers cost) and $\theta$ (the relative slope).

For an innovation that reduces abatement cost, it follows from (11) and (14) that

$$s^E = \frac{\alpha(4\alpha^2 + \alpha - 1) + \theta(1+\alpha)^2}{(2\alpha+1)(\alpha(3\alpha+1) + \theta(1+\alpha)^2)}. \tag{19}$$

We have $s^M = \frac{P^M}{V^M} > \frac{P^M}{V^E}$ because $V^E$ is always greater than $V^M$ (Proposition 3). Moreover, for all combinations of $\alpha$ and $\theta$ for which $P^M > P^E$ we have $\frac{P^M}{V^E} > \frac{P^E}{V^E} = s^E$, and thus $s^M > s^E$ (for these combinations of $\alpha$ and $\theta$). To learn more about the ranking of the subsidies, we solve the equation $s^E = s^M$ wrt. $\alpha$, which gives us the function $\theta = s(\alpha)$, where $s'(\alpha) > 0$. Therefore, the curve $s^E = s^M$ is upward sloping ($s^E > s^M$ above the curve); this curve is similar to the one in Figure 4. Becasue $s(1) = 1.25$, we have the following Proposition:

**Proposition 7** *If the slope of the demand curve/marginal benefit of abatement curve relative to the slope of the marginal cost curve ($\theta$) exceeds 1.25, then R&D subsidy for environmental R&D should exceed the R&D subsidy for market goods innovation ($s^E > s^M$). In the special case of a given world market price/a given marginal benefit of abatement ($\beta = 0$), the R&D subsidy for market goods innovation should exceed the R&D subsidy for environmental R&D ($s^M > s^E$).*

One argument in favor of a subsidy is that the expected fiscal outlay is lower with a subsidy than with an innovation prize: The total subsidy outlay is $(\frac{V-v}{V})k$, while the expected outlay with an innovation prize is $z(k)(V-v)$. Using the property that $z(k) > kz'(k)$ together with (16) and (17), it immediately follows that

$$\left(\frac{V-v}{V}\right)k < z(k)(V-v).$$

Hence, we have:

**Proposition 8** *It is cheaper for the government to use an R&D subsidy than an innovation prize.*

This result is similar to the property that for a producer with a standard concave production function (corresponding to $z(k)$ being concave in our problem), it is cheaper for the government to subsidize the input than to subsidize production in order to obtain a prespecified level of output. The reason is that with a concave production function, average productivity - which is related to the outlay when the government subsidizes output - exceeds marginal productivity - which is related to the outlay when the government subsidizes the input.

## 5.3 Asymmetric information

So far we have assumed that the government knows $\alpha$, that is, how radical the potential innovation is. Assume, however, that only the innovator, not the government, knows how radical the innovation is going to be *ex ante*.[5] Thus, $\alpha$ will be revealed for the government only if the innovation materializes. If the government can commit to an innovation prize that is contingent on $\alpha$, $P(\alpha) = V(\alpha) - v(\alpha)$, the results above on innovation prizes still hold.

If, alterntively, the government uses an R&D subsidy, it is still simple to set the correct subsidy for market goods R&D - it is simply 1/3, see (18). However, it is far more involved to set the optimal subsidy in the environmental R&D case. Assume, for instance, that the regulator knows $z(k)$ and believes $\alpha$ is uniformly distributed on $[0, 1]$. To find the optimal subsidy, the government must solve the following problem:

$$\max_{s^E} \left\{ \int_0^1 [z(k(\alpha, s^E))V(\alpha) - k(\alpha, s^E)]d\alpha \right\} \tag{20}$$

In (20) the R&D effort $k(\alpha, s^E)$ is the solution of (16), and it determines the probability to innovate $z(k(\alpha, s^E))$. Denote the solution to (20) $\bar{s}^E$. For some $\alpha$-values $\bar{s}^E$ will be too low (relative to the optimal subsidy without uncertainty), and for other $\alpha$-values $\bar{s}^E$ will be too high. This reasoning must

[5] The government specifies some criteria that have to be met in order to receive an innovation prize without knowing the implied cost reduction ($\alpha$).

also hold if the regulator does not know $z(k)$. Thus, in the environmental R&D case we must have:

**Proposition 9** *If the government does not know how radical the innovation will be ex ante, then for environmental R&D expected welfare is higher with an innovation prize than with an R&D subsidy.*

## 5.4 Tax rebate

In the literature a government purchase commitment is mentioned as an instrument that may trigger more R&D, see, for example, Kremer (2001a; 2001b). This policy tool is used to develop, for example, drugs and military equipment, and can take the form of a promised tax rebate on sales of the new technology. Below we include a tax rebate in our innovation prize model (assuming that both the innovator and the government know how radical the innovation will be ex ante).

The moves of the game in the market good case are now: I) The government announces an innovation price, II) The innovator invests in R&D, III) If an innovation materializes, the government sets a tax rebate $\tau$ for adoption of the new technology, and IV) the innovator sets the licence fee. In the pollution abatement case, the government sets *both* an emission tax and a tax rebate in stage III).

Note that the tax rebate will be time consistent as long as the innovation prize $P_\tau$ ensures the efficient amount of R&D. The tax rebate is then solely used to increase diffusion of the new technology.

With a tax rebate $\tau$ to every firm that adopts the new technology, the revenue function of the innovator is:

$$v(x, \ell, \tau) = \ell \left[ x - \frac{\ell - \tau}{(1-\alpha)\gamma} \right]. \tag{21}$$

We solve the model in Appendix 4. In both the market good case and the pollution abatement case the government can obtain the maximum increase in social value $V^*$ by setting the tax rebate equal to the equilibrium licence fee. Because demand for the new technology differs between the two cases, the equilibrium license fee also differs. We show that the licence fee $\ell$ and the resulting licence income $v$ are highest with market goods R&D. Further, with market goods R&D the optimal prize $P_\tau^M$ is always negative:

$$P_\tau^M = -\frac{1-\alpha}{\gamma} \frac{1}{2\left(1+\beta/\gamma\right)\left(\alpha+\beta/\gamma\right)} < 0. \tag{22}$$

With environmental R&D, the optimal prize is:

$$P_\tau^E = \frac{1-\alpha}{\gamma} \frac{(1-2\alpha)(\beta/\gamma)-\alpha}{2\left(1+\beta/\gamma\right)\left(\alpha+\beta/\gamma\right)^2}, \tag{23}$$

which is positive if $\alpha < \frac{\beta/\gamma}{1+2\beta/\gamma}$. Because $v_\tau^M > v_\tau^E$ and $V_\tau^M = V_\tau^E = V^*$, we have $P_\tau^E > P_\tau^M$.

**Proposition 10** *If the government uses a tax rebate $\tau$ to promote adoption of the technology in addition to an innovation price, the innovation prize should always be highest for pollution abatement innovations ($P_\tau^E > P_\tau^M$). For market goods R&D, the innovation prize is negative.*

Without a tax rebate, the government had to balance two concerns when setting the environmental tax: On the one hand, a high environmental tax brought abatement closer to the first-best level, but on the other hand, a high environmental tax increased the licence fee and therefore fewer firms chose the new technology. With a tax rebate, the regulator does not need a high environmental tax to bring abatement closer to the first-best level, and therefore the emission tax is set lower in the case with a tax rebate than in the case without a tax rebate.

## 5.5 Product subsidy

In the previous subsection we examined the case of a tax rebate; to counteract the market power of the monopoly innovator, which materializes as a licence fee, the government covered a share of the licence fee (the equilibrium share was 100 percent). With market goods R&D, an alternative strategy to counteract the market power of the innovator is to stimulate *demand* for the market good by offering a product subsidy. While such an instrument is not widely used, we include it in our comprehensive examination of how to provide social correct incentives for R&D.

We assume that the government offers a product subsidy $s$. Therefore, consumers pay $p - s$ for the product. Hence, demand for the product is $(p - s) = 1 - \beta x$. As in the other cases, total production is determined in a competitive equilibrium such that the $N$ew $P$rivate $M$arginal $C$ost ($\alpha\gamma x + \ell^M$) is equal to demand ($1 + s - \beta x$). Moreover, the firm that is indifferent between using the old and the new technology is determined in the same way as in the previous cases.

As in the case with environmental R&D, we assume that the innovator determines her licence fee after the government has determined its policy instrument, here the product subsidy $s$. The innovator finds the licence fee that maximizes her innovation income. This fee is given by (see Appendix 5 for the derivation of all equations):

$$\ell^M(s) = \frac{\gamma(1-\alpha)(s+1)}{2(\beta+\gamma)}. \tag{24}$$

We assume that the government determines the product subsidy $s$ such that social benefits minus social costs are maximized, taking into account how the technology switching point and total production depend on $s$ (either directly or through the license fee $\ell^M(s)$). The optimal subsidy is

$$s = \frac{1-\alpha}{3\alpha + 4\frac{\beta}{\gamma} + 1}. \tag{25}$$

The resulting optimal licence fee follows from inserting (25) into (24):

$$\ell_s^M = \frac{(1-\alpha)(\alpha + 2\frac{\beta}{\gamma} + 1)}{(3\alpha + 4\frac{\beta}{\gamma} + 1)(\frac{\beta}{\gamma} + 1)}. \tag{26}$$

We then calculate the innovation income, $v_s^M$, as well as the social value of the innovation, $V_s^M$. Finally, we find the optimal innovation prize:

$$P_s^M = V_s^M - v_s^M = \frac{\gamma(1-\alpha)(4\alpha^2 + 9\alpha\frac{\beta}{\gamma} + \alpha + 4(\frac{\beta}{\gamma})^2 - \frac{\beta}{\gamma} - 1)}{2\gamma(3\alpha + 4\frac{\beta}{\gamma} + 1)^2(1 + \frac{\beta}{\gamma})(\alpha + \frac{\beta}{\gamma})}. \tag{27}$$

Comparing $P_s^M$ to $P^E$ in Section 3.2, see (14), we find $P^E > P_s^M$.

# 6 Discussion and conclusion

This paper examines how the government should design an innovation prize that provides incentives for private firms to choose an efficient amount of R&D. We study innovation prizes both for market good innovations and for environmental innovations. With a pollution abatement innovation, the government determines demand for the new technology through the choice of environmental policy.

We find that if the slope of the demand curve/marginal benefit of abatement curve relative to the slope of the marginal cost curve exceeds 0.75, then the innovation prize for environmental R&D should be greater than the innovation prize for market goods R&D (Proposition 2). We have also studied the case when the government uses both an innovation prize and a tax rebate - the aim of the latter instrument is to promote adoption of the technology. Then the innovation prize should be highest for pollution abatement innovations (Proposition 10).

In most of the paper we have assumed that both the government and the innovator know how radical the innovation will be ex ante. However, in Section 5.3 we studied the case when the innovator knows how radical the innovation will be ex ante ($\alpha$), whereas the government does not know how radical the innovation will be ex ante but this actor can commit to an innovation prize that is contingent on $\alpha$. Then for environmental R&D expected welfare is higher with an innovation prize than with an R&D subsidy.

In our model the government commits to an emission tax after the R&D is carried out, but before the innovator sets her license fee for the new technology. There are, however, two other possible cases: First, the innovator commits to a license fee once the innovation has materialized, but before the government sets the emission tax (*innovator commitment).* Second, the emission tax and the license fee are set simultaneously (Neither the regulator nor the innovator can commit).

These cases are analyzed in a supplementary paper, see Golombek et al. (2015). We show that in the *innovator commitment* case, the innovation prize for market goods R&D should always be greater than the innovation prize for environmental R&D. With simultaneous moves, a result rather similar to Proposition 2 is obtained: if the slope of the demand curve/marginal benefit of abatement curve relative to the slope of the marginal cost curve exceeds 2, then the innovation prize for environmental R&D should be greater than the innovation prize for market goods R&D.

In the supplementary paper we also examine the model in Sections 2-4 when the government uses emissions quotas, not an emission tax. We show that when the government moves first (as in the present paper), the innovation prize for market goods R&D should always be greater than the innovation prize for environmental R&D. Finally, the supplementary paper examines the case of a product specific subsidy under simultaneous moves and when the innovator moves first.

Throughout the paper we have assumed that R&D takes place in an R&D firm that sells its innovation to a competitive downstream sector, which produces a market good (or the downstream firms abate pollution). If R&D instead took place in the competitive downstream sector and new knowledge became available to all firms free of charge, then there would be 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 access to new knowledge, and the regulator's implementation of environmental policy to counteract this negative effect, that causes the difference in incentives for environmental R&D versus market goods R&D.

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# 7 Appendices

## 7.1 Appendix 1: Market goods R&D

As explained in the text, firms with index up to $\hat{x}^M$ will choose the old technology, where $\hat{x}^M$ is determined by $\gamma\hat{x}^M = \alpha\gamma\hat{x}^M + \ell^M$, implying

$$\hat{x}^M = \frac{\ell^M}{\gamma(1-\alpha)}. \tag{28}$$

With market goods R&D, total production $\bar{x}^M$ is determined in a competitive equilibrium such that the $N$ew $P$rivate $M$arginal $C$ost $(\alpha\gamma x + \ell)$ is equal to demand $(1-\beta x)$. Hence, $\bar{x}^M$ is the solution of $\alpha\gamma\bar{x}^M + \ell = 1 - \beta\bar{x}^M$, implying

$$\bar{x}^M = \frac{1-\ell^M}{\alpha\gamma+\beta}. \tag{29}$$

Further, let $x^0$ be the pre-innovation competitive equilibrium, that is, $x^0$ is the solution to $O$ld $M$arginal $C$ost $(\gamma x)$ being equal to demand $(1-\beta x)$. Thus, $x^0$ is the solution of $\gamma x^0 = 1 - \beta x^0$, implying

$$x^0 = \frac{1}{\gamma+\beta}. \tag{30}$$

The inovator chooses the licence fee $l^M$ such that her revenues are maximized:

$$v^M = \max_{\ell^M} \left\{ \ell^M \left[ \bar{x}^M - \hat{x}^M \right] \right\}. \tag{31}$$

Using (28) and (29) we find that

$$\ell^M = \frac{\gamma(1-\alpha)}{2(\gamma+\beta)}. \tag{32}$$

Using (32) to calculate the reveneus of the innovator, $v^M = \ell^M(\bar{x}^M - \hat{x})$, gives relation (4).

As explained in Section 3, the social value of innovation in the market good case, $V^M$, is the area $FABCE$ in Figure 1. This area can be calcualted as

$$\int_{\hat{x}^M}^{x^0} (\gamma x - \alpha\gamma x)dx + \int_{x^0}^{\bar{x}^M} (1 - \beta x)dx - \int_{x^0}^{\bar{x}^M} \alpha\gamma x dx \tag{33}$$

where the first integral represents the cost savings of producing the units $(x^0 - \hat{x}^M)$ with the new technology, and the second and third integral represent the net social benefit of increasing production from $x^0$ to $\bar{x}^M$ once the innovation has materialized. Using (28) to (30) to calculate (33) gives (3).

## 7.2 Appendix 2: Environmental R&D

Relation (28), which determines which firm is indifferent between the old and the new technology, applies also in the case of environmental R&D. In this case firms are emitting harmful emissins, and abatement $\bar{x}^E$ is determined by private marginal abatement costs being equal to the emission tax $t$, i.e., $\alpha\gamma\bar{x}^E + \ell = t$, giving

$$\bar{x}^E = \frac{t - \ell^E}{\alpha\gamma}. \tag{34}$$

Inserting (28) and (34) into the innovator's optimization problem

$$v^E = \max_{\ell^E} \left\{ \ell^E \left[ \bar{x}^E - \hat{x}^E \right] \right\}$$

gives the license fee:

$$\ell^E(t) = \frac{(1-\alpha)t}{2}. \tag{35}$$

Further, inserting this license fee back into (28) and (34) gives

$$\hat{x}^E(t) = \frac{t}{2\gamma} \tag{36}$$

$$\bar{x}^E(t) = \frac{t(1+\alpha)}{2\alpha\gamma}. \tag{37}$$

The government chooses its emission tax $t$ to maximize social benefits minus social costs, and it takes into consideration that this tax affects both the license fee $\ell^E$ and total abatement $\bar{x}^E$, i.e.,

$$\max_t \left\{ B(\bar{x}^E(t)) - C(\bar{x}^E(t), \ell^E(t) \right\} \tag{38}$$

where $\ell^E(t)$ and $\bar{x}^E(t)$ is given by (35) and (37) respectivelly. $B(\bar{x}^E)$ is the quadratic benefit function, which corresponds to the area under the marginal benefit of abatement function $1 - \beta x$ between 0 and $\bar{x}^E$. Further, $C(\bar{x}^E(t), \ell^E(t))$ is the aggregate social abatement cost function, which covers costs for those firms using the old technology ($x \leq \hat{x}^E$), that is, $OMC$ is their marginal cost curve, as well as costs for firms using the new technology, that is, $NPMC$ is their marginal cost curve:

$$C(\bar{x}^E(t), \ell^E(t)) = \int_0^{\hat{x}^E(t)} \gamma x dx + \int_{\hat{x}^E(t)}^{\bar{x}^E(t)} \alpha\gamma x dx = \frac{t^2(3\alpha+1)}{8\alpha\gamma}. \tag{39}$$

where we have used (36) and (37). The solution to problem (38) is the optimal tax is

$$t = \frac{2\alpha(1+\alpha)}{\alpha(1+3\alpha) + \frac{\beta}{\gamma}(1+\alpha)^2}. \tag{40}$$

Using (40) we find $\bar{x}^E$ and $\ell^E$ as functions of $\alpha$ and $\beta$:

$$\bar{x}^E = \frac{(1+\alpha)^2}{\gamma(\alpha(1+3\alpha)+\frac{\beta}{\gamma}(1+\alpha)^2)}. \tag{41}$$

$$\ell^E = \frac{\alpha(1+\alpha)(1-\alpha)}{\alpha(1+3\alpha)+\frac{\beta}{\gamma}(1+\alpha)^2}. \tag{42}$$

Further, $\hat{x}^E$ as functions of $\alpha$ and $\beta$ follows from (36) and (40). These expressions are used to calculate the income of the innovator, $v^E = \ell^E \left[\bar{x}^E - \hat{x}^E\right]$, as well as the social value of innovation, $V^E$, which also in this case is given by (33) (when $\hat{x}^M$ is replaced by $\hat{x}^E$ and $\bar{x}^M$ is replaced by $\bar{x}^E$).

## 7.3 Appendix 3: Limit pricing

In this Appendix we derive the conditions for when it is optimal for the innovator to use limit pricing. Prior to the innovation, marginal cost is $\sigma + \gamma x$, where $x$ is production in the market good case and abatement in the environmental case, and $\sigma$ and $\gamma$ are parameters ($0 \leq \sigma$, $0 < \gamma$). Let $\delta$ be the cost reduction due to the innovation, which is equal to AE in Figure 6, and let $\ell$ be the licence fee. After a successful innovation, the new social marginal cost is $\sigma - \delta + \gamma x$,whereas $\sigma - \delta + \ell + \gamma x$ is the new private marginal cost. Finally, demand is given by $1 - \beta x$.

We start with the case of an ordinary market good. In the post-innovation equilibrium, the consumer price $1 - \beta x$ is equal to the new private marginal cost, giving

$$x = \frac{1-\sigma+\delta-\ell}{\gamma+\beta}. \tag{43}$$

The innovator chooses the licence fee such that the income $\ell x$ is maximized. As explained in the text, the optimal licence fee will either be equal to *EA* in Figure 6 (limit pricing), or lower (internal solution). Let us first consider the internal solution, that is, $\ell < \delta$. In this case the optimal $\ell$ is

$$\ell = \frac{1-\sigma+\delta}{2}. \tag{44}$$

Clearly, this expression is lower than $\delta$ if $1-\sigma<\delta$. Hence, if $1-\sigma\geq\delta$, it is optimal for the innovator to set $\ell=\delta$ (limit pricing).

Consider next an innovation that reduces abatement costs. Again, assume initially that the equilibrium satisfies $\ell<\delta$. As above, the equilibrium value of $\ell$ must maximize $\ell x$. In the present case the environmental tax $t$ is given when the innovator sets her license fee, and therefore $x$ follows from the new private marginal cost being equal to the tax:

$$x=\frac{t-(\sigma-\delta+\ell)}{\gamma}. \tag{45}$$

The value of $\ell$ maximizing $\ell x$ is hence given by

$$\ell=\frac{t-\sigma+\delta}{2}, \tag{46}$$

which inserted into (45) gives

$$x=\frac{t-\sigma+\delta}{2\gamma}. \tag{47}$$

The socially optimal value of $x$ equates marginal benefit of abatement with the new social marginal cost, giving

$$x=\frac{1-\sigma+\delta}{\gamma+\beta}. \tag{48}$$

The government will choose the tax rate $t$ such that social surplus is maximized, and hence the quantity following from profit maximization of the innovator, see (47), will coincide with the socially optimal quantity in (48). This requires that

$$t=\frac{2\gamma}{\gamma+\beta}\left(1-\sigma+\delta\right)+\sigma-\delta. \tag{49}$$

Inserting (49) into (46) gives the equilibrium value of the license fee:

$$\ell=\frac{\gamma}{\gamma+\beta}\left(1-\sigma+\delta\right). \tag{50}$$

This expression gives the equilibrium value of the license fee provided $\ell < \delta$. We find that $\ell < \delta$ if $\frac{\gamma}{\beta}(1-\sigma) < \delta$. Hence, if $\delta \leq \frac{\gamma}{\beta}(1-\sigma)$, it is optimal for the innovator to set $\ell = \delta$ (limit pricing).

As demonstrated above, in the market good case the condition for limit pricing is independent of $\gamma$ and $\beta$, whereas with environmental R&D the condition for limit pricing depends on $\frac{\gamma}{\beta}$. Hence, we may have limit pricing in one case, but not in the other: if limit pricing is optimal in the market good case, then limit pricing is not optimal in the environmental case provided $\frac{\gamma}{\beta}$ is sufficiently low.

If there is an internal solution in the environmental case ($E$), it follows from (48) and (50) that the innovator's income is

$$v^E = \frac{\gamma}{(\gamma+\beta)^2}\left(1-\sigma+\delta\right)^2 = \frac{1}{\gamma(1+\frac{\beta}{\gamma})^2}\left(1-\sigma+\delta\right)^2.$$

We immediately see that $v^E$ approaches zero as $\gamma$ approaches zero (horizontal cost curves), that is, $\frac{\beta}{\gamma}$ approaches infinity.

With environmental R&D the social value of the innovation ($V^E$) will always exceed the cost saving at the pre-innovation output level $x^0 = \frac{1-\sigma}{\gamma+\beta}$:

$$V^E > \delta\frac{1-\sigma}{\gamma+\beta}.$$

It follows that

$$P^E = V^E - v^E > \frac{1}{\gamma+\beta}\left[\delta(1-\sigma) - \frac{1}{1+\frac{\beta}{\gamma}}\left(1-\sigma+\delta\right)^2\right],$$

implying that $P^E > 0$ for a sufficiently high value of $\frac{\beta}{\gamma}$.

## 7.4 Appendix 4: Tax rebate

The main differences between the present case and the cases discussed in Appendices 1 and 2 are that i) each downstream firm that adopts the new technology now receives a tax rebate $\tau$, and ii) the government chooses the tax rebate such that the social gain from the innovation is maxmized.

As a reference case, we first examine how the first-best outcome changes due to an innovation. Prior to the innovation, the first-best quantity is $x^0$, see (30), whereas after an innovation, the first-best quantity $x^*$ is characterized by the $N$ew $S$ocial $M$arginal $C$ost ($\alpha\gamma x$) being equal to demand $(1 - \beta x)$, that is, $x^* = \frac{1}{\alpha\gamma+\beta}$. The change in welfare from the first-best outcome prior to the innovation to the first-best outcome after the innovation is therefore $V^* = \int\limits_0^{x^*}(1 - \beta x - \alpha\gamma x)dx - \int\limits_0^{x^0}(1 - \beta x - \gamma x)dx = \frac{(1-\alpha)\gamma}{2(\gamma+\beta)(\alpha\gamma+\beta)}$.

#### 7.4.1 Market goods R&D

We follow the same procedure as in Appendix 1, except that $\ell$ is replaced by $\ell - \tau$. The social gain obtained from the innovation, see (33), which is now a function of the tax rebate, is

$$V^M(\tau) = \frac{(\alpha\gamma - \beta\tau - \gamma\tau - \gamma)(3\alpha\gamma + \beta\tau + \gamma\tau - 3\gamma)}{8\gamma\,(1-\alpha)\,(\beta+\gamma)(\alpha\gamma+\beta)}. \tag{51}$$

This expression corresponds to (3). The government maximizes (51) wrt. $\tau$, which gives the optimal tax rebate:

$$\tau^M = \frac{1-\alpha}{1+\frac{\beta}{\gamma}}. \tag{52}$$

We then use (52) to find the other variables as functions of $\alpha$, $\beta$ and $\gamma$: $\hat{x}^M_\tau = 0$, $\bar{x}^M_\tau = x^*$, $\ell^M_\tau = \tau^M$, $V^M_\tau = V^*$, $v^M_\tau = \frac{\gamma(1-\alpha)}{(\alpha\gamma+\beta)(\gamma+\beta)}$ and

$$P^M_\tau = V^M_\tau - v^M_\tau = -\frac{1-\alpha}{2\gamma(1+\frac{\beta}{\gamma})\left(\alpha+\frac{\beta}{\gamma}\right)} < 0.$$

### 7.4.2 Environmental R&D

We follow the same procedure as in Appendix 2, except that $\ell$ is replaced by $\ell - \tau$. Hence, all variables are now functions of $t$ and $\tau$. The government maximizes welfare wrt. to $t$ and $\tau$:

$$\max_{t,\tau} \left\{ B(\bar{x}^E(t,\tau)) - C(\bar{x}^E(t,\tau), \ell^E(t,\tau) \right\} \tag{53}$$

The solution of (53) is

$$t^E = \frac{\alpha}{\alpha + \frac{\beta}{\gamma}} \tag{54}$$

$$\tau^E = \frac{(1-\alpha)\,\alpha}{\alpha + \frac{\beta}{\gamma}} \tag{55}$$

We then use (54) and (55) to find the other variables as functions of $\alpha$, $\beta$ and $\gamma$: $\hat{x}_\tau^E = 0$, $\bar{x}_\tau^E = x^*$, $\ell_\tau^E = \tau^E$, $V_\tau^E = V^*$, $v_\tau^E = \frac{(1-\alpha)\alpha\gamma}{(\alpha\gamma+\beta)^2}$ and

$$P_\tau^E = V_\tau^E - v_\tau^E = \frac{(1-\alpha)(\frac{\beta}{\gamma} - \alpha - 2\alpha\frac{\beta}{\gamma})}{2\gamma(1+\frac{\beta}{\gamma})(\alpha+\frac{\beta}{\gamma})^2}.$$

It is straight forward to show that $\ell_\tau^M > \ell_\tau^E$ and $v_\tau^M > v_\tau^E$ for $\alpha < 1$.

## 7.5 Appendix 5: Product subsidy

With a product subsidy, demand for the market good is $p - s = 1 - \beta x$. Total production $\bar{x}^M(s, \ell^M)$ is determined in a competitive equilibrium such that the $N$ew $P$rivate $M$arginal $C$ost $(\alpha\gamma x + \ell^M)$ is equal to demand $(1 + s - \beta x)$. Hence, $\bar{x}^M(s, \ell^M)$ is given by

$$\bar{x}^M(s, \ell^M) = \frac{1 + s - \ell^M}{\alpha\gamma + \beta}. \tag{56}$$

The firm that is indifferent between using the old and the new technology, $\hat{x}^M(\ell^M)$, is determined in the same way as before, see (28); it depends on the licence fee (but not directly on the subsidy $s$). As in the case with environmental R&D, we assume that the innovator determines her licence fee after the government has determined its policy instrument, here the product subsidy $s$. The innovator finds the licence fee that maximizes her innovation income $\ell^M\left[\bar{x}^M(s,\ell^M) - \hat{x}^M(\ell^M)\right]$. This fee is given by

$$\ell^M(s) = \frac{\gamma(1-\alpha)(s+1)}{2(\beta+\gamma)}. \tag{57}$$

We assume that the government determines the product subsidy $s$ such that social benefits minus social costs are maximized, taking into account how the technology switching point and total production depend on $s$: $\hat{x}^M(s) = \hat{x}^M(\ell^M(s))$ and $\bar{x}^M(s) = \bar{x}^M(s,\ell^M(s))$. As in the cases with environmental R&D, social benefits are given by the area below the demand curve, whereas social costs are given by the area below the marginal cost curves; *OMC* for firms using the old technology and *NPMC* for firms using the new technology, see (39) with $\hat{x}^E(t)$ replaced with $\hat{x}^M(s)$ and $\bar{x}^E(t)$ replaced with $\bar{x}^M(s)$. Maximizing net social benefit with respect to the subsidy $s$ gives

$$s = \frac{1-\alpha}{3\alpha + 4\frac{\beta}{\gamma} + 1}. \tag{58}$$

Inserting (58) into (57) gives the optimal licence fee:

$$\ell_s^M = \frac{(1-\alpha)(\alpha + 2\frac{\beta}{\gamma} + 1)}{(3\alpha + 4\frac{\beta}{\gamma} + 1)(\frac{\beta}{\gamma} + 1)}. \tag{59}$$

Using (28), (56), (58) and (59) we find the equilibrium quantities $\hat{x}_s^M$ and $\bar{x}_s^M$. We then calculate the innovation income, $v_s^M$, as well as the social value of the innovation, $V_s^M$, see (33) with $\hat{x}^M$ repalced with $\hat{x}_s^M$ and $\bar{x}^M$ replaced with $\bar{x}_s^M$. Finally, we find the optimal innovation prize:

$$P_s^M = V_s^M - v_s^M = \frac{\gamma(1-\alpha)(4\alpha^2 + 9\alpha\frac{\beta}{\gamma} + \alpha + 4(\frac{\beta}{\gamma})^2 - \frac{\beta}{\gamma} - 1)}{2\gamma(3\alpha + 4\frac{\beta}{\gamma} + 1)^2(1+\frac{\beta}{\gamma})(\alpha + \frac{\beta}{\gamma})}. \tag{60}$$

Comparing $P_s^M$ to $P^E$ in Section 3.2, see (14), we find $P^E - P_s^M = \frac{N}{D} > 0$, where

$N = \gamma(\alpha-1)^2\beta(4\alpha^5\beta\gamma^2 + 24\alpha^5\gamma^3 + 9\alpha^4\beta^2\gamma + 75\alpha^4\beta\gamma^2 + 26\alpha^4\gamma^3 + 4\alpha^3\beta^3 + 68\alpha^3\beta^2\gamma + 65\alpha^3\beta\gamma^2 + 6\alpha^3\gamma^3 + 20\alpha^2\beta^3 + 70\alpha^2\beta^2\gamma + 31\alpha^2\beta\gamma^2 + 6\alpha^2\gamma^3 + 28\alpha\beta^3 + 36\alpha\beta^2\gamma + 15\alpha\beta\gamma^2 + 2\alpha\gamma^3 + 12\beta^3 + 9\beta^2\gamma + 2\beta\gamma^2) > 0$

$D = 2(\gamma\alpha + \beta)(\beta + \gamma)(3\alpha\gamma + 4\beta + \gamma)^2(\alpha^2\beta + 3\alpha^2\gamma + 2\alpha\beta + \alpha\gamma + \beta)^2 > 0.$

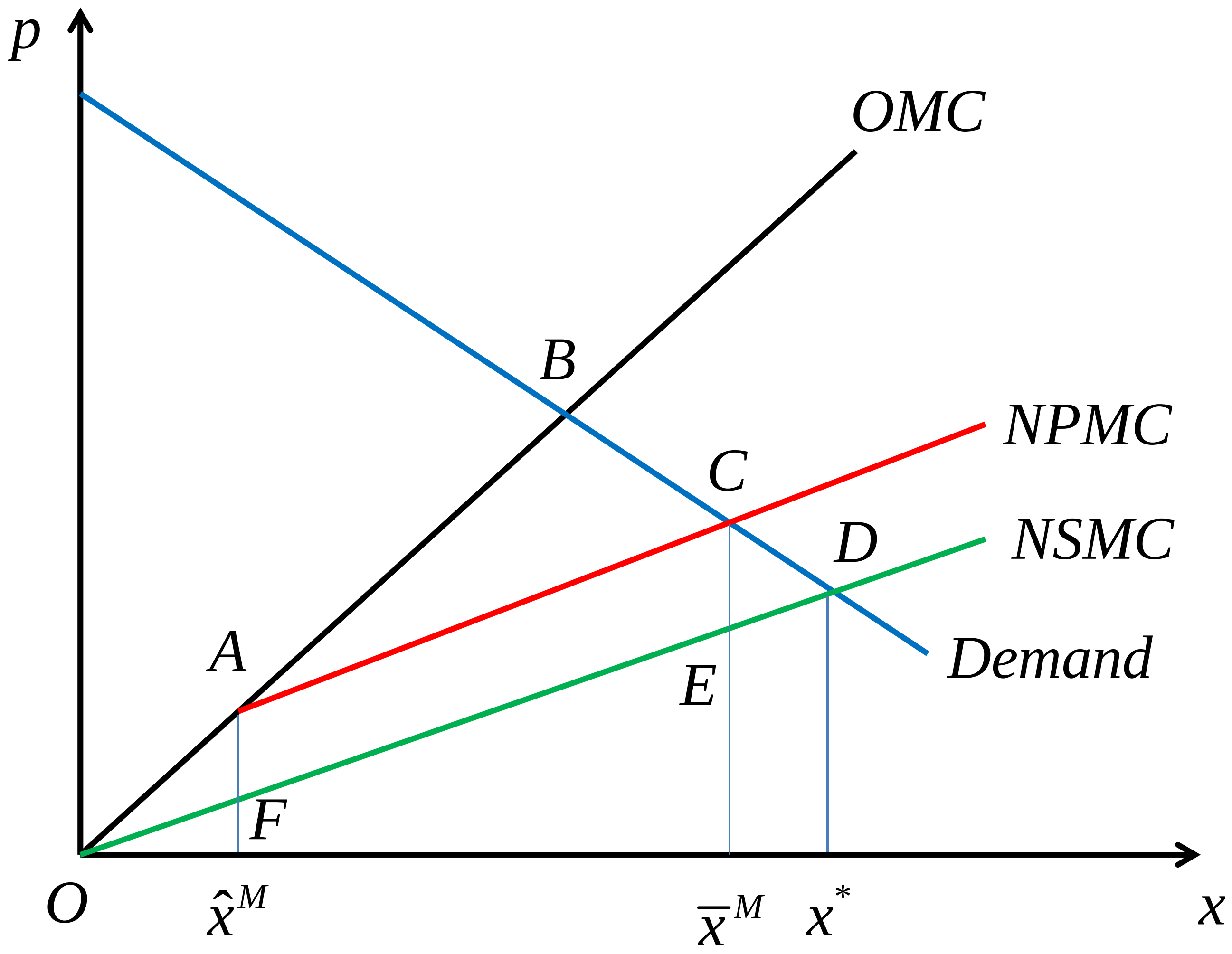


Figure 1　The appropriability problem with a market good

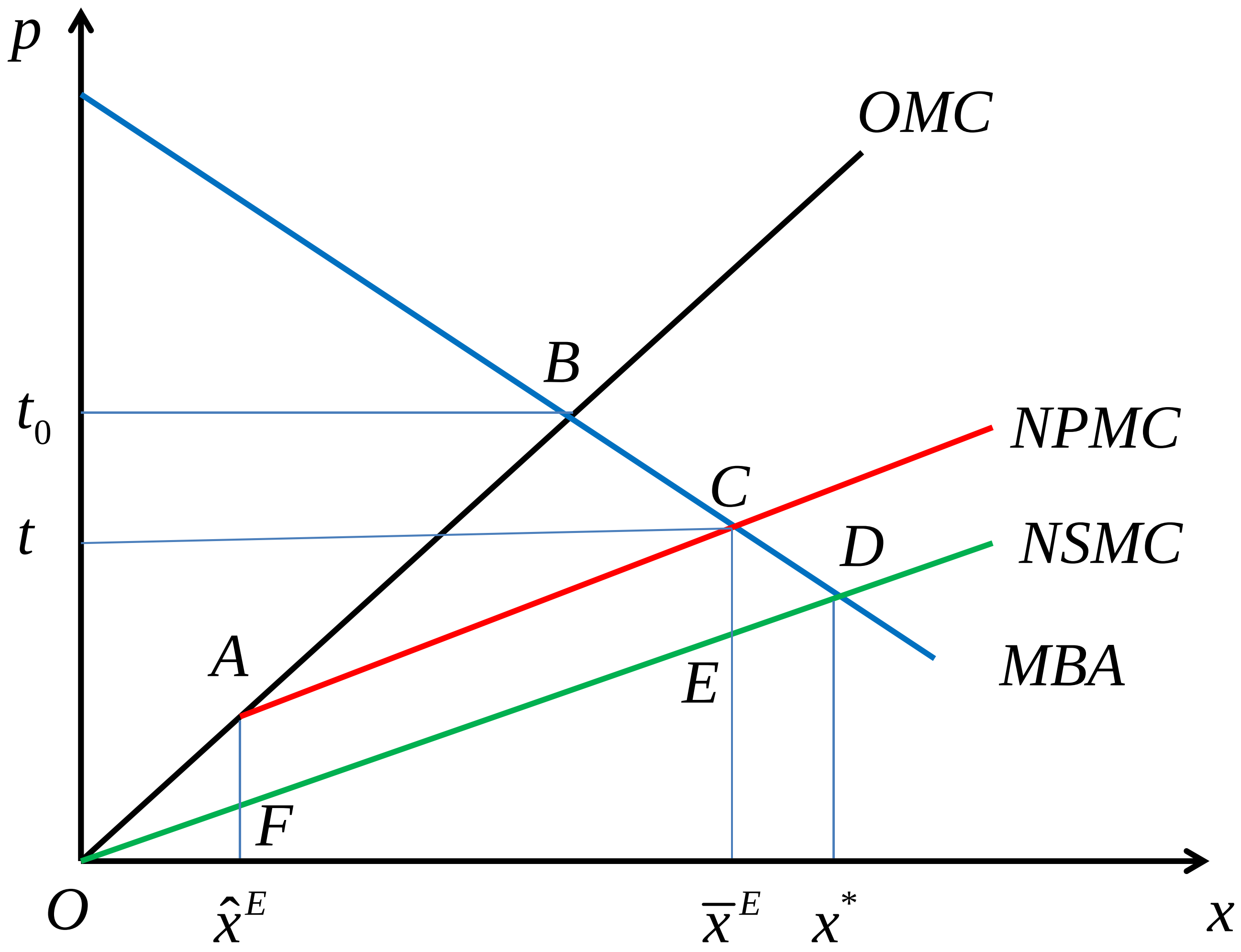


Figure 2　The appropriability problem with an abatement technology

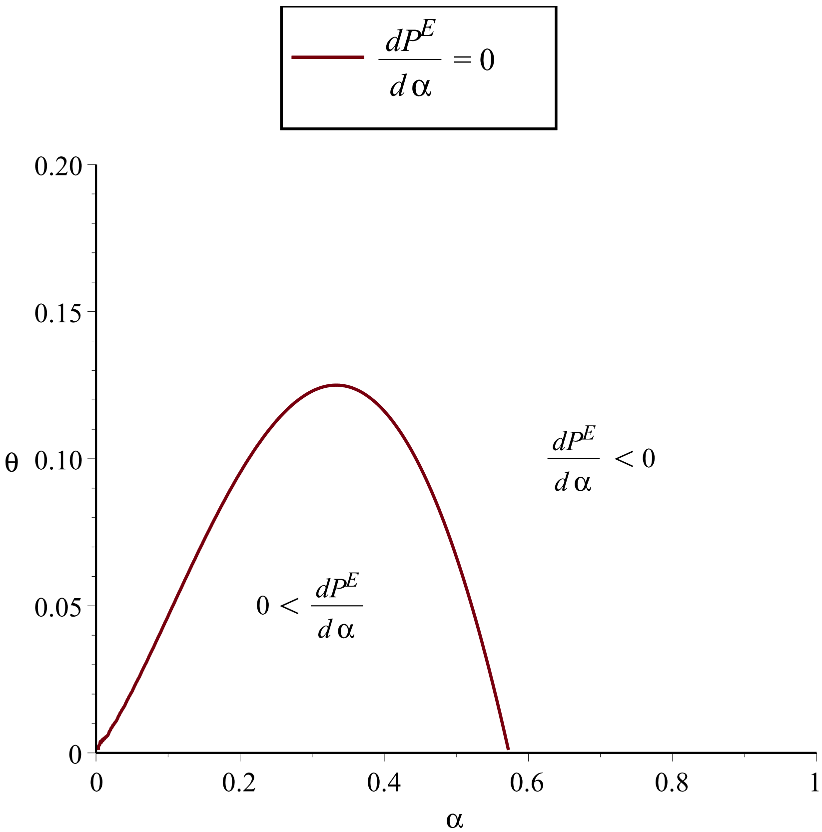


Figure 3. Innovation prize for environmental R&D

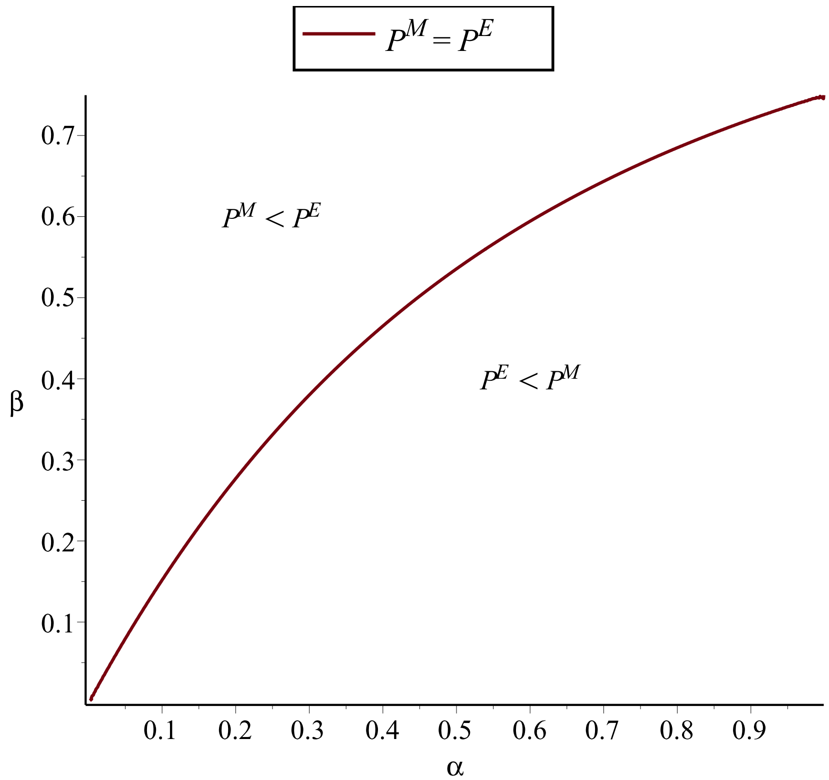


Figure 4. Innovation prizes for market goods R&D ($P^M$) and environmental R&D ($P^E$)

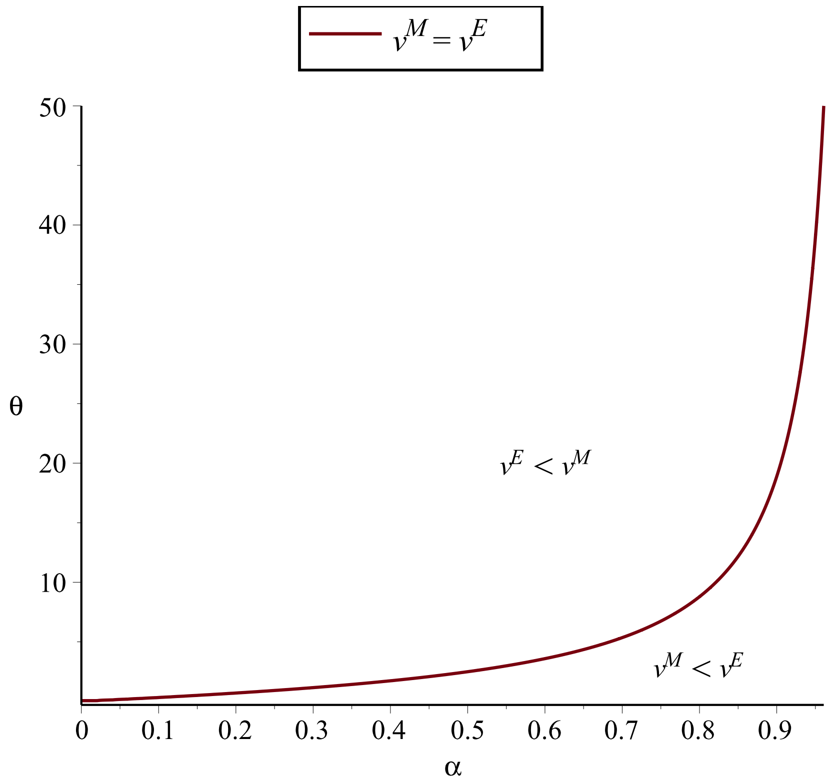


Figure 5. Licence income of innovator for market goods R&D ($v^M$) and environmental R&D ($v^E$)

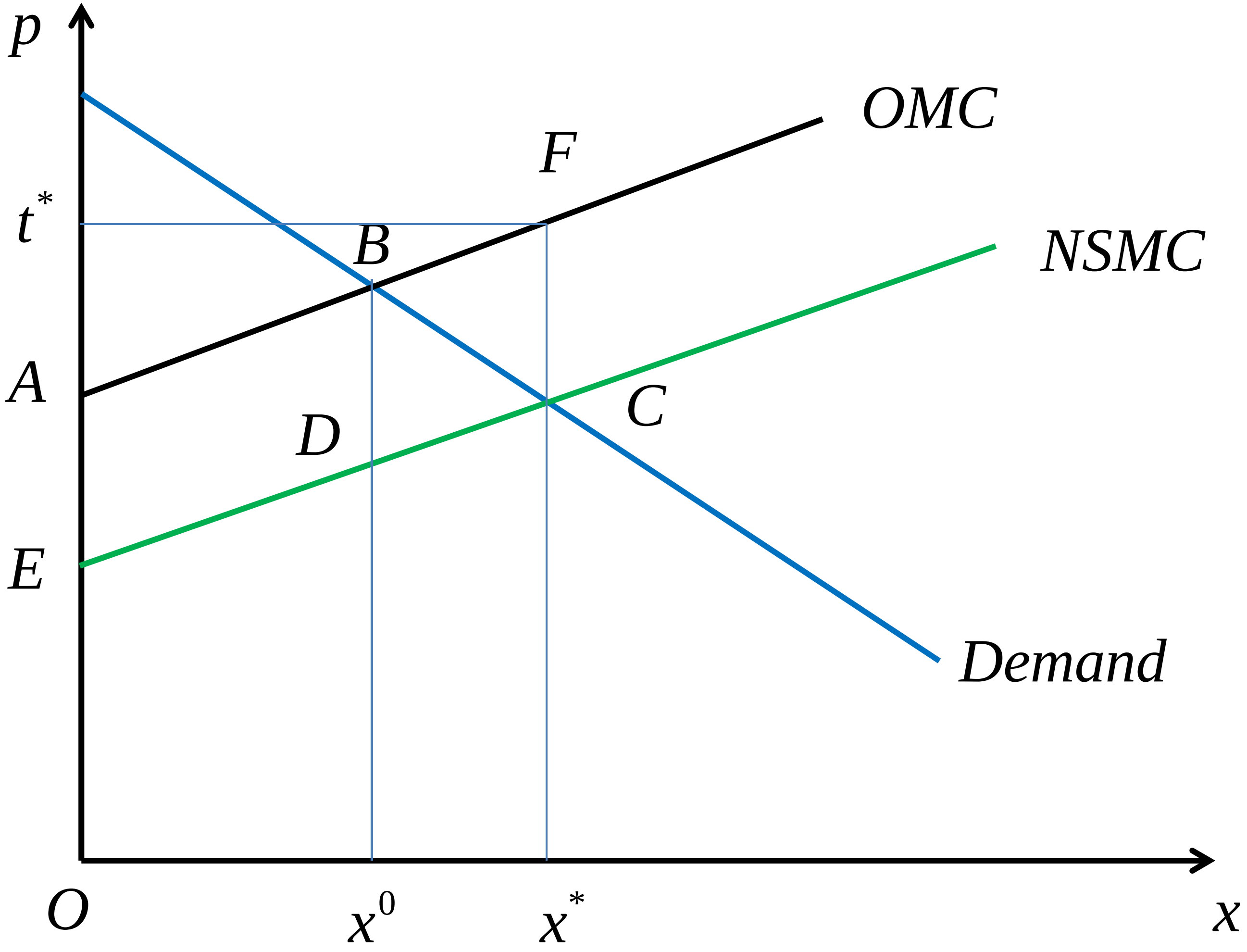


Figure 6　Limit pricing when all users have identical benefit of innovation

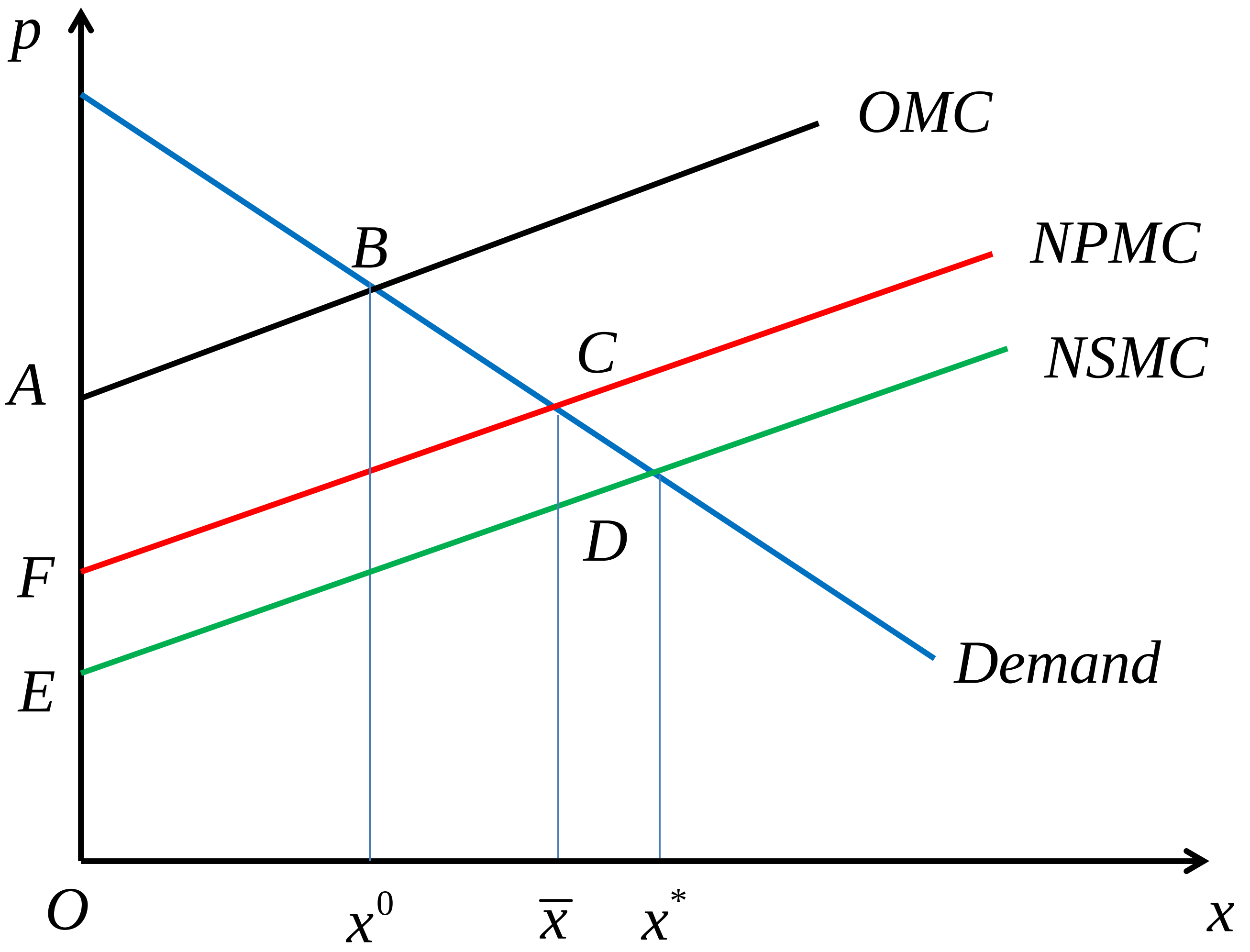


Figure 7 Interior solution (not limit pricing) when all users have identical benefit of innovation