Should environmental R&D be supported more than other R&D projects?

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October 19, 2017

Abstract

An innovator may not be able to capture the full social benefit of her innovation. Governments therefore support private R&D through various measures. We compare a market good innovation with an abatement technology innovation with the same potential to increase social surplus. The first-best outcome can be reached by offering an innovation prize and a diffusion subsidy. The innovation prize should be greatest for an abatement technology innovation, whereas the diffusion subsidy should be greatest for a market good innovation.

Keywords: R&D, environmental R&D, innovations, endogenous technological change, innovation prize, diffusion subsidy

JEL classification: H23, O30, Q55, Q58

1 Introduction

In 2015, the ongoing UN climate negotiations reached a treaty in Paris where nearly all countries in the world restated their commitment to the 2^0C target. To reach this ambitious target, a major share of all fossil fuel reserves must stay in the ground (McGlade and Ekins, 2015). Without extensive investments in environmentally friendly research and development (R&D), drastically reducing the use of fossil fuels seems hard to reconcile with the

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IEA (2011) prediction of a 50% growth in total energy demand over the next 25 years.

In a market economy, the level of environmentally friendly R&D may however be lower than the social optimum because the 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). In order to deal with the appropriability problem, governments use policy measures like R&D subsidies, innovation prizes and legal protection of intellectual property rights (patents) to increase the supply of private R&D.

While many argue that such measures should be neutral, that is, all kinds of R&D should receive the same support, some of the literature on environmental R&D suggests that the appropriability problem might be larger for environmental R&D than for regular market good R&D. The reason is that the regulator could use environmental policy to partly or fully expropriate the value of the patented innovation, thereby amplifying the appropriability problem, see Laffont and Tirole (1996) and Montgomery and Smith (2007). However, the earlier literature has neither compared environmental R&D with market good R&D, nor examined regulators with access to a full set of policy instruments.

Our paper analyses in a game theoretic model whether the government should support innovations in standard market goods and environmentally friendly innovations equally, or whether priority should be given to environmental R&D. In the first stage of the game, a monopoly innovator invests in R&D, which determines the probability of a successful innovation. The innovator takes into account that she will receive an innovation prize if she develops a new technology. In the next stages of the game, the regulator sets a subsidy aimed at promoting competitive downstream firms to switch to the new technology, and the innovator sets a license fee that firms have to pay in order to use the innovation. In the case of environmental R&D, the regulator also sets an emission tax. In the last stage of the game, firms in the downstream industry decide whether to rent the new technology or continue with the old, less efficient, technology.

In the market good case, both an innovation prize and a subsidy promoting the diffusion of the new technology are needed to induce the first-best social outcome. This also holds for environmental R&D, even though the government has an emission tax at its disposal. Without the innovation prize, the revenue of the innovator equals the license income, which in general differs from the social value of the innovation implying that the private level of R&D will be inefficient. Furthermore, it is necessary to offer a diffusion subsidy because the license fee discourages some producers from adopting the new technology even if it is efficient that they do so. This is also the case when the emission tax is set optimally.

In our model the two types of innovations have exactly the same potential to increase social welfare. Hence, we can compare the innovation prize for environmental R&D with the innovation prize for market good R&D. In the first-best outcome, we find that the innovation prize for environmental R&D should always be greater than the innovation prize for market good R&D. Thus, in the first-best outcome, the appropriability problem is smaller for a market good innovation than for an environmental innovation.

The ranking of the equilibrium diffusion subsidies is the opposite; the diffusion subsidy should always be higher for a market good innovation than for an environmental innovation. This reflects that demand for the new technology is less price elastic under market good innovation – where the price of the market good increases when the license fee is increased – than under environmental innovation – where the "price", that is, the emission tax, is set by the regulator and thus does not change if quantity is altered. Because the equilibrium license fee is higher the less elastic demand, the equilibrium diffusion subsidy is higher under market good innovation. Moreover, since the license fee is higher under market good innovation, there is less need for supporting R&D.

In the paper we also show that these mechanisms are not invariant to the choice of environmental policy instruments. If the regulator uses an emission quota instead of an emission tax, the demand for the new innovation becomes less elastic. Consequently, the emission quota case looks more like market good case with respect to both the size of the innovation prize and the diffusion subsidy.

Moreover, we compare the innovation price with a subsidy to private R&D effort. With symmetric information between the regulator and the innovator, a subsidy that covers a share of the R&D cost will implement the efficient level of R&D. However, under asymmetric information, we demonstrate that only an innovation prize, and not an R&D subsidy, can obtain the efficient level of environmental R&D.

Finally, we look at the case with competing innovators, and show that our main results still hold; in the first-best outcome, the appropriability problem is smaller for a market good innovation than for an environmental innovation.

The rest of the paper is laid out as follows. Section 2 discusses our contribution in light of the the literature on environmental R&D and R&D policy instruments. In Section 3, we present our model of private R&D. In Section 4 we study optimal innovation policy for a market good, while in Section 5 we compare this to optimal innovation policy for environmental innovation. Section 6 considers extensions of the basic model (R&D subsidy, asymmetric information and multiple innovators), while Section 7 concludes.

2 Contributions and related literature

Our paper is linked to different strands of the environmental economics literature. First, the key topic in our paper is whether the appropriability problem plays out differently for environmental innovations compared to market good innovations. A related question is whether clean R&D should be supported more than dirty R&D. Acemoglu et al. (2012), Gerlagh et al. (2014) and Greaker et al. (2017) all find that clean R&D should be given priority. The reason is that in their models, the social value of knowledge spillovers in the R&D production function is higher for clean R&D than for dirty R&D. We do not include knowledge spillovers in our model, but focus on how environmental policy affects market appropriability.

Second, earlier contributions, for example Downing and White (1986), compare different environmental policy instruments with respect to how they affect environmental R&D. In contrast to later studies, and also our study, the earlier literature assumed that polluting firms could innovate, and did not include patents and licensing of innovations. However, according to for instance Requate (2005), most pollution abatement innovations happen outside the polluting industry. Laffont and Tirole (1996), Denicolo (1999), Requate (2005), Perino (2011) and Montero (2011) all separate the innovator from the polluting sector, as we do. This gives rise to a potential commitment problem; when setting environmental policy, the government would like the license fee to be low in order to increase adoption of the the new technology. However, because this may hamper the profit of the innovator, the incentives to invest in R&D are undermined.

Requate (2005) shows that social welfare could be increased if the government could pre-commit to an emission tax that would be implemented if the innovation occurs. However, like Laffont and Tirole (1996), Denicolo (1999), Requate (2005), Perino (2011) and Montero (2011), he does not consider other types of innovation policy instruments. In contrast, we demonstrate that in order to reach the first-best outcome, the government has to use one instrument, for example, an innovation prize, to spur R&D, and another instrument, for example, a diffusion subsidy, to trigger more adoption of the new technology (in addition to the environmental policy tool).

Third, both Laffont and Tirole (1996) and Montgomery and Smith (2007) suggest that the appropriability problem is greatest for environmental R&D. Their results hinge, however, on their assumption that all polluting firms obtain the same benefit from the new technology. It is then possible for the regulator to set a very low emission tax and still get all downstream firms to adopt the new clean technology. With heterogeneous firms, such as in Requate (2005), this is no longer possible. In our paper, we consider a general set-up where identical benefit from the innovation is a special case. Hence, our results are valid both under homogenous and heterogenous benefit to the downstream firms of the innovation.

In our paper we also assume, in line with most other papers, that a successful innovation leads to a downward shift in the marginal cost curve for *all* quantities. With respect to environmental innovations, Amir et al. (2008) show that this is likely to hold for end-of-pipe abatement equipment. However, they also show that innovations that allow for low emission input substitution do not always lead to downward shifts in the marginal abatement cost curve. While such a case is interesting, it is not examined in the present paper.

We have chosen to focus on an innovation prize instead of a subsidy to R&D effort. One advantage of an innovation prize is that it can easily be targeted to a specific field of technology as for instance zero carbon technologies. Both Brennan, Macauley and Whitefoot (2012) and Newell and Wilson (2005) therefore argue for the use of innovation prizes as an environmental R&D policy tool. Innovation prizes have also attracted attention in the general literature about innovation policy. Some examples are Wright (1983) on patent buyouts; Weyl and Tirole (2012) as well as Chari et al. (2012) on partial patent buy-outs; Kremer (2001a; 2001b) on advanced market commitment; and Brunner et al. (2011) on the effect of innovation prizes. Our contribution to this literature is to provide an analytical examination of innovation prizes directed at environmental innovation.

Finally, we have chosen to focus on an innovation prize that comes in addition to patent rights. According to both Brennan et al. (2012) and Newell and Wilson (2005), patent buyouts are very rare, possibly because they will be very costly for the government. The EU Horizon 2020 prizes are examples of prizes that come in addition to patent rights. They promise a cash reward to whoever can most effectively meet a defined challenge within antibiotics, transmission barriers, city air improvement, spectrum sharing, and food skanner, but do not limit the patent rights of the innovator.

3 R&D investments

We consider a potential innovation that reduces production or pollution abatement costs by a specific amount. Building on Laffont and Tirole (1996), we assume that by investing k, the innovator succeeds in obtaining the specific exogenous cost reduction with probability $z(k)$. The function $z(k)$ has the following properties: $z(0) = 0$, $z(k) < 1$, $z' > 0$, $z'' < 0$ and $z'(0) = \infty$.

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

$$\max_k \{z(k)V - k\} \tag{1}$$

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

$$z'(k)V = 1 \tag{2}$$

The properties of $z(k)$ ensure that k is uniquely defined and strictly increasing in V.

Without public support to R&D, the innovator solves a similar problem, except that V is now repaced by v, where v is the income earned from a patent. Hence, the innovator will choose the R&D level k that is the solution of the following first-order condition:

$$z'(k)v = 1 \tag{3}$$

Clearly, there is a market failure if $v \neq V$. If $v < V$ (as in the case of market good R&D in Section 4.1), this market failure can be corrected by introducing an innovation prize P. From (2) and (3) we see that if the innovator receives an innovation prize $P = V - v$ in addition to the patent revenue v, that is, she obtains in total V, the amount of R&D undertaken will be identical to what is socially optimal.

The innovation prize can be interpreted as follows: the government specifies some technical criteria that must be met in order to receive the award.

If these criteria are fulfilled, a specific (exogenous) cost-reduction follows. We assume that the government can check whether the technical criteria are met. If they are fulfilled, the corresponding cost reduction is known to the government, and the innovator receives the prize. Starting with the market good case, we then proceed to look at how V and v are decided.

4 Market good R&D

4.1 The appropriability problem

As explained in the previous section, we consider an innovation project that has the potential of reducing the cost of a production process, and where the probability of a successful innovation depends on the size of the R&D investment. If the innovator has success, she rents out her new technology to downstream firms producing a standard market good.

The social and private value of an innovation is illustrated in Figure 1. Demand for the market good is given by the downward sloping curve, while the curve OMC is the Old Marginal Cost curve, i.e., marginal cost prior to a successful innovation. We assume that a successful innovation will benefit all downstream firms, but not necessarily equally. Thus, a successful innovation shifts the old marginal cost curve (OMC) downwards to NSMC (New Social Marginal Cost curve), see Figure 1.[1]

[1] For simplicity all curves are assumed linear, but this assumption does not influence our main results. Moreover, we have assumed that firms with an inefficient production technology benefits more from the innovation than firms with an efficient production technology. This is also not crucial for our results as long as all downstream firms benefit from the new technology.

Figure 1 "Market good innovation"

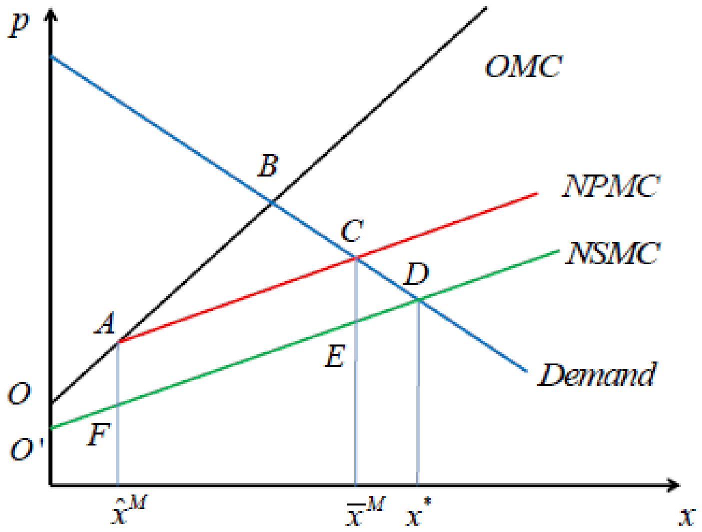

Figure 1

The pre-innovation equilibrium is at the point B in Figure 1, while the first-best, post-innovation outcome would be the equilibrium point D. Here, total production is equal to x^* and all firms use the new technology. If the first-best outcome were achieved, the social value of the innovation would be the sum of reduced costs and increased consumer benefits, given by the area $OBDO'$ in Figure 1. Henceforth we denote this area by V^*, and we will refer to it as the maximum social value of the innovation.

The first-best outcome D would be achieved if the private marginal cost curve of the downstream producers after an innovation was equal to the social marginal cost curve ($NSMC$). However, if the innovator charges a license fee ℓ per unit of output, the first-best outcome will not be achieved.

If the license fee exceeds the minimum distance between the $NCMC$- and OMC-curves ($\ell > OO'$ in Figure 1), some output will be produced using the old technology. More precisely, output up to $\hat{x}^M$ (M - market good) in Figure

1 will be produced using the old technology, because for output up to $\hat{x}^M$ the cost difference between the old and new technology is smaller than the license fee. 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 license fee ℓ.

Total production $\bar{x}^M$ is determined in a competitive equilibrium such that the *N*ew *P*rivate *M*arginal *C*ost (*NPMC*) 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, is therefore equal to the area $FABCE$.

The payoff to the innovator, denoted v^M, is equal to the area $FACE$ in Figure 1, where the length of AF is the equilibrium size of the license fee. Whatever the size of the license fee, it is clear that the area *FACE* is smaller than the area *FABCE,* implying that $v^M < V^M$. Thus, the innovator is not able to appropriate the whole social surplus from the innovation. As we argued above, R&D will therefore be lower than what is socially optimal.

4.2 Policies to achieve the social optimum

Not only is $v^M < V^M$, but we also have $V^M < V^*$ for two reasons.[2] 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 $OAFO'$ 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 the two deadweight losses $OBDO'$ and $FABCE$. In order to obtain $V^M = V^*$ the regulator must offer

[2] If $\ell < OO'$, only the second reason is relevant.

a subsidy σ to all producing firms that adopt the new innovation. We will refer to σ as a *diffusion subsidy.*

To study the optimal diffusion subsidy, consider the following stage game: In the first stage the government offers an innovation prize, and in the second stage the innovator invest in R&D. If an innovation materializes, ther game moves on to the third stage in which the government pays the innovation prize P, and offers a subsidy σ to all firms in a downstream production sector that adopt the new technology. In the fourth stage the innovator sets the license fee ℓ an offers her innovation to the firms in the downstream production sector. Finally, the equilibrium price and quantity of the good produced by the downstream sector is determined in the market by the equality of supply and demand. The innovator then recieves v, that is, the patent value of the innovation, and the social value of the innovation V is realized.

With a diffusion subsidy, the net price of the license facing the downstream sector is $z = \ell - \sigma$. The revenue v of the innovator is hence given by

$$v = \ell D(z, x) \tag{4}$$

where D is demand for the new technology, and x is the amount produced as in Figure 1.

The demand function D is assumed to have the property that there will be full use of the new technology for all values of z below a threshold $\bar{z}$. For values of z below $\bar{z}$, the demand is hence independent of z (but see discussion below). In Figure 1 we have $\bar{z} = O - O'$. For values of z above $\bar{z}$, the new technology will be used less the higher is the price z. Hence, the demand function is declining in z, i.e., $D_z < 0$ for $z > \bar{z}$.

For any given value of z, the demand for the new technology will be higher the higher is output, that is, $D_x > 0$. Furthermore, total output is determined by the intersection between the demand for the downstream good and the private marginal cost of producing the good (that is, C in Figure 1). The private marginal cost curve after an innovation ($NPMC$) is higher the higher is the net price z of using the new technology. Hence, we have $x = x(z)$ with the property $x'(z) < 0$.

When setting the license fee ℓ, the innovator takes the diffusion subsidy σ as given. On the margin the innovator balances the demand reduction of an increase in ℓ with the direct positive effect of increased ℓ on the revenue (for any σ set by the regulator). In particular, the innovator chooses ℓ to maximize $v = \ell D(\ell - \sigma, x(\ell - \sigma))$. The first-order condition is[3]

$$D + \ell \left[D_z + D_x x'(z) \right] = 0. \tag{5}$$

Note that (5) can be interpreted as the optimal responce function of the innovator to any diffusion subsidy σ.

If the innovation materializes, it is socially optimal that all downstream firms use the new technology. Moreover, the diffusion subsidy must ensure that the first-best optimum (where $x = x^*$) is realized. Taking the optimal responce function (5) into account, the regulator sets the diffusion subsidy σ so that the net price to license the new technology, z, is zero: If $\bar{z} \geq z > 0$, there would be too little output.[4] Denoting the optimal subsidy σ^M and $\ell(\sigma^M) = \ell^M$, the equilibrium revenue to the innovator is $v^M = \ell^M D(0, x^*)$. From (5) we therefore have

$$\ell^M = \frac{D}{-D_z - D_x x'(z)} \tag{6}$$

where $-D_z > 0$ if $\bar{z} = 0$ and $-D_z = 0$ if $\bar{z} > 0$ (as in Figure 1).

The patent income of the innovator v^M is given as $\ell^M x^*$. Since ℓ^M is set by the innovator, there is no reason to belive that v^M is equal to V^*. That is, when setting σ, the regulator only wants no assure that $V^M = V^*$, and do not take into account whether $v^M \neq V^*$. To achieve the correct incentives for the innovation, the innovator's revenue (if the innovation materializes)

[3] Below we show that in equilibrium, z may have the value $\bar{z}$, where D_z is discontinuous. In the Appendix we explain that in this case, it is the right derivative that enters (5).

[4] If $z < 0$, there would be too much output.

must therefore be supplemented by an innovation prize $P^M = V^* - v^M$.

Even if we have assumed away knowledge spill-overs in our model, we still obtain the following result:

Proposition 1 *Both an innovation prize and a subsidy promoting the diffusion of the new technology are needed to induce the first-best outcome.*

In growth models (see e.g. Acemoglu et al, 2012) both instruments are needed to implement the first best. However, then the R&D support deals with the dynamic knowledge spill-over included in theses models. Note, however, that the innovation prize may be negative if $v^M > V^*$ due to the diffusion subsidy.

5 Environmental R&D

We assume that the timing in our game theoretic model is similar to the case of market good R&D, but now the government also sets an emission tax in fourth stage of the game, that is, simultaneously with the determination of the innovator's license fee ℓ. This tax serves as a "price" for abatement, and hence, in contrast to the market good case, the "price" is determined by the regulator before the market clears.[5]

We let x measure the amount of emissions abated, and we interpret the demand curve as the *marginal benefit of abatement* (*MBA* in Figure 2). All unabated emissions are subject to a tax p, and the marginal cost of abatement prior to the innovation is given by the curve OMC. The innovator invests in R&D in order to develop a technology that reduces both total and marginal abatement cost. Moreover, if she has success, she rents out the new technology, and polluting firms can then choose to abate using the new technology.

[5] The timing of this tax is discussed in detail in the end of this section, where we also discuss the consequences of the government imposing emission quotas instead of an emission tax as the environmental policy instrument.

Figure 2 "Environmental innovation"

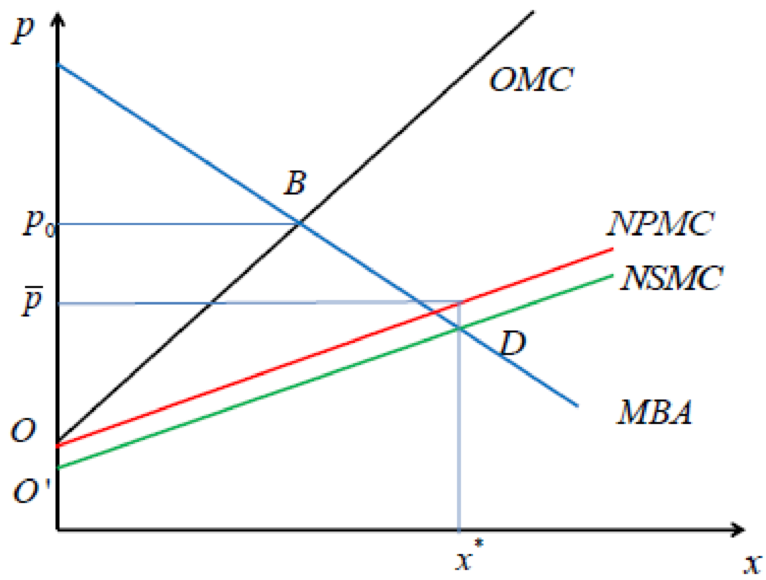

Figure 2

The MBA curve is assumed to have exactly the same properties 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; this solution can be implemented with the tax p_0.

Just like in the case of market good R&D, we assume that a successful innovation shifts the social marginal abatement cost from *OMC* to *NSMC.* Clearly, the new social optimum is at point D in Figure 2, and the socially optimal level of abatement is x^*. As explained in the previous section the new private marginal abatement cost (*NPMC* in Figure 2) will lie above the new social marginal abatement cost if the net price $z = \ell - \sigma$ of the license facing the downstream sector is positive.

In the market good case, the equilibrium output price p was passively determined in the downstream market as a response to the net price z the downstream sector had to pay for using the new technology. In the case of environmental R&D, there is no such "market price" for abatement. Once the tax p is set by the regulator, total abatement, x, is determined by private marginal abatement cost being equal to this tax. In particular, note that the regulator can obtain the first best as long as the net price z does not exceed *O'O* in Figure 2. In Figure 2 this holds, and the social optimum is achieved by setting $p = \bar{p}$.

The private marginal cost curve is higher the higher is the net price z of using the new technology. Hence, $x = x(z)$ with the property $x'(z) < 0$ also in the present case. The magnitude of $x'(z)$ differs, however, between the cases of market good R&D and environmental R&D. With environmental R&D, the emission tax is set simultaneously with the license fee, and hence "the output price", that is, the tax, does not change if the license fee is increased. Thus, under environmental R&D (see Figure 2) an increase in the license fee will trigger a decrease in quantity but no change in the "price". In contrast, under market good R&D (see Figure 1) a higher license fee will also lower supply, but in addition increase the output price dampening the effect on supply (movement along the demand curve). In particular, the output decline in the market good case is *less* than it would have been had the output price remained unchanged. Hence, the innovator faces a more elastic demand under environmental R&D than under market good R&D. In other words, $-x'(z)$ is larger in the case of environmental R&D than under market good R&D.

As in the market good case, the innovator chooses ℓ to maximize $v = \ell D(\ell - \sigma, x(\ell - \sigma))$ taking as given the diffusion subsidy σ, giving the first-order condition (5). This optimization gives a response function for the innovator with ℓ depending on σ. In the Appendix we show that the net price z is a declining function of σ. In other words, as the diffusion subsidy σ is increased, the license fee is never going to increase so much that it completely neutralizes the initial increase in the subsidy. Moreover, we assume that if it is possible to achieve the social optimum for several values of σ, the government will choose the smallest value of σ consistent with reaching the social optimum.

The government wants to set σ so that $z \leq \bar{z}$, otherwise the new technology would not be used in a socially efficient manner. Since z is a declining function of σ, the lowest possible value of σ consistent with $z \leq \bar{z}$ is $z = \bar{z}$. Hence, we must have $z = \bar{z}$ in equilibrium.

The optimal license fee follows from (5). Using E as a superscript for the present case we therefore get

$$\ell^E = \frac{D}{-D_z - D_x x'(z)} \tag{7}$$

Comparing this with the market good case (6), the numerator D is the same in both cases ($= D(\bar{z}, x^*) = D(0, x^*)$). The denominator, however, is larger in the environmental innovation case. First, the term $-x'(z)$ is larger in the case of environmental R&D, as explained above, while the derivative D_x is the same as the equilibrium quantity is x^* in both cases. Second, if $\bar{z} = 0$, the term $-D_z$ in the dominator is the same in the two cases. However, if $\bar{z} > 0$ the term $-D_z$ will be zero in the case of market good R&D; the equilibrium value of z is zero for market good R&D. Thus, we must have $\ell^E < \ell^M$.

As above, when setting σ, the regulator only wants no assure that $V^E = V^*$, and do not take into account whether $v^E \neq V^*$. To achieve the correct incentives for the innovation, the innovator's revenue (if the innovation materializes) must therefore be supplemented by an innovation prize $P^E = V^* - v^E$. Assume that the government uses an innovation prize to trigger more R&D in addition to a diffusion subsidy to stimulate adoption of the new technology. We then have for the two games described above:

Proposition 2 *To achieve the first-best optimum, the innovation prize must be higher for environmental innovations than for market good innovations, whereas the diffusion subsidy must be highest for market good innovations.*

In the market good case $\sigma = \ell^M$, while in the environmental innovations case $\sigma \leq \ell^E$. The proposition then follows directly from the fact that $\ell^E < \ell^M$, and that supply in both cases is x^*. For the innovation prize, we must have $V^* - v^E > V^* - v^M$.

6 Extensions

In this section we examine five extensions. First, we consider alternative timing assumptions of the games considered. Second, we consider the case where the government uses quotas instead of an emission tax as the environmental policy instrument. Third, we let the government use an R&D subsidy instead of an innovation prize to spur innovation. Fourth, there is asymmetric information; only the innovator has full information. Finally, we consider the case of multiple innovators.

6.1 The timing of the license fee and the policy instruments

We assumed above that the diffusion subsidy was set before the license fee. An alternative assumption would be to assume that if the innovation materializes, the diffusion subsidy is set simultanously with the license fee. The innovator's optimal response function is the same in the two games: the innovator chooses the optimal license fee taking the diffusion subsidy as given. Moreover, since the regulator has no incentive to change the diffusion subsidy given the license fee of the innovator, the solution to the simultanous game is identical to the solution to the sequential game. This must be the case since the regulator obtains the first-best outcome in both games.

In our model, it is not meaningful to assume that the license fee is set before the diffusion subsidy: In this case, the innovator could set its fee "infinitely high", since in our model (with zero costs of public funds) the government would respond with a subsidy that is so high that $z = \bar{z}$, that is, an "infinitely high" subsidy.

In the case of environmental R&D, we assumed that the emission tax was set simultaneously with the license fee. In most of the literature, see, for example Laffont and Tirole (1996) and Requate (2005), it is assumed that the emission tax is set before the license fee. In our model, the innovator's optimal response function is the same in the two games: the innovator chooses the optimal license fee, taking the tax rate as given. Given this response function, the optimal emission tax is also the same in both games because the government achieves the first-best outcome anyhow.

From the discussion above we get the following Proposition:

Proposition 3 *The equilibrium outcome of the game in which the policy instruments (diffusion subsidy and environmental tax) are set before the license fee is identical to the equilibrium of the game in which policy instruments and the license fee are set simultaneously.*

We finally consider the case where the tax is set after the license fee. This is the case most similar to the marked good case, where the equilibrium price of the downstream good was determined passively in the market after the license fee had been set.

Once σ and ℓ are set, the optimal policy for the regulator is to set a tax p so that the first-best optimum x^* is achieved.[6] Because the equilibrium abatement is independent of the license fee and the diffusion subsidy, this case is identical to the case in which a quota is used as the policy instrument instead of a tax; we hence turn to this case.

6.2 Quotas as the environmental instrument

So far, we have assumed that the environmental instrument is an emission tax. An alternative policy instrument could be a quota. The optimal quota is clearly x^* in Figure 2. It makes no difference for the equilibrium whether

[6] In Figure 2, the optimal tax is set so that it intersects the NPMC-curve at the value x^*.

the quota is set before or after the license fee (or simultaneously). In any case, total abatement will be x^*.

Knowing that abatement will be x^*, the innovator will set ℓ so that $z \geq \bar{z}$: For $z < \bar{z}$, the demand facing the innovator would be completely inelastic (Since she knows that x will for sure be equal to x^*). The innovator could therefore increase her revenue by increasing ℓ. The government wants to set σ so that $z \leq \bar{z}$; otherwise the new technology would not be used in a socially efficient manner. Combining these two requirements implies that the equilibrium must satisfy $z = \bar{z}$.

In the equilibrium satisfying $z = \bar{z}$, the innovator faces a less elastic demand than it would in the corresponding market good case. Recall that in the market good case, there were two reasons why the demand facing the innovator was reduced if ℓ was increased; the direct effect and the effect via x. However, with x given (equal to the first-best quantity x^*), the second reason vanishes. A less elastic demand implies a higher equilibrium license fee ℓ. Formally, this follows from the first-order condition (5), where the term $x'(z)$ now is zero. Using Q as a superscript for the present case, it hence follows from (5) that

$$\ell^Q = \frac{D}{-D_z} \tag{8}$$

Comparing this with the market good case (6), we see that the numerator D is the same in both cases ($= D(\bar{z}, x^*) = D(0, x^*)$). If $\bar{z} = 0$, the term $-D_z$ in the dominator is also the same in the two cases. Since the second term in the denominator of (6) is positive, it follows that $\ell^Q > \ell^M$ if $\bar{z} = 0$. However, if $\bar{z} > 0$ the term $-D_z$ in (6) is zero, and we do not know the sign of $\ell^Q - \ell^M$. In particular, it follows from (6) and (8) that $\ell^Q < \ell^M$ if $-D_z$ is "large" and $-D_x x'$ is "small".

The revenue $v^Q = \ell^Q D$ will generally differ from the social value of the innovation, V^*. To achieve the correct incentives for R&D, the innovator's revenue (if the innovation materializes) must therefore be supplemented by an innovation prize $P^Q = V^* - v^Q$.

Because the sign of $\ell^Q - \ell^M$ and hence $v^Q - v^M$ is ambiguous, it follows that the sign of $P^Q - P^M$ is ambiguous as well.

We see from (7) and (8) that $\ell^Q > \ell^E$ because the numerator and the term $-D_z$ is the same in the two expressions. Hence, $v^Q > v^E$ and therefore $P^Q < P^E$. We thus have the following proposition:

Proposition 4 *To achieve the first-best optimum, the innovation prize must be higher when an emission tax is used than when quotas are used, whereas the ranking is opposite for the diffusion subsidy.*

As mentioned in the end of Section 5.3, the quota case is equivalent to the case in which an emission tax is the policy tool and this tax is set after the license fee. An important property of this tax case is that the equilibrium is *not time-consistent*: If the innovator had the possibility to reset its license fee after having observed the emission tax, she would do so. Lowering the license fee would, for the given emission tax, increase abatement so much that this positive effect on revenue would more than outweigh the direct negative effect on revenue of the reduced license fee.

In our opinion, there are no good reasons to believe that one of the players is more likely to be able to commit to its price (tax or license fee) than the other player. This suggests that if the policy tool is an emission tax, the simultaneous move game is the best description of the real world. For this sequence of moves, it follows from Proposition 1 that the socially optimal innovation prize is higher for environmental innovations than for market good innovations.

6.3 R&D subsidy

Governments often use targeted R&D subsidies to promote a particular field of study - one example is the EU Horizon 2020 program. In our model, an R&D subsidy rate s implies that the innovator pays $(1-s)k$ of the R&D cost, while the government pays sk. Thus, when setting k the innovator solves:

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

where the private income from an innovation v depends on the cost reduction following from the innovation.

The privately optimal k is given from:

$$z'(k)v = 1 - s. \tag{9}$$

The government wants $z'(k)V = 1$, see (2). Hence, the optimal subsidy rate is given by:

$$s = \frac{V - v}{V} = \frac{P}{V}, \tag{10}$$

that is, the optimal innovation prize relative to the social value of the innovation. Note that in the first-best outcome, $V = V^*$. Proposition 2 states that the innovation prize should be higher for environmental innovations than for market good innovations. It then follows that the R&D subsidy should also be greater for environmental innovations than for market good innovations.

6.4 Asymmetric information

So far we have implicitly assumed that both the regulator and the innovator know the function $z(k)$ and all the parameters of the model *ex ante*, that is, prior to the innovator invests in R&D. Because of private information, it is more probable that the innovator has full information than the government. In particular, only the innovator may know $z(k)$ and the cost reduction following from a successful innovation. In this subsection we discuss properties of the instruments innovation prize and R&D subsidy when only the innovator has full information.

Assume first that the government does not know the function $z(k)$. By inspecting the conditions that determine the R&D effort of the innovator and the social efficient level of R&D, that is, (2) and (3), we see that the government does not need to know $z(k)$ in order to determine the innovation prize that ensures the efficient level of R&D. In the case of an R&D subsidy, (9) determines the R&D effort of the innovator. Again, we see from (10) that the government does not need to know $z(k)$ in order to determine the subsidy that ensures the efficient level of R&D.

Next, assume that the government does not know the potential cost reduction *ex ante*. Then, the government can announce an innovation prize that is *contingent* on the the increase in social surplus $P(V)$ (which depends solely on the cost reduction). As long as the government can learn the true value of the cost reduction after an innovation has materialized, the optimal amount of R&D can be achieved. This holds for both market good R&D and environmental R&D.[7]

On the other hand, the optimal R&D subsidy depends on the expected increase in social surplus from the cost reduction V, and the government has to offer the subsidy based on its expectations. If the true potential cost reduction turns out to be lower than expected, the regulator will realize (ex post) that the offered subsidy was too high. Alternatively, if the true potential cost reduction is higher than the one expected by the government, the R&D subsidy offered by the government might be insufficient to promote success, that is, the innovation may not materialize. Thus, with environmental R&D expected welfare is higher with an innovation prize than with an R&D subsidy, and therefore in this case a contingent innovation prize should be the preferred policy instrument.

6.5 Multiple innovators

Above we assumed that there is a single innovator. If she develops a technology that will reduce cost of producing a standard market good (or cost of abating harmfull emissions), she will receive the prize. We now consider the case of two innovators. An innovator will receive a prize if she is the

[7] The historical longitude award can be seen as an example of this type of an innovation prize. In 1714 The British government announced a prize contest as a response to a petition from the Royal Navy and Captains of Her Majesty's Ships to improve navigation at sea by finding a solution of measuring longitudes. A grand prize of £20,000 was offered to the method accurate within 0.5 degree, a prize of £15,000 was offered to a method accurate within 40 minutes, and there was a £10,000 reward for measures of longitudes within 1 degree, see Horrobin (1986).

only innovator developing the new technology. If both innovators develops the new technology, a lottery will determine who will receive the prize (see below).

Let k_i, $i = 1, 2$, be the R&D investment of innovator i, and let $z_i(k_i)$ be the probability that innovator i will develop the new technology. Assume first that there is no innovation prize. Innovator 1 will be the monopoly innovator, and receive the license income v, if she is the only actor succeeding in developing the new technology; the expected income of this outcome is $z_1(k_1)(1 - z_2(k_2))v$. If both actors develop the new technology, there will be a lottery, organized by the regulator, which will determine who will be granted the right to license the new technology to downstream firms.[8] The expected income of the second outcome is $z_1(k_1)z_2(k_2)v/2$. Hence, innovator 1 maximizes her expected profit $z_1(k_1)(1 - z_2(k_2))v + z_1(k_1)z_2(k_2)v/2 - k_1$ with respect to k_1, and innvator 2 solves a similar problem. The first-order condition of the problem of innovator 1 is:

$$z_1'(k_1)(1 - \frac{z_2(k_2)}{2})v = 1 \tag{11}$$

A benevolent government will determine k_1 and k_2 such that social surplus is maximized. As above, let V^* denote the social value of the innovation. The new technology will be available if at least one innovator succeeds in developing the new technology. The probability of this outcome is $[1 - (1 - z_1)(1 - z_2)]$. Hence, the government maximizes $[1 - (1 - z_1(k_1))(1 - z_2(k_2))]V^* - (k_1 + k_2)$ with respect to k_1 and k_2. The first-order condition with respect to k_1 is

$$z_1'(k_1)(1 - z_2(k_2))V^* = 1 \tag{12}$$

[8] If both firms are granted permission to license the new technology, firms may bid the license fee down to zero, thereby removing the license income v. Rational innovators will be aware of this outcome, and therefore hold back on their R&D investment. A forward-looking regulator can overcome this problem by granting permission to one successful innovator only, thereby ensuring a positive expected income in the case both innovators develop the new technology.

Let k_i^* denote the solution of the problem solved by the benevolent government, and let P_i^* denote the innovation prize offered to innovator i if she develops the new technology. The government wants to determine P_i^* such that innovator i chooses k_i^*. This requires that the prize offered to innovator 1 has to satisify

$$(1 - \frac{z_2(k_2^*)}{2})(v + P_1^*) = (1 - z_2(k_2^*))V^* \tag{13}$$

where we have used (11) and (12). Solving (13) we find that

$$P_1^* = \frac{1 - z_2(k_2^*)}{1 - \frac{z_2(k_2^*)}{2}} V^* - v < V^* - v \tag{14}$$

Because of the symmetry of the problem, the optimal prize P_2^* has the same structure as P_1^*, that is, $P_2^* = [(1 - z_1(k_1^*))/(1 - z_1(k_1^*)/2)]V^* - v$. Note that the prize offered to an innovator is not directly dependent on her own choice of R&D, but it depends on the R&D choice made by the competitor. However, k_i^* depends on $z_1(k_1)$ and $z_2(k_2)$, see (12), and thus P_i^* is dependent on both k_1^* and k_2^*. Note alos that with heterogeneous actors, the optimal innovation prize differs across actors, which is not the case with identical actors.[9] Finally, whereas we have derived innovation prizes when there are two competitors, it is straight forward to generalize to n actors; the derived innovation prizes will have the same type of properties as in the case of two competitors.

As seen from (14), innovation prizes should be less than $V^* - v$, which is in contrast to the case of one innovator. However, since only one inno-

[9]The fact that the optimal support scheme may treat heterogeneous actors differently is well known: Consider, for example, a Betrand game between two actors, each producing a heterogeneous product. In the non-cooperative equilibrium, each price will exceed the corresponding marginal cost, whereas the first-best outcome is characterized by price being equal to marginal cost. In order to achieve the first-best outcome, each producer can be offered a production subsidy. These should in general differ in order to attain the first-best outcome.

vator is granted the patent, the rest of our results about the relative size of the innovation prize and diffusion subsidy for market good innovations and environmental innovations should still be valid.

7 Discussion and conclusion

The aim of this paper is to examine whether the appropriability problem is greater for environmental R&D than for market good R&D. If this is the case, there should be more government support to environmental innovations than to market good innovations.

We have demonstrated that in order to reach the first-best outcome (where there is no appropriability problem), the government needs one instrument to promote R&D, and another instrument to promote diffusion of the new technology. In the model, the government uses either an innovation prize or a research subsidy to stimulate R&D. We have shown that both instruments can induce the efficient amount of R&D. To reach the first-best outcome, the innovation prize for environmental R&D should always be greater than the innovation prize for market good R&D. Alternatively, the R&D subsidy should be greater for environmental innovations than for market good innovations.

To reach the first-best outcome, a diffusion subsidy is also required. We have demonstrated that the diffusion subsidy should be greater for market good innovations than for environmental innovations.

The ranking of instruments reflects that the innovator faces a more inelastic demand under market good innovations than under environmental innovations. The equilibrium license fee is therefore greatest under market good innovations. Hence, the revenue of the innovator is highest under market good innovations, which tends to reduce the appropriability problem. This explains why the innovation prize should be lowest under market good innovations. Further, because the equilibrium license free is greater for market good innovations than for environmental innovations, and it is optimal for the government to set a diffusion subsidy that neutralizes the license fee (the net license fee should be zero), the diffusion subsidy should be highest under market good innovations.

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 6.4 we studied the case in which only the innovator knows how radical the innovation will be ex ante. Although the government does not know ex ante the size of the cost shift, we assumed that this actor can commit to an innovation prize that is contingent on the (realized) size of the cost shift. Then for environmental R&D, expected welfare is higher with an innovation prize than with an R&D subsidy.

In the paper we have mainly examined the case of a single innovator. In Section 6.5 we examined, however, the case of two innovators within a set up that is in line with how we determine the innovation prize when there is one innovator. With more than one innovator, there are alternative designs of the rule determining who wins the prize. For example, the winner might be the innovator who i) first develops the new technology that lowers the cost of downstream firms by a pre-specified amount, or ii) develops a technology that lowers the cost of downstream firms by more than the technology developed by the competitor (given that the cost reduction is at least the pre-specified amount). With the alternative set-ups, the probability that an innovator succeeds will depend also on the R&D investment of the competitor because increased R&D by the competitor will increase her chance of winning the competition and thus decrease the chance that the other innovator wins. Still, the properties of the optimal innovation prizes will be similar to the case discussed in Section 5.

Throughout the paper we have assumed that the government has access to a complete set of policy instruments, here an innovation prize (or a R&D subsidy) and a diffusion subsidy. If the regulator cannot use a subsidy to promote the uptake of the new technology, adoption of new technology will not be efficient (second-best outcome). In a supplementary material, see

Golombek et al. (2015), we have shown that whether the innovation prize should be greatest for environmental R&D then depends on relative slopes of the demand curve/marginal benefit of abatement curve and the marginal cost curves (prior to an innovation).

Finally, we have analysed an innovation prize that comes in addition to the income from the patent. With a complete patent buy-out, both innovations could be licensed by the downstream firms to marginal cost, and there would be no need for a diffusion subsidy. In the market good case first best would be realized by the "invisible hand". Furthermore, an emission tax equal to marginal environmental damage would ensure first best adoption of the new technology and first best pollution abatement. On the other hand, the environmental patent might recieve a lower price than the market good patent even though their social values are identical. When bargaining over the price, the market good innovator would have a more valuable outside option, that is, we have shown that the patent value of a market good innovation exceeds that of an environmental innovation.

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Acknowledgement 5 *The authors are associated with CREE – Oslo Centre for Research on Environmentally Friendly Energy. Earlier versions of this paper have been presented at research seminars at Norwegian Business School, University of Stavanger, Frisch Centre, Indian Statistical Institute, Resources for the Future, Vista analyse, Conference on Sustainable Resource Use and Economic Dynamics (SURED), the 22nd Annual conferance of the European Association of Environmental and Resource Economists, Ifo Institute, and GREDEG - Université Nice Sophia Antipolis. The authors are grateful for comments and suggestions from the participants at the seminars. This research was made possible through financial support from the Research Council of Norway to the CREE centre as well as through financial support from the European Commission under the 7th Framework Programme of the European Union to the project Economic iINsTRuments to Achieve Climate Treaties in Europe (ENTRACTE), project number 308481.*

8 Appendix The net price of the license fee

For any given value of the diffusion subsidy σ, the innovator maximizes

$$v(z,\sigma) = (z+\sigma)D(z,x(z)) \tag{15}$$

with respect to z, that is, the difference between the license fee l and the diffusion subsidy. The FOC is $v_z(z,\sigma) = 0$ if v_z is continuous at the optimal value of z. However, if $z = \bar{z}$ is optimal, the following two conditions must hold:

$$v_{z+}(\bar{z},\sigma) = D(\bar{z},x(\bar{z})) + (z+\sigma)\left[D_{z+}(\bar{z},x(\bar{z})) + D_x x'(\bar{z})\right] \leq 0 \tag{16}$$

$$v_{z-}(\bar{z},\sigma) = D(\bar{z},x(\bar{z})) + (z+\sigma)\left[D_{z-}(\bar{z},x(\bar{z})) + D_x x'(\bar{z})\right] \geq 0 \tag{17}$$

To see that the first weak inequality must be a strict equality in equilibrium, assume the opposite, i.e., that $v_{z+}(\bar{z},\sigma) < 0$. Then the terms in square brackets in (16) and (17) are negative. A small reduction in σ will therefore increase the left hand side of both inequalities. The second inequality hence remains valid after the reduction in σ. The same is true for the first inequality when $v_{z+}(\bar{z},\sigma) < 0$ initially and the reduction in σ is sufficiently small. Since the government wants σ to be as low as possible, it will reduce σ so much that we achieve $v_{z+}(\bar{z},\sigma) = 0$ instead of $v_{z+}(\bar{z},\sigma) < 0$.

The equation $v_z(z,\sigma) = 0$ defines the function $z(\sigma)$ with the property

$$z'(\sigma) = \frac{v_{z\sigma}}{-v_{zz}} \tag{18}$$

Due to the second order conditions, the denominator is positive, and $v_{z\sigma} < 0$ since the terms in square brackets in (16) and (17) are negative. It is thus clear that $z'(\sigma) < 0$.