



Should environmental R&D be prioritized?

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ABSTRACT

An innovator may not be able to capture the full social benefit of her innovation and, therefore, governments support private R&D through various measures. We compare a market good innovation—to develop a more efficient technology to produce a standard market good—with an environmental innovation—to develop a more efficient abatement technology—that has the same potential to increase the social surplus. In the first-best outcome, which can be achieved by offering an R&D subsidy and a diffusion subsidy, the R&D subsidy should be greatest for an environmental innovation, whereas the diffusion subsidy should be greatest for a market good innovation. The ranking of the two types of subsidies reflects that the appropriability problem is greater for an environmental innovation than for a market good innovation.

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1. Introduction

The creation and diffusion of environmentally friendly technologies makes lowering pollution levels less costly and facilitates more stringent environmental policies. Thus, as acknowledged already by [Kneese and Schulze \(1975\)](#), the long-term incentives provided by environmental policy to adopt and to develop new, less polluting technology are at least as important as other aspects of environmental policy. On the other hand, even with optimally chosen environmental policies, the level of environmentally friendly R&D in a market economy may be lower than the social optimum because innovators may not be able to capture the full social benefit of their innovations. In the innovation literature, this is referred to as the *appropriability problem* (see [Arrow, 1962](#)).

To address the appropriability problem, governments use general policy measures such as R&D subsidies, innovation prizes and legal protection of intellectual property rights (patents) to increase the supply of private R&D. Although many argue that such measures should be neutral, that is, all kinds of R&D should receive the same support, the literature on

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environmental R&D indicates that the appropriability problem might be larger for environmental R&D than for regular market goods R&D.¹ However, to the best of our knowledge, this question is not yet settled.

This paper examines whether the appropriability problem is greater for environmental R&D than for market good R&D. Our point of departure is that governments seek to realize the maximum welfare benefit from an innovation. To obtain this first-best outcome, governments must offer an R&D subsidy to ensure the socially optimal level of R&D, and a diffusion subsidy to promote adoption of the new technology among downstream firms. The earlier literature has neither compared analytically environmental R&D with market goods R&D, nor given governments access to a full set of policy instruments.

Equipping the government with a full set of policy instruments turns out to be important. If the government only has an emission tax at its disposal, the government may experience a commitment problem. Prior to the innovation, the government prefers the future emission tax to be *high* giving incentives to increase environmental R&D today. However, after the innovation, the government may want a *low* tax rate in order to force the monopoly innovator to set a low license fee, which stimulates adoption of the new technology. Thus, the government might end up expropriating the value of the patented innovation, thereby amplifying the appropriability problem.

We show that when the government uses all instruments, the commitment problem vanishes. The reason is that the emission tax is used exclusively to determine abatement, and not to trigger innovation or diffusion. However, even though the commitment problem vanishes, the optimal policy package for a market good innovation still differs from that of an environmental innovation. First, we find that the R&D subsidy should be higher under environmental R&D than under market good R&D. Second, we find that the diffusion subsidy should be lower for an environmental innovation than for a market good innovation. The ranking of the two types of subsidies reflects that the appropriability problem is greater for an environmental innovation than for a market good innovation.

The intuition for our first result can be explained by looking at the price elasticity of demand for the new technology in the two cases. When the license fee for the market good innovation is increased, the consumer price of the market good also increases making the private value of the innovation higher. Hence, the demand response to an increase in the license fee is dampened. Under environmental innovation, the “price” of abatement, that is, the emission tax, is set by the government, and thus the private value of the innovation stays constant making the demand response to an increase in the license fee larger. Because demand is less price elastic under market good innovation, the license fee set by the innovator is highest under market good innovation. It then follows that the innovator earns more on a market good innovation than on an environmental innovation. This is why the R&D subsidy should be lower under market good R&D than under environmental R&D.

As mentioned above, both an R&D subsidy and a subsidy promoting the diffusion of the new technology are required to induce the first-best social outcome. Without the R&D subsidy, the profit of the innovator equals the net license income, which, in general, differs from the social value of the innovation. Therefore, the private level of R&D will be inefficient. Further, it is necessary to offer a diffusion subsidy because the license fee discourages downstream firms to adopt the new technology even though it may be socially efficient that all downstream firms switch to the new technology.

For environmental innovations, the optimal combination of the R&D subsidy and the diffusion subsidy is not invariant to the choice of environmental policy instruments. If the government uses an emission quota instead of an emission tax, demand for the new innovation becomes less elastic. Consequently, the emission quota case is more similar to the market good outcome with respect to the R&D subsidy and the diffusion subsidy than the environmental tax case.

We also analyze the game in which the government uses an innovation prize instead of a R&D subsidy, to stimulate R&D. With an innovation prize, the innovator receives an amount of money if she manages to innovate. We show that with symmetric information between the government and the innovator, it does not matter whether the government offers an R&D subsidy or an innovation prize; both instruments will lead to an efficient level of R&D. However, under asymmetric information, we demonstrate that only an innovation prize can achieve the efficient level of environmental R&D.

Finally, we examine the case of competing innovators (as opposed to a single innovator), 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 organized as follows. Section 2 discusses our contribution in light of the literature on environmental R&D and R&D policy instruments. In Section 3, we present our model of the technology adoption process. Then in Section 4, we analyze the R&D decision by the two types of innovators, and compare the optimal innovation policy for the two types of innovations. Section 5 considers extensions of the basic model (an innovation prize, asymmetric information and multiple innovators). Section 6 concludes.

2. Contributions and related literature

Our paper is linked to different strands of the environmental economics literature. The key topic in our paper is whether the appropriability problem plays out differently for environmental innovations compared with 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.](#)

¹ In our paper, environmental R&D refers to innovations implying more efficient abatement technologies like, for example, abatement of NO_x or SO₂. Market good R&D, on the other hand, refers to innovations leading to more efficient technologies to produce a standard market good, for example, a new cell phone.

(2014) and Greaker et al. (2017) 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. In our analysis, we assume that all kinds of R&D give rise to knowledge spillovers with the same social value. Thus in our model, we can abstract away from dynamic knowledge spillovers, and instead focus on the static part of the appropriability problem.²

Furthermore, earlier contributions, for example, that of Downing and White (1986), compare the effect of different environmental policy instruments on environmental R&D. In contrast to later studies, including ours, the earlier literature assumes that polluting firms could innovate and it does not include patents and licensing of innovations. However, according to Requate (2005), for instance, most pollution abatement innovations happen outside the polluting industry. Laffont and Tirole (1996), Denicolo (1999), Perino (2010) and Montero (2011) separate the innovator from the polluting sector, as we do. As described above, this gives rise to a potential commitment problem; when setting environmental policy, the government would prefer a low license fee to increase adoption of the new technology. However, because this may reduce the profit of the innovator, the incentives to invest in environmental R&D might be 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), Perino (2010) and Montero (2011), Requate does not consider other types of innovation policy instruments. In contrast, we demonstrate that to reach the first-best outcome, the government has to use one instrument, for example, an R&D subsidy (or an innovation prize), to spur R&D, and another instrument, for example, a diffusion subsidy, to trigger greater adoption of the new technology.³

Both Laffont and Tirole (1996) and Montgomery and Smith (2007) suggest that the appropriability problem is greatest for environmental R&D. However, their results hinge on the assumption that all polluting firms obtain the same benefit from the new technology. Then, it is possible for the government to set a very low emission tax and still achieve adoption of the new clean technology by all the downstream firms. With heterogeneous firms, such as in Requate (2005), this is no longer possible, and hence the result that governments expropriate the value of patented environmental innovations should not be considered a general result. In our paper, we consider a setup in which identical benefits from the innovation is a special case. Hence, our results are valid in the cases of both homogeneous and heterogeneous benefits to the downstream firms that switch to the new technology.

In our paper, we 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 a low emission-input substitution do not always lead to downward shifts in the marginal abatement cost curve. Although this is an interesting case, it is not examined in the present paper.

In the main part of the paper, we assume that the government uses an R&D subsidy as the instrument to ensure efficient R&D efforts. However, in an extension in Section 6 we examine the equilibrium when the government uses an innovation prize. One advantage of an innovation prize is that it can easily be targeted to a specific field of technology, for instance, zero-carbon technologies. Brennan et al. (2012) and Newell and Wilson (2005) argue for the use of innovation prizes as an environmental R&D policy tool on this basis. Innovation prizes have also attracted attention in the general innovation policy literature. Some examples are Wright (1983) on patent buyouts; Weyl and Tirole (2012) on partial patent buyouts and Brunt et al. (2012) on the effect of innovation prizes.

3. The post-innovation game

Our analysis is carried out in a game theoretic model. In the first stage of the game, a monopoly innovator invests in R&D, which determines the probability of a successful innovation. The innovator receives an R&D subsidy that covers part of her cost of innovation. If the innovation materializes, the game moves on to the following three stages; in the second stage, the government sets a diffusion subsidy aimed at promoting competitive downstream firms switching to the new technology. Then, in the third stage, the innovator sets a license fee that these downstream firms must pay to use the innovation. In the final 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 case of environmental R&D, the government also sets an emission tax in addition to the diffusion subsidy in the second stage of the game.

We solve the game by backwards induction. Hence, in this section we analyze the situation in which a successful innovation has occurred. We return to the first stage of the game in Section 4.

In order to compare environmental innovations with market good innovations, we normalize the market impacts of the two types of innovations such that they have the same potential to increase social welfare. Moreover, we first consider the market good case, which is the simpler of the two since there is no emission tax involved. We then proceed by showing how the case of a successful environmental innovation differs from the market good innovation case.

² Greaker et al. (2017) conduct a simulation in which both clean and dirty R&D contribute to each other's knowledge base. The need for prioritizing clean R&D then vanishes.

³ Under environmental innovation, the government needs, of course, to use also an environmental policy instrument in order to reach the first-best outcome.

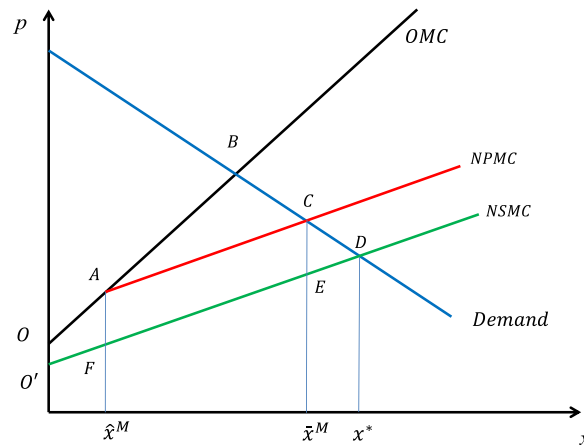


Fig. 1. Market good innovation.

3.1. The market good R&D case

We consider a successful innovation that reduces the cost of producing a market good (M). Most of the analysis can be carried out based on Fig. 1. Demand for the market good is given by the downward sloping curve, whereas the curve OMC is the Old Marginal Cost curve, i.e., the marginal cost of production prior to a successful innovation. We assume that a successful innovation will reduce the marginal cost of all downstream firms, but the magnitude of the shift may vary between firms. Thus, a successful innovation shifts the old marginal cost curve (OMC) downwards to $NSMC$ (New Social Marginal Cost curve), see Fig. 1.⁴

The pre-innovation equilibrium is at the point B in Fig. 1, while the first-best, post-innovation outcome is the point D . Here, total production is equal to x^* and all firms use the new technology. The social value of the innovation is thus given by the area $OBDO'$ in Fig. 1. We denote this social value by V^* .

The first-best outcome D would be achieved if the private marginal cost curve of the downstream producers after an innovation $NPMC$ (New Private Marginal Cost) was equal to the social marginal cost curve $NSMC$. However, since the successful innovator will be a monopolist producer of the new technology, she will charge a license fee ℓ on downstream firms using the new technology. If the license fee exceeds the minimum distance between the $NSMC$ and OMC curves ($\ell > O'O$ in Fig. 1), some output will be produced by the downstream firms using the old technology. More precisely, output up to \hat{x}^M in Fig. 1 will be produced using the old technology. It then follows that the New Private Marginal Cost ($NPMC$) 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 New Private Marginal Cost ($NPMC$) is equal to demand at point C in Fig. 1. Therefore, the increase in social benefit resulting from the innovation when the innovator is a monopolist is equal to the area $FABCE$, which is less than the social value of the innovation, V^* ($OBDO'$).

3.1.1. The profit maximizing license fee

To obtain the social value V^* , the government offers a diffusion subsidy σ to all downstream firms that adopt the new innovation. The net price of the license facing the downstream sector is then given by $z = \ell - \sigma$. When setting the license fee ℓ in the third stage of the game, the monopoly innovator takes the diffusion subsidy σ as given.

Let x be the amount produced of the market good, and let D denote demand for the new technology (which should not be mixed with demand for the market good). The revenue v of the innovator is then given by:

$$v = \ell D(z, x) \quad (1)$$

Let $\bar{z} > 0$ be the benefit of switching from the old to the new technology of the firm obtaining the lowest gain of adopting the new technology. In Fig. 1, we have $\bar{z} = O'O$.⁵ The demand function D has the property that for all values of z below \bar{z} , there is full use of the new technology. Hence, for values of z below \bar{z} , the demand is independent of z . 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 $z > \bar{z}$. This can be seen from Fig. 1 by shifting the right segment of the $NPMC$ curve upwards.

For any given value of z , the demand for the new technology will be higher the higher is total output from the downstream firms, that is, $D_x > 0$. Further, total output is determined by the intersection between the demand for the downstream good

⁴ In the figure, all curves are linear, but this has no consequences for our results. The critical assumption is that the cost curve shifts downwards in such a way that point B in Fig. 1 is no longer an equilibrium.

⁵ To simplify the analysis as much as possible, we assume $\bar{z} > 0$. However, it is easily shown that our results are valid also for $\bar{z} = 0$.

and the private marginal cost of producing the good (that is, C in Fig. 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 $x^M = x^M(z)$ with the property $\frac{dx^M}{dz} = x_z^M < 0$.

When setting the license fee ℓ , the monopoly innovator takes the diffusion subsidy σ as given because it was determined by the government in the previous stage of the game. The innovator chooses ℓ to maximize the license income given by (1). On the margin, the innovator balances the demand reduction of an increase in ℓ with the direct positive effect of increased ℓ on her revenue (for any σ set by the government). The first-order condition is:

$$D + \ell [D_z + D_x x_z^M] = 0 \tag{2}$$

where $D_z + D_x x_z^M < 0$. Note that (2) can be interpreted as the optimal response function of the innovator to any diffusion subsidy σ .

3.1.2. The optimal diffusion subsidy

When the monopolist innovator charges a license fee, there are two reasons why the social value of the innovation, V^* , is not reached.⁶ First, the positive license fee implies that the first \hat{x}^M producers will not use the new technology, even though it is socially optimal to do so. This loss is represented by $OAF O'$ in Fig. 1. Second, the positive license fee implies that downstream producers will choose the output level x^M , whereas the socially optimal output level is x^* . This loss is given by ECD in Fig. 1.

From Fig. 1, we see that these losses can only be eliminated if the government sets the diffusion subsidy σ so that the net price to license the new technology, z , is zero. With $z < \bar{z}$, but larger than 0, there would be too little output. Denoting the optimal diffusion subsidy by σ^M and let $\ell(\sigma^M) = \ell^M$, from (2) we now have:

$$\sigma^M = \ell^M = \frac{D(0, x^*)}{-D_z - D_x x_z^M} \tag{3}$$

The numerator must be positive. Moreover, the second term in the denominator ($-D_x x_z^M$) is also positive. The first term ($-D_z$, evaluated at $z=0$) is zero since $\bar{z} > 0$; a small increase in z from $z=0$ will have no direct effect on the demand for the new technology because there is full use of this technology. Hence, $\sigma^M = \ell^M > 0$.

The payoff to the innovator is $\ell^M D(0, x^*)$. Since the diffusion subsidy is set exclusively to ensure that $z = \ell^M - \sigma^M = 0$, we may have $\ell^M D(0, x^*) < V^*$. In other words, even though the diffusion subsidy ensures that the welfare gain V^* is realized, it cannot at the same time ensure that the revenue of the innovator equals the social value of the innovation.

3.2. The environmental R&D case

We now go through the same stages as above for environmental R&D except that now the government sets both a diffusion subsidy and an emission tax in the second stage of the game.⁷

Production by the downstream firms implies pollution, and firms can either pay the emission tax p , or abate pollution. In Fig. 2, we let x measure the amount of pollution abated. Initially, the marginal cost of abatement is given by OMC , and as in the case of market good R&D, we assume that a successful innovation shifts the marginal abatement cost function from OMC to $NSMC$. The downward sloping curve is the *marginal benefit of abatement* (MBA), which is assumed to have exactly the same properties as the demand function in the market good case. Prior to an environmental innovation, an optimal environmental policy will give the equilibrium point B in Fig. 2; this solution can be implemented with the tax p_0 .

The post-innovation social optimum is at the point D in Fig. 2, and the socially optimal level of abatement is x^* . As explained in the previous section, the new private marginal abatement cost (the solid line $NPMC^*$ in Fig. 2) will lie above the new social marginal abatement cost if the net license fee $z = \ell - \sigma$ facing the downstream sector is positive.

Once the tax p and the diffusion subsidy σ are set by the government in stage two, and the net license fee $z = \ell - \sigma$ is determined in stage three, total abatement x is determined by downstream firms setting private marginal abatement cost $NPCM^*$ equal to the emission tax. This can be formalized as $x^E = x^E(p, z)$.

Note that with a market good innovation, the optimal quantity x^* can only be reached by making $NPMC$ (in Fig. 1) equal to $NSMC$, which requires the equilibrium net license fee, $z = \ell - \sigma$, to be equal to zero. In contrast, with an environmental innovation, any abatement level can be realized by a suitable environmental tax. Hence, it is not required to ensure that $NPMC^*$ in Fig. 2 is equal to $NSMC$ in order to reach the optimal quantity x^* . This is illustrated by the tax $p = \bar{p}$ in Fig. 2: Even though the MBA and the $NPMC^*$ curves do not intersect at x^* , the government still obtains the optimal abatement level x^* .⁸

⁶ If $\ell < 0$, only the second reason is relevant.

⁷ It is not obvious how best to model the timing of the emission tax. 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; we follow this assumption in this section. However, the timing of the tax is discussed in Section 5.1.

⁸ $NPMC^*$ in Fig. 2 is the $NPMC$ curve that supports the first-best outcome.

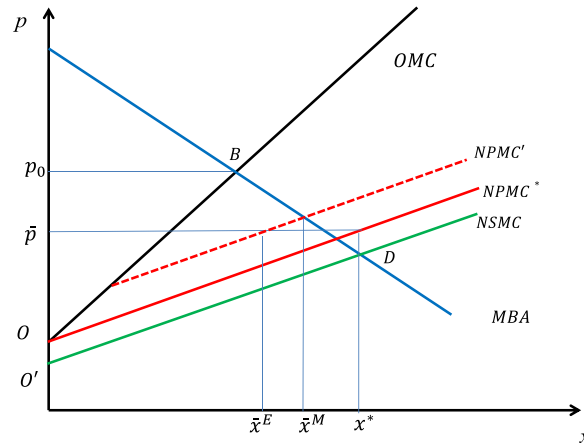


Fig. 2. Environmental innovation.

As in the previous section, the innovator chooses ℓ in the third stage of the game to maximize her profits $\ell D(z, x^E)$, now taking the diffusion subsidy σ and the emission tax p as given. The expression for the optimal licence fee is similar to what we found for the market good case:

$$\ell^E = \frac{D(z, x^E(p, z))}{-D_z - D_x x_z^E} = \ell^E(\sigma, p) \quad (4)$$

In the market good case, $x_z^M < 0$, see above. Similarly, in the environmental case, $\frac{\partial x^E}{\partial z} = x_z^E < 0$ because the private marginal cost curve is higher the higher is the net license fee z of using the new technology. However, the magnitudes of x_z^M and x_z^E differ. To see this, consider a hypothetical increase in ℓ that shifts the $NPMC$ -curve from $NPMC^*$ to $NPMC'$ in Fig. 2.⁹ Under an environmental innovation, this will trigger a decrease in abatement from x^* to \bar{x}^E , since the emission tax was set prior to the license fee and hence remains unchanged. This contrasts to the market good case, where the same shift in the $NPMC$ -curve will make the output price increase, thereby dampening the quantity effect. The output reduction in the market good case will therefore only be from x^* to \bar{x}^M . The decline in output in the market good case is thus less than it would have been had the output price remained unchanged. To sum up, the innovator faces a more elastic demand under environmental R&D than under market good R&D. Hence, $-x_z^E > -x_z^M$.

The government sets σ and p in the second stage of the game, taking the innovator's response $\ell^E(\sigma, p)$ given by (4) into consideration. 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 that is consistent with reaching the social optimum. With this assumption, we show in Appendix A.1 that the equilibrium of the game is to set σ so that $\ell(\sigma, p) - \sigma = \bar{z}$.

Comparing (4) with (3) from the market good R&D case, we note that the numerator D is the same in both cases ($D(\bar{z}, x^*) = D(0, x^*)$). However, the denominator is larger in the environmental innovation case. First, $-x_z^E > -x_z^M$, as explained above, whereas the derivative D_x is the same in the two cases because the equilibrium quantity is x^* in both cases. Second, since $\bar{z} > 0$, the term $-D_z$ will be zero in the case of a market good innovation, since the equilibrium value of z is zero in this case, while $-D_z > 0$ in the environmental case (since $\ell^E - \sigma = \bar{z}$). Because the denominator in (4) is higher than in (3), it follows that $\ell^E < \ell^M$.

In the market good case, the social optimum is achieved by $\sigma^M = \ell^M(z=0)$, whereas in the environmental innovation case, $\sigma^E \leq \ell^E(\bar{z} \geq 0)$. Hence, $\ell^E < \ell^M$ implies that $\sigma^E < \sigma^M$. This gives the following proposition:

Proposition 1. *To achieve the first-best optimum, the diffusion subsidy must be higher for market good innovations than for environmental innovations ($\sigma^M > \sigma^E$).*

The payoff to the innovator is $\ell^E D(\bar{z}, x^*)$ in the environmental innovation case and $\ell^M D(0, x^*)$ in the market good innovation case. Since $\ell^E < \ell^M$ and $D(\bar{z}, x^*) = D(0, x^*)$, we also have:

Proposition 2. *The revenue from an environmental innovation is smaller than the revenue from a market good innovation.*

As discussed above, the diffusion subsidy is set exclusively to ensure that $z = \ell^E - \sigma^E = \bar{z}$. Hence, we may have $\ell^E D(0, x^*) < V^*$. We are now ready to look at the first stage of the game.

⁹ In Fig. 2, $NPMC'$ is located above $NPMC^*$ because by assumption the value of z associated with $NPMC'$ is higher than the value of z associated with $NPMC^*$. The purpose of $NPMC'$ is to illustrate that the innovator faces a more elastic demand under environmental R&D than under market good R&D. The exact location of $NPMC'$ relative to $NPMC^*$ is of no importance.

4. R&D investments

We have normalized the market impacts of the two types of innovations such that they have the same potential to increase social welfare. In line with this normalization, we also assume symmetrical R&D production functions. In particular, building on Laffont and Tirole (1996), we assume that by investing k^j in R&D, there will be a successful innovation of type j with probability $\xi(k^j)$, $j = E, M$. The function $\xi(\cdot)$ has the following properties: $\xi(0) = 0$, $\xi(k^j) < 1$, $\xi' > 0$, $\xi'' < 0$ and $\xi'(0) = \infty$.

Let $v^j = \ell^j D(0, x^*)$ be the private income from an innovation of type j . These are determined in the post-innovation games described in Section 3, given optimal policies. In this section, we will assume that the government uses an R&D subsidy s^j to promote innovation, that is, the innovator pays $(1 - s^j)k^j$ of the R&D cost, whereas the government pays $s^j k^j$. The innovator maximizes expected profits by choosing the R&D amount k^j :

$$\max_{k^j} \{ \xi(k^j)v^j - (1 - s^j)k^j \}$$

Notice that the innovator takes into account the equilibrium value of v^j from the post-innovation game.

The privately optimal k^j is given by:

$$\xi'(k^j)v^j = 1 - s^j \tag{5}$$

which simply states that the increase in expected profit following from a marginal increase in R&D ($\xi'(k^j)v^j$) should be equal to the corresponding cost increase born by the private innovator ($1 - s^j$). The properties of $\xi(k)$ ensure that k^j is uniquely defined and strictly increasing in v^j .

The increase in social benefit caused by the innovation is V^* (given optimal policies in the post-innovation games). Hence, the social optimal amount of R&D follows from

$$\max_{k^j} \{ \xi(k^j)V^* - k^j \}$$

The first-order condition of this problem is

$$\xi'(k^*)V^* = 1 \tag{6}$$

where k^* is the social optimal investment in both the environmental and the market good R&D case. Hence, $\xi(k^*)$ is the optimal probability that the innovation materializes. From (5) and (6) we find that the optimal subsidy rate, s^j , is given by:

$$s^j = \frac{V^* - v^j}{V^*} \tag{7}$$

Hence, if the social value of the innovation exceeds the private value ($V^* > v^j$), the government should offer an R&D subsidy, and this subsidy is increasing in $V^* - v^j$. Moreover, if $v^E \neq v^M$, then $s^E \neq s^M$.

From the discussion after (4) we know that $\ell^E < \ell^M$. Moreover, $x = x^*$ for both market good and environmental innovations, implying that $v^E = \ell^E D(\bar{z}, x^*) < \ell^M D(0, x^*) = v^M$. Using (7), we have $s^E = (V^* - v^E)/V^* > (V^* - v^M)/V^* = s^M$. This gives the following proposition:

Proposition 3. *To achieve the first-best optimum, the R&D subsidy must be higher for environmental innovations than for market good innovations ($s^E > s^M$).*

In the next section, we investigate to what extent this result is robust to different assumptions about the game with respect to (i) the timing of moves, (ii) the use of an emission quota instead of an emission tax, (iii) the use of an innovation prize instead of a R&D subsidy, and (iv) the number of innovators, that is, multiple innovators instead of one innovator.

5. Extensions

5.1. The timing of the license fee and the policy instruments

Above, we assumed that the diffusion subsidy and the tax rate are set prior to the license fee. This equilibrium is time consistent because the first-best outcome is achieved and therefore, the government has no incentive to change the diffusion subsidy or the tax after observing the license fee. Hence, the government's optimal diffusion subsidy and tax rate are the same as in an alternative game where the diffusion subsidy and the tax are set simultaneously with the license fee (the simultaneous move game). The innovator's optimal response function is also the same in the two games: in both games, the innovator chooses the optimal license fee taking the diffusion subsidy and the tax rate as given. From these two observations, we obtain the following proposition:

Proposition 4. *The equilibrium outcome of the game in which the policy instruments (the diffusion subsidy and environmental tax) are set before the license fee is identical to the equilibrium of the game in which both policy instruments and the license fee are set simultaneously.*

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” because the government (with zero costs for public funds) would respond with a subsidy that is so high that $z = \bar{z}$, i.e., an “infinitely high” subsidy. This is the case irrespective of when the environmental tax is determined.

Finally, we consider the case where the license fee and the diffusion subsidy are set in the third stage of the game, whereas the tax is set in the fourth stage. This sequence of moves is the most similar to the market 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 government is to set a tax p so that the first-best optimum x^* is achieved.¹⁰ 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; hence, we turn to the quota case.

5.2. 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 Fig. 2. It makes no difference to the equilibrium outcome whether the quota is set before or after the license fee (or simultaneously). In all cases, 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 (because she knows that x will definitely be equal to x^*). Therefore, the innovator could increase her revenue by increasing ℓ . The government wishes 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 she 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 (2), where the term x_z^M is now zero. Hence, using Q as a superscript for the present case, it follows from (2) that:

$$\ell^Q = \frac{D}{-D_z}. \quad (8)$$

Comparing this with the market good case (3), we can see that the numerator D is the same in both cases ($= D(\bar{z}, x^*) = D(0, x^*)$). For $\bar{z} > 0$, the term $-D_z$ in (3) is zero whereas the second term in the denominator in (3) is positive. Therefore, we do not know the sign of $\ell^Q - \ell^M$. In particular, it follows from (3) and (8) that $\ell^Q < \ell^M$ if $-D_z$ is “large” and $-D_x x_z^M$ is “small”.

Generally, the revenue $v^Q = \ell^Q D$ will differ from the social value of the innovation, V^* . Therefore, to achieve the correct incentives for R&D, the innovator must be offered an R&D subsidy $s^Q = \xi'(k^*)(V^* - v^Q)$.

Because the signs of $\ell^Q - \ell^M$ and hence, of $v^Q - v^M$ are ambiguous, it follows that the ranking of s^Q and s^M is ambiguous as well.

We can see from (4) and (8) that $\ell^Q > \ell^E$ because the numerator and the term $-D_z$ are the same in the two expressions. Hence, $v^Q > v^E$ and, therefore, $s^Q < s^E$. Thus, we have the following proposition (when the emission tax is set before the license fee or simultaneously with the license fee):

Proposition 5. *To achieve the first-best optimum under environmental R&D, the R&D subsidy 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 at the end of Section 5.1, 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 case is that the equilibrium is *not time consistent*: If it was possible for the innovator to reset the license fee after having observed the emission tax, she would do so. For the given emission tax, lowering the license fee would 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.

5.3. Innovation prizes and asymmetric information

Alternatively to subsidizing private R&D, governments may announce innovation prizes. One example is the EU Horizon 2020 innovation prize program. This program promises a cash reward to whoever can most effectively meet a defined challenge within the areas of antibiotics, transmission barriers, city air improvement, spectrum sharing and food scanners. Another example of an innovation prize is The H-Prize, which was launched by the U.S. Department of Energy in 2007. This is a series of competitions to encourage and reward advances in hydrogen energy technologies.

We now briefly look at the use of an innovation prize instead of an R&D subsidy. The government promises the innovator an amount of money, P , if she manages to develop an innovation that meets a set of pre-specified criteria. We focus on an innovation prize that is offered in addition to patent rights, which for instance is the case for the EU Horizon 2020 prizes.

¹⁰ In Fig. 2, the optimal tax is set so that it intersects the NPMC curve for $x = x^*$.

According to Brennan et al. (2012) and Newell and Wilson (2005), patent buyouts are very rare, possibly because they will be very costly for the government. Hence, if an innovation materializes, the income of the private innovator is $v + P$.

The private innovator now maximizes $\xi(k)(v + P) - k$, which leads to the first-order condition $\xi'(k)(v + P) = 1$. Because the social optimal amount of R&D investment is given by $\xi'(k^*)V^* = 1$, see (6), the optimal innovation prize must ensure that total income of the innovator, $v + P$, is equal to V^* . Hence, the optimal innovation prize is simply $P = V^* - v$. Since $v^E < v^M$, it follows that also the optimal innovation prize will be greater for environmental innovations than for market good innovations.

So far, we have implicitly assumed that the government knows all the parameters of the model *ex ante*. However, for R&D projects, many would argue that it is more reasonable to assume that only the innovator has full information about the R&D project, that is, the probability of an innovation $\xi(k)$ and the cost reduction following from a successful innovation. Clearly, even if the government does not know the function $\xi(k)$, the government can still set the correct innovation prize or the correct R&D subsidy, confer (7), as long as the government knows V^* and v . However, if the government does not know the potential cost reduction *ex ante*, then the government knows neither V^* nor v *ex ante*. It is then impossible to set the correct R&D subsidy.

With an innovation prize, the situation is different. The government can simply announce an innovation prize that is *contingent* on the cost reduction. The reason is that both the increase in social surplus, V^* , and the private value of an innovation, v , depend solely on the cost reduction. Thus, 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 by an innovation prize in both the market good and the environmental R&D cases even with asymmetric information.

5.4. Multiple innovators

Above, we assumed that there is a single innovator. In Appendix A.2, we examine the case with two innovators.¹¹ If only one innovator succeeds in developing the technology, she will receive a patent and an innovation prize. If both innovators develop the new technology, a lottery will determine who will receive the patent and the prize.

In the special case of two identical innovators, the optimal innovation prize does of course not differ across the innovators. However, with heterogeneous innovators, that is, when the R&D production functions $\xi_i(k_i)$ are not identical, the optimal prize should differ across actors. More important, with two innovators, the optimal prize should be lower than in the case of one innovator. Furthermore, when an emission tax is used as the policy instrument, we still find that an environmental innovation should receive a higher innovation prize than a market good innovation.

6. 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 for environmental innovations than for market good innovations.

We have demonstrated that 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 R&D subsidy or an innovation prize 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 R&D subsidy for environmental R&D should always be greater than the R&D subsidy for market good R&D. Alternatively, the innovation prize 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 the fact that the innovator faces a less elastic demand under market good innovations than under environmental innovations. Therefore, the equilibrium license fee is greatest under market good innovations. Hence, the revenue of the innovator is highest in the case of market good innovations, which tends to reduce the appropriability problem. This explains why the R&D subsidy should be lowest for market good innovations. Further, because the equilibrium license fee 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 diffusion subsidy should be highest for 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 5.3, 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, the optimal amount of R&D can be achieved by an innovation prize, whereas it is impossible to set the correct R&D subsidy. In addition, also from a political economy point of view, an innovation prize might be preferable to an R&D subsidy. For example, there might be political resistance to a government offering an R&D subsidy to innovators that might fail to develop a new technology. In contrast, an innovation prize is offered to successful innovators only.

¹¹ It is straightforward to generalize from two innovators to n innovators; the derived innovation prize will have the same type of properties as in the case of two competitors.

Most of the paper focused on the case of a single innovator. However, in Section 5.4, we examined the case of two innovators, assuming that an innovator will receive an innovation prize if she is the only innovator developing the new technology. If both innovators develop the new technology, a lottery will determine who will receive the prize. This setup is in line with how we determine the innovation prize when there is one innovator.

With more than one innovator, there are alternative designs for the rule determining who wins the prize. For example, the winner might be the innovator who (i) first develops a 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 exceeds a pre-specified amount). With the alternative setups, the probability that an innovator succeeds will also depend on the R&D investment of the competitor; increased R&D by the competitor will increase her chance of winning the competition and, thus, decrease the chance that the first innovator wins. We conjecture that the properties of the optimal innovation prize will be similar to the case discussed in Section 5.4.

Throughout the paper, we have assumed that the government has access to a complete set of policy instruments, that is, an R&D subsidy (or an innovation prize) and a diffusion subsidy. If the government cannot use a diffusion subsidy to promote the uptake of the new technology, adoption of the new technology will not be efficient (second-best outcome). In Golombek et al. (2015) we have shown that whether the innovation prize should be greatest for environmental or market good R&D then depends on the relative slope of the demand curve/marginal benefit of abatement curve and the marginal cost curve (prior to an innovation).

Finally, we have analyzed an R&D subsidy that is offered to the innovator in addition to the income from the patent. With a complete patent buyout, both types of innovation could be licensed by the downstream firms to marginal cost and, thus, there would be no need for a diffusion subsidy. In the market good case, the first-best outcome would be realized without any additional government policies. Further, an emission tax equal to the marginal environmental damage would ensure the first-best level of abatement.

Will the price for a complete patent buyout differ by type of innovation? Throughout the paper, we have assumed that the social value of the environmental innovation is identical to the social value of the market good innovation. Then, according to Proposition 1, the R&D subsidy should be higher for environmental innovations than for market good innovations. This means that the license income is greatest under market good innovations ($v^M > v^E$) and, thus, the patent value of the market good innovation exceeds that of an environmental innovation. Therefore, the market good innovator has a more valuable outside option than does the environmental innovator when bargaining with the government over the price for a complete patent buyout. Hence, the market good innovator might receive the highest buyout price.

Conflict of interest

None declared.

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Appendix

A.1 The determination of the diffusion subsidy and the license fee

In the third stage of the game, the values of the diffusion subsidy σ and the emission tax p are predetermined, whereas the innovator chooses its license fee ℓ to maximize its profits. Since σ is given, choosing ℓ is equivalent to choosing $z = \ell - \sigma$. The innovator hence chooses z to maximize

$$v(z, \sigma) = (z + \sigma)D(z, x^E(z)) \quad (9)$$

The FOC is

$$v_z(z, \sigma) = D + (z + \sigma) [D_z + D_x x_z^E(\bar{z})] = 0 \quad (10)$$

if v_z is continuous at the optimal value of z , which will be the case if $z < \bar{z}$. Assume first that $z < \bar{z}$. The value of z will then depend on σ , with

$$Z'(\sigma) = \frac{v_{z\sigma}}{-v_{zz}} \tag{11}$$

Due to the second-order conditions, the denominator is positive. Moreover, $v_{z\sigma} < 0$ because the terms in square brackets in (10) is negative. Thus, it is clear that $z'(\sigma) < 0$. But this means that as long as $z < \bar{z}$ initially, the government can reduce σ without making z exceed \bar{z} . Given that the government wants to achieve the first-best outcome with σ being as low as possible, it sets σ at the lowest possible value that is consistent with \bar{z} solving the innovator's maximization problem. Hence, $\ell(\sigma, p) - \sigma = \bar{z}$.

Note that the derivative v_z is not continuous at the value \bar{z} . For $z = \bar{z}$ to solve the innovator's maximization problem, the following two conditions, involving the left derivatives v_{z-} and D_{z-} , and the right derivatives v_{z+} and D_{z+} , must hold:

$$v_{z+}(\bar{z}, \sigma) = D(\bar{z}, x^E(\bar{z})) + (z + \sigma) [D_{z+}(\bar{z}, x^E(\bar{z})) + D_x x_z^E(\bar{z})] \leq 0 \tag{12}$$

$$v_{z-}(\bar{z}, \sigma) = D(\bar{z}, x^E(\bar{z})) + (z + \sigma) [D_{z-}(\bar{z}, x^E(\bar{z})) + D_x x_z^E(\bar{z})] \geq 0 \tag{13}$$

To see that the first weak inequality must be a strict equality in equilibrium, assume the opposite, that is, that $v_{z+}(\bar{z}, \sigma) < 0$. The terms in square brackets in (12) and (13) are negative. Therefore, a small reduction in σ will increase the left-hand side of both inequalities. Hence, the second inequality 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 to achieve the first-best optimum with σ being as low as possible, it will choose the value of σ making $v_{z+}(\bar{z}, \sigma) = 0$ (instead of a higher value giving $v_{z+}(\bar{z}, \sigma) < 0$).

Given the equality in (12), equation (4) immediately follows, with D_z interpreted as D_{z+} , which is negative.

A.2 Multiple innovators

Let k_i , $i = 1, 2$ be the R&D investment of innovator i and let $\xi_i(k_i)$ be the probability that innovator i will develop the new technology. First, assume 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 from this outcome is $\xi_1(k_1)(1 - \xi_2(k_2))v$. If both innovators develop the new technology, there will be a lottery, organized by the government, which will determine who will be granted the right to license the new technology to downstream firms. The expected income of the second outcome is $\xi_1(k_1)\xi_2(k_2)v/2$. Hence, innovator 1 maximizes her expected profit $\xi_1(k_1)(1 - \xi_2(k_2))v + \xi_1(k_1)\xi_2(k_2)v/2 - k_1$ with respect to k_1 , and innovator 2 solves a similar problem.¹²

The first-order condition of the problem of innovator 1 is:

$$\xi'_1(k_1)(1 - \frac{\xi_2(k_2)}{2})v = 1 \tag{14}$$

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 $[1 - (1 - \xi_1)(1 - \xi_2)]$. Hence, the government maximizes $[1 - (1 - \xi_1(k_1))(1 - \xi_2(k_2))]V^* - (k_1 + k_2)$ with respect to k_1 and k_2 . The first-order condition with respect to k_i is:

$$\xi'_i(k_i)(1 - \xi_{-i}(k_{-i}))V^* = 1 \tag{15}$$

where $i = 1, 2, i \neq -i$.

Let k_i^* denote the solution to (15) 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 satisfies the following condition:

$$\left(1 - \frac{\xi_2(k_2^*)}{2}\right)(v + P_1^*) = (1 - \xi_2(k_2^*))V^* \tag{16}$$

where we have used (14) and (15). Solving (16), we find that:

$$P_1^* = \frac{1 - \xi_2(k_2^*)}{1 - \frac{\xi_2(k_2^*)}{2}} V^* - v < V^* - v \tag{17}$$

The symmetry of the problem implies that the optimal prize P_2^* has the same structure as P_1^* , that is, $P_2^* = [(1 - \xi_1(k_1^*)) / (1 - \xi_1(k_1^*)/2)]V^* - v$. As in the case of a single innovator, the prize consists of two terms. The first term depends on the social

¹² This game has clear similarities to a contest. Note, however, that a standard contest meets four axioms, see Clark and Riis (1998), whereas in our model some of these axioms are not fulfilled.

value of the innovation (V^*) and the optimal R&D choice made by the competitor (k_{-i}^*). Note that k_i^* depends on $\xi_1(k_1)$ and $\xi_2(k_2)$, see (15), and thus P_i^* is dependent on both k_1^* and k_2^* .

Only the second term of the prize (ν) depends on the timing of the game, and thus on which environmental instrument the government uses. Remember that $\nu^M > \nu^E$ when an emission tax is used as the policy instrument, see discussion before Proposition 3. Hence, since the first term in (17) is the same for both environmental and market good innovations, we still have that an environmental innovation should receive a higher prize than a market good innovation.

References

- Acemoglu, D., Aghion, P., Bursztyn, L., Hémous, D., 2012. *The Environment and Directed Technical Change*. *Am. Econ. Rev.* 102, 131–166.
- Amir, R., Germain, M., van Steenberghe, V., 2008. *On the impact of innovation on the marginal abatement cost curve*. *J. Publ. Econ. Theory* 10, 985–1010.
- Arrow, K., 1962. *Economic welfare and the allocation of resources for invention*. In: Nelson, R. (Ed.), *The Rate of Direction of Inventive Activity*. Princeton University Press.
- Brennan, T.J., Macauley, M.K., Whitefoot, K.S., 2012. *Prizes or Patents for Technology Procurement*, RFF Discussion Paper, 11–21.
- Brunt, L., Lerner, J., Nicholas, T., 2012. *Inducement prizes and innovation*. *J. Ind. Econ.* LX (4), 657–696.
- Clark, D.J., Riis, C., 1998. *Contest success functions: an extension*. *Econ. Theory* 11, 201–204.
- Denicolo, V., 1999. *Pollution-Reducing Innovations Under Taxes or Permits*. *Oxford Economic Papers* 51-1., pp. 184–199.
- Downing, P.B., White, L.J., 1986. *Innovation in pollution control*. *J. Environ. Econ. Manag.* 13, 18–29.
- Gerlagh, R., Kverndokk, S., Rosendahl, K.E., 2014. *The optimal time path of clean energy r&d policy when patents have finite lifetime*. *J. Environ. Econ. Manag.* 67, 2–19.
- Golombek, R., Greaker, M., Hoel, M., 2015. *Innovation Prizes for Environmental R&D*, CREE Working Paper 19/2015 and Supplementary Material to CREE Working Paper 19/2015, available from: http://www.cree.uio.no/publications/2015.19/Innovation_prizes_supplementary_CREE_WP19_2015.pdf.
- Greaker, M., Heggedal, T.R., Rosendahl, K.E., 2017. *On the rationale for directing R&D to zero emission technologies*. *Scand. J. Econ.*, <http://dx.doi.org/10.1111/sjoe.12254/epdf>.
- Kneese, A.V., Schulze, C.L., 1975. *Pollution, Prices and Public Policy*. Brookings, Washington, DC.
- Laffont, J.-J., Tirole, J., 1996. *Pollution permits and environmental innovation*. *J. Publ. Econ.* 62 (1–2), 127–140.
- Montero, J.-P., 2011. *A note on environmental policy and innovation when governments cannot commit*. *Energy Econ.* 33 (Supplement), 13–S19.
- Montgomery, W., Smith, A., 2007. *Price, quantity, and technology strategies for climate change policy*. In: Kheshgi, H.S., Schlesinger, M.E. (Eds.), *Human-Induced Climate Change—An Inter-disciplinary Assessment*. Cambridge University Press.
- Newell, R.G., Wilson, N.E., 2005. *Technology prizes for climate change mitigation*. RFF Discussion Paper 05-33.
- Perino, G., 2010. *Technology diffusion with market power in the upstream industry*. *Environ. Resour. Econ.* 46, 403–428.
- Requate, T., 2005. *Timing and commitment of environmental policy, adoption of new technology and repercussions on R&D*. *Environ. Resour. Econ.* 31, 175–199.
- Weyl, E.G., Tirole, J., 2012. *Market power screens willingness-to-pay*. *Quart. J. Econ.* 127 (4), 1971–2003.
- Wright, B.D., 1983. *The economics of invention incentives: patents, prizes and research contracts*. *Am. Econ. Rev.* 73 (4), 691–707.