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Pollution permits and environmental innovation

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Abstract

This paper starts with a warning about the negative impact of *plain* pollution allowance markets on environmental pollution innovation. Stand-alone spot markets enable the government to expropriate an innovation by offering a competing 'technology' (pollution permits) that puts an arbitrary downward pressure on the licensing price. Advance allowances reduce expropriation but still create suboptimal incentives for innovation. They have the further drawback that permits are inefficiently used when the innovation occurs.

Options to pollute at a given striking price fare better than allowances because they create private incentives to phase out pollution in the case of innovation. We characterize the social optimum and show that it can be implemented by issuing options to pollute, inter alia.

Finally, the paper compares ex ante and ex post government procurement. Surprisingly, ex post licensing by the innovator to the government may yield a higher licensing fee than an ex ante contract.

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1. Introduction

In Laffont and Tirole (1996) we analyze the impact of spot and futures

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markets for tradeable pollution permits on the potential polluters' compliance decisions. The focus there is on the individual incentives to *adopt* pollution abatement devices. In contrast, this exploratory paper considers technological *innovation*, namely the invention of substitutes or pollution abatement devices that can be used by all polluters. The innovation is therefore a *public* good, while the investments considered in the companion paper are purely *private*.

The literature on innovation (see, for example, Tirole, 1988, for a review) has emphasized the trade-off between the creation of knowledge and its (uncompensated) use. Widespread diffusion of the innovation often lowers the innovator's payoff and accordingly reduces the incentive to innovate. The patent institution, and more generally the protection of intellectual property rights, are viewed as second-best policies to induce innovation. However, the protection granted by a patent is limited if the final goods it helps produce can alternatively be produced by technologies using unrelated ideas and therefore not infringing on the property right. A similar idea can be applied in the context of pollution control: pollution permits compete with licenses for a pollution abatement device for sales to producers of a final good, but they do not infringe on any patent granted for the pollution abatement device. Thus, even though they are an inferior means of allowing the production of the final good in the occurrence of an innovation, pollution permits exert downward pressure on licensing fees; this pressure is particularly strong when the issuer of the pollution permits, namely the government, internalizes the welfare of licencees and thus tries to curb the inventor's market power.

In the model described in Section 2 the current technology for producing a good pollutes. An innovator can invent a pollution abatement device or a pollution-free perfect substitute for the existing polluting good. The innovator receives a patent on the innovation, and no imitation is feasible. However, the government can sell pollution permits. While these permits create pollution and thus are poor substitutes for the innovation on the supply side, they are perfect substitutes on the demand side.

Some of the environmental economics literature argues that market-based instruments tend to provide good incentives for innovation. This paper, without arguing that market-based instruments are incapable of properly dealing with innovation, points to various inefficiencies induced by markets for *plain* pollution permits with regard to innovation and the diffusion of new technologies. Section 3 observes that the government can, in the case of innovation, put arbitrary downward pressure on the licensing fee by giving potential polluters the right to purchase pollution permits at a low price. The innovator is then forced to undercut the permits price. In equilibrium, the innovator does not benefit from innovation, and no R&D is performed.

Section 4 analyzes whether the government could improve welfare by committing not to issue permits on a spot market. Since innovation may not occur, it is generally optimal to issue advance allowances, though. However, two inefficiencies occur when the advance allowances do not include a buyback or trade-in provision that allows their owners to hand them back to the government at some prespecified price in the case of innovation. First, while the innovator now conducts R&D, her incentives are still socially suboptimal. Secondly, the advance allowances give rise to undesirable pollution in the case of innovation.

The efficiency of the advance allowance market is much improved if they include trade-in provisions that provide flexibility in a world in which the use of these allowances cannot be contractually conditioned on the occurrence of an innovation. Alternatively, *options* rather than rights to pollute are attractive instruments, a theme that echoes the conclusions of our companion paper. This brings us to a second point of general interest: a (private or public) supplier of an input should write long-term contracts with his customers, which take the form of options to purchase or include a trade-in covenant, whenever an uncertain innovation may reduce the need for the input in the future. Such contracts provide flexibility to react efficiently to the occurrence of innovation.

While the first part of the paper adopts an incomplete contract perspective of taking institutions (such as allowance markets) as given, Section 5 analyzes the optimal procurement policy in the case in which the governement can describe the innovation ex ante (or, more generally, can observe that the innovation allows users to produce without polluting), and signs a binding incentive contract with the innovator. Section 6 investigates whether this second-best outcome can be implemented through a system of option allowances and taxes. This analysis provides further intuition about the shortcomings of a plain allowances system.

Section 7 compares the two situations in which the government purchases the patent *before* R&D is performed (this is the procurement situation of Section 5) and *after* innovation occurs (ex post licencing to the government). It demonstrates a result of independent interest by providing conditions under which the innovator receives *more* for the innovation by signing the contract ex post rather than ex ante. There are two separate reasons why the standard Williamsonian underinvestment result may not hold. Section 8 concludes.

2. The model

There are two dates, $t = 1, 2$, and a continuum of agents/potential polluters. For notational simplicity, we assume no discounting. Also, without loss of generality, we do not consider first-period pollution. The agents' demand curve for second-period pollution rights is given by $n = N(p)$, where p is the (second-period) spot price. (This function can be interpreted as resulting from the polluting production of a final good. Assuming that one unit of output creates one unit of pollution, $N(p)$ is the amount of output optimally produced by the agents when they are charged p per unit of pollution.) The function $N(\cdot)$ is decreasing. The inverse demand curve is denoted $p = P(n)$. Unlike Laffont and Tirole (1996), we do not allow agents to make individual investments in pollution abatement (although this could be incorporated into the analysis). So, the demand function is fixed.

Let $D(n)$ denote the social damage of pollution, where $D' > 0$ and $D'' > 0$. The government faces a shadow cost of public funds $\lambda > 0$, i.e. raising \$1 of public money costs society $\$(1 + \lambda)$ because of distortionary taxation. So, for instance, when selling $N(p)$ permits at price p, the government can reduce the burden on taxpayers by $(1 + \lambda)pN(p)$. (The reader will verify that our main conclusions do not hinge on the assumption that no other tax is displaced by the tax on pollution—an assumption that is important in some other areas of environmental economics: see, for example, Bovenberg and de Mooij, 1994, on the issue of the 'double dividend'. In other words, we could allow pollution taxes to have no extra benefit, perhaps even negative benefits, beyond the reduction of pollution.)

We model innovation in a simple way. There is one potential innovator, who at private cost $C(x)$ incurred at date 1 ($C(0) = 0$, $C'(0) = 0$, $C'(1) = +\infty$, $C' > 0$, and $C'' > 0$ for $x > 0$) innovates with probability x at the beginning of date 2. The innovation is a pollution-free perfect substitute for the existing polluting good, or else is a pollution abatement device that can be installed at no cost on any existing equipment and eliminates all pollution (we will use this second interpretation). We will consider two cases depending on whether a contract can be signed with the potential innovator before she performs R&D. If such an ex ante contract can be signed (as in Section 5), then we will assume that the innovator is protected by limited liability (or, equivalently, is very risk averse under income zero). It will become clear that we could consider more sophisticated descriptions of the R&D process. When no ex ante contract is signed (Sections 3, 4 and 6), the innovator is simply granted a patent on her innovation.

Finally, we assume that profits are taxed at an economy-wide rate, which we normalize to be zero. Clearly, if the government had the discretion to set individual profit tax rates, it would confiscate the profit from the innovation once it occurs, and no R&D would be undertaken. Here, we presume a minimal level of commitment, through a non-discriminatory profit tax, for the State. However, Section 3 shows that this form of commitment is very insufficient if the government can ex post manipulate the number of permits (an instrument that, by necessity, is industry-specific). Section 4 will therefore investigate a stronger commitment for the State, in the form of a preset number of advance allowances.

3. Spot market

This section assumes that the government issues pollution permits in period 2 after observing whether the innovation occurs. The second-period timing is as follows: (i) the innovator invents or not; (ii) the government sets a price p for pollution permits;[1] and (iii) the innovator sets a price (on licenses.

Let us first analyze the pricing game. *In the absence of innovation*, the regulator chooses price p so as to solve:

$$\max_p W_0(p) = \max_p \left\{ \int_p^\infty N(x)\mathrm{d}x + (1+\lambda)pN(p) - D(N(p)) \right\}.$$

Letting

$$\eta(p) \equiv -\frac{\mathrm{d}N/\mathrm{d}p}{N/p}$$

denote the elasticity of demand for pollution permits, we obtain the standard Ramsey formula:

$$\frac{p - \dfrac{D'(N(p))}{1+\lambda}}{p} = \frac{\lambda}{1+\lambda}\frac{1}{\eta(p)}, \tag{1}$$

where $D'/(1+\lambda)$, the marginal damage expressed in monetary units, is the marginal cost of "producing the 'good pollution'". Let p_0^* denote the solution of (1).

In the case of innovation, the inventor, who has a lower cost (namely 0) of enabling agents to produce than the regulator (who has marginal cost $D'/(1+\lambda)$), always undercuts slightly the price for pollution permits. Welfare is therefore equal to

$$W_1(p) \equiv \int_p^\infty N(x)\mathrm{d}x + pN(p).$$[2]

[1] We could alternatively allow the government to choose the *number* of permits instead of their price. The treatment of this case would follow the lines of the analysis in Section 4.

[2] This expression holds as long as the price does not exceed the inventor's monopoly price. But it is clearly inefficient to set a price above the monopoly price.

The regulator therefore chooses

$$p = 0\,. \tag{2}$$

Because the innovator does not make a profit in either state of nature, she rationally chooses not to perform R&D ($x = 0$). This conclusion echoes the standard expropriation argument (see, for example Williamson, 1975). What is perhaps new here is that expropriation occurs despite the existence of a patent. The regulator can use a costly substitute for the invention, namely pollution permits, to exert downward pressure on the license price.

Proposition 1. If the government cannot commit at date 1 on the number of allowances sold at date 2 and just issues allowances on the spot market at date 2, then the inventor does not perform R&D: in the case of innovation, the government 'expropriates' the inventor's innovation by putting arbitrary pressure on the licensing price through its pollution permits policy.

Discussion of the timing

We have modelled the competition between the government and the innovator as a Stackelberg price game. Clearly, simultaneous Bertrand competition (in which simultaneously the inventor sets a license fee and the government picks a price for pollution permits) would yield a different outcome. Namely, there can be equilibria at which the innovator takes the entire market at licensing fee p such that $W_0(p) = W_1(p)$, i.e. $\lambda pN(p) = D(N(p))$. The gain in tax revenue for the government at such points is just offset by the pollution cost of taking the market away from the innovator, and so the government does not want to undercut the innovator. Note also that such prices may not even exist. Indeed, if the shadow cost of public funds is small, then the innovator charges her monopoly price under simultaneous Bertrand competition.

So, how reasonable is our timing assumption? Note that the government can give all agents the option to purchase pollution permits at a very low price with a stiff enough penalty if the government breaches the contract. The innovator's only possible reaction is then to undercut the permits price. Furthermore, the agents should rationally anticipate this outcome and not sign up early at a high price with the innovator. Thus, we feel that the Stackelberg timing makes more sense here than it does in other price competition games.

4. Advance allowances

This section shows that, while spot markets may destroy incentives for innovation (see Section 3), futures markets bring limited improvement. To prevent the ex post expropriation of the innovation described in the previous section, we assume that the government can commit not to issue permits on a spot market in period 2. However, the government may want to issue at date 1 advance allowances, since innovation may not occur. We assume that the government issues $\bar{n}$ advance allowances at date 1, where each allowance is a right to emit one unit of pollution at date 2.

The key assumption here is that these allowances are *plain* allowances, i.e. they are not indexed by a contingency (namely, by the occurrence of innovation), nor do they contain options that would indirectly make their use contingent upon the state of nature. We observe that advance allowances still provide suboptimal incentives for innovation and may induce a suboptimal adoption. In the case of innovation, *the spot price adjusts downward so as to allow permits to compete with the innovation*. By exerting price pressure on the licenses of the innovation, allowances devalue the innovator's property right and reduce the incentive to innovate. Furthermore, they have no built-in mechanism that phases them out in the presence of innovation.

Let us first assume that the innovator is not allowed to trade on the permits market. Suppose that the inventor innovates. Unless the equilibrium price for pollution control (through either a license from the innovator or a permit) is equal to zero (in which case the innovation does not take place anyway), the existing $\bar{n}$ permits are used ex post even though the innovation could completely eradicate pollution. As earlier, let $N(p)$ denote the second-period demand curve, with inverse demand $P(n)$. And consider the following timing after the innovation occurs: (a) the innovator sets a license price p; (b) then the market for permits clears. Either $p \geq P(\bar{n})$ and no license is sold (which is not optimal for the innovator), or $p < P(\bar{n})$ and the innovator de facto picks the price on the spot market for permits. The number of licenses sold is then $[N(p) - \bar{n}]$. So, *the level of pollution is the same as in the absence of innovation*. The only positive effect of innovation is that it allows more potential polluters to produce.

Let us now analyze the innovator's choice of pricing and R&D intensity. Let $p^{m}(\bar{n})$ denote the constrained monopoly price for the innovator:

$$p^{m}(\bar{n}) = \arg\max\{p[N(p) - \bar{n}]\}\,. \tag{3}$$

The permits play the role of a competitive fringe and, by a standard revealed preference argument, force the innovator to charge a lower license price than she would charge in their absence. Let $\Pi^{m}(\bar{n})$ denote the resulting maximand. The innovator chooses R&D level x so as to solve:

$$x = \arg\max\{x\Pi^{m}(\bar{n}) - C(x)\}\,. \tag{4}$$

To summarize: the sale of advance permits has two perverse effects compared with the situation where there are no permits. First, the permits partially prevent the adoption of a superior, pollution-free technology. Secondly, they reduce the innovator's profit and therefore incentive to innovate (this incentive is already suboptimal in the absence of permits because the innovator does not internalize the increase in 'consumer surplus' brought about by the innovation). However, pollution permits are useful in the state of nature in which there is no innovation.

Let us now allow the innovator to trade on the permits market. In the absence of licensing costs, the innovator's profit is independent of the number of permits she purchases. When purchasing $n \leq \bar{n}$ permits, she faces the residual demand curve $N(p) - (\bar{n} - n)$, pays np and has profit $p[N(p) - \bar{n}]$. The innovator's incentives are the same as when she is not allowed to purchase permits. But, if $n = \bar{n}$, the $\bar{n}$ units of pollution are eradicated, and welfare is higher than when the innovator does not trade in the permits market.

Unfortunately, the innovator's (weak) willingness to buy permits on the market in the case of innovation disappears when she faces an arbitrarily small marginal cost ϵ of licensing. The innovator's profit, $(p - \epsilon)[N(p) - (\bar{n} - n)] - pn$, is then a strictly decreasing function of the number of repurchased permits, n. Allowing the innovator to trade on the market then has no effect.

Proposition 2. Suppose that the government sells $\bar{n}$ advance allowances at date 1, and can commit not to issue any further permits on the spot market at date 2. (i) In the case of innovation, the $\bar{n}$ permits act as a competitive fringe for the innovator. The allowances (inefficiently) play a dual role in fixing the level of pollution in the absence of innovation, and of determining the inventor's profit in the case of innovation. (ii) The inventor's profit is independent of whether she can purchase the allowances from the agents. In the presence of licensing costs, the inventor does not repurchase the allowances, and the level of pollution is $\bar{n}$, whether innovation occurs or not.

The crux of the matter is that none of the date-2 market participants (polluters, innovator) internalizes the social cost of pollution of the leftover permits. To induce market participants to phase out the wasteful permits in the case of innovation, one possibility is to replace these permits to pollute by options with a striking price γ exceeding the marginal licensing cost ϵ of the innovator. *In contrast to final sales of permits, sales of options have the desirable property that they provide incentives to make full use of the innovation and therefore to retire previous rights to pollute.* They furthermore have a beneficial impact on the incentive to innovate because they restore some of the innovator's monopoly power lost with the issuance of permits (more on this in Section 6). Alternatively the government, which internalizes the social cost of pollution of the leftover permits, could respond to innovation by buying back some permits. The government could also purchase the innovation from the innovator (see Section 7).

5. Procurement: The optimal ex ante contract

In contrast with the market-oriented approach of the previous section, this section considers the ideal planning solution. We make the assumption that the government can ex ante identify the potential innovation (it can ex ante describe the innovation or at least recognize when an innovation eliminates pollution) and designs an incentive contract for the innovator so as to maximize social welfare.

The government optimally issues no advance permits at date 1. Rather it promises to purchase the innovation at some price q. Once the government acquires the (exclusive) property rights on the innovation, it sells the license at the Ramsey price for the pollution-free technology, namely the price p_1^* that solves

$$\eta \equiv \frac{-\mathrm{d}N/\mathrm{d}p}{N/p} = \frac{\lambda}{1+\lambda}\,. \tag{5}$$

Let W_1^{R} denote the associated social welfare. Similarly, let W_0^{R} denote social welfare when there is no innovation and the government sells the corresponding optimal number of permits in period 2.[3] The innovator reacts to incentive q by choosing x so as to maximize $\{xq - C(x)\}$ or

$$C'(x) = q\,. \tag{6}$$

The optimal procurement policy consists in choosing q, or equivalently x, so as to maximize

$$\begin{aligned} &xW_1^{\mathrm{R}} + (1-x)W_0^{\mathrm{R}} - (1+\lambda)xq + [xq - C(x)] \\ &= xW_1^{\mathrm{R}} + (1-x)W_0^{\mathrm{R}} - C(x) - \lambda x C'(x). \end{aligned}$$

We obtain:

$$W_1^{\mathrm{R}} - W_0^{\mathrm{R}} = (1+\lambda)C'(x^*) + \lambda x^* C''(x^*)\,. \tag{7}$$

For instance, in the case of a quadratic cost function ($C'(x) = xC''(x)$), we have

$$q^* = \frac{W_1^{\mathrm{R}} - W_0^{\mathrm{R}}}{1+2\lambda}.$$

[3] W_1^{R} and W_0^{R} are equal to the maximal values of $\left\{-\tilde{D}(N(p)) + (1+\lambda)pN(p) + \int_p^{\infty} N(x)\mathrm{d}x\right\}$ for $\tilde{D}(\cdot) \equiv 0$ and $\tilde{D}(\cdot) \equiv D(\cdot)$, respectively.

Because it is costly to leave rents to the innovator, the price $q^* = C'(x^*)$ is lower than the social value of the innovation computed at the shadow cost of public funds $[(W_1^R - W_0^R)/(1+\lambda)]$.

6. Implementation of the social optimum through options or trade-in provisions

Suppose now that, unlike in Section 5, the government is unable to write an ex ante contract with the innovator. For example, the current administration may not be able to promise an inventor a prize to be paid by the next administration. Is it nevertheless possible to implement the procurement outcome through market-based instruments? The analysis of Sections 3 and 4 demonstrates that such instruments must be more sophisticated than plain allowances

Recall that p_0^* and p_1^* are the socially optimal prices in the absence and presence of an innovation ($p_0^* > p_1^*$). Consider the following market-based mechanism. At date 1, the government issues $N(p_1^*)$ securities at some price v_1. The holder of such a security is offered a choice for date 2: either he exercises an option to purchase a pollution permit at price $(p_0^* - \Delta)$ or he redeems the security to the government and receives Δ from it. Let

$$\Delta \equiv p_0^* - p_1^* - \frac{q^*}{N(p_1^*)}.$$

We assume that Δ is positive (this is automatically satisfied if the moral hazard problem is such that the optimal price q^* is small).[4]

Finally, the government specifies at date 1 that an inventor offering a pollution abatement device can license his device and simultaneously repurchase the agents' securities, but must pay a unit tax equal to $p_1^* + \Delta$. Note that the 'net tax' is only p_1^*, because the inventor, who has no use for the permits, then redeems the permits for value Δ to the government.

Remark. The informational (or legal) requirements for levying the previous tax may seem strong. It should be borne in mind that this tax is designed solely to adjust the inventor's profitability. If the actual tax cannot be set close to the optimal tax $(p_1^* + \Delta)$, and if no alternative instrument can be found to provide the inventor with the appropriate profit, then incentives for innovation will be biased; on the other hand, the permits will be phased out properly thanks to the option mechanism.

[4] We can do without this assumption if we assume that there is no free disposal of the security (its holders can be taxed at the level $(-\Delta)$ if $\Delta < 0$).

- In the *absence of innovation*, the fictitious price for the right to pollute is p_0^*. So, $N(p_0^*)$ security holders exercise the option while $N(p_1^*) - N(p_0^*) > 0$ redeem it (the security holders may or may not be the ultimate polluters as long as an efficient second-hand market for pollution rights allows a reshuffling of these rights).
- In the case of *innovation*, let n denote the number of licenses-cum-repurchases chosen by the inventor: $n \leq N(p_1^*)$. When charging price p_1 for the licenses, the inventor makes profit:

$$[p_1 - (p_1^* + \Delta) + \Delta]n = (p_1 - p_1^*)n.$$

So, for n given, the inventor wants to charge as high a price as is consistent with the agent's individual rationality. The latter can refuse to purchase a license and pollute at cost $p_0^* - \Delta$. Hence,

$$p_1 \leq p_0^* - \Delta$$

So, $p_1 = p_0^* + \Delta$, and the inventor's profit is

$$(p_0^* - \Delta - p_1^*)n = q^* \frac{n}{N(p_1^*)}.$$

It is then optimal for the inventor to repurchase all securities. Its profit is then q^* and the number of licenses is $N(p_1^*)$, as desired. Last, the ex ante price v_1 for the securities is set at the highest level that is consistent with individual rationality. We thus conclude:

Proposition 3. The second-best optimum can be implemented through a market for option allowances together with a licensing tax.

7. Ex post licensing to the government

Suppose now that no contract between the potential innovator and the government is signed at date 1, but that the government can purchase the innovation (i.e. an exclusive license from the patent holder) at date 2 and, as in Section 5, sublicense it to the agents. We assume frequent-offer, alternating-move bargaining between the government and the innovator starting at the beginning of date 2. The government issues short-term pollution permits as long as it has not yet agreed with the innovator (so, we are now treating 'period 2' as an infinite-horizon game following period 1). The reader will check that the licensing fee is equal to the one given by the

Nash bargaining solution with reservation value W_0^R for the government (as in Binmore et al., 1986):[5]

$$q = \frac{W_1^R - W_0^R}{2\lambda}. \tag{8}$$

Note that (as is for instance the case for quadratic cost functions) q may exceed q^*. This may seem surprising in view of the asset specificity literature, which emphasizes the role of long-term contracts in reducing expropriation by the buyer and encouraging investment by the supplier through the promise of a high transfer price. There are two differences with the asset specificity literature.

First, the buyer (the government) here partly internalizes the seller's (the inventor's) welfare. The possibility that ex post bargaining will yield a higher licensing price than (ex ante) procurement is nicely illustrated by the case of a very low shadow cost of public funds. The government is then willing ex post to accept almost an infinite licensing price in order not to delay the adoption of the innovation. But it would never agree ex ante to such a price because this would give excessive incentives for R&D.

Secondly, the seller faces limited liability. The utilities are then not quite transferable, and a long-term procurement contract does not maximize total surplus of the two parties. The licensing fee is reduced so as to limit the innovator's rent. This effect differs from the first one. Indeed, it may be the case that ex post licensing leads to more investment than a long-term contract even if the purchaser of the innovation is a private party and does not internalize the inventor's welfare.[6]

The case in which $q > q^*$ actually raises several issues. First, it is not in the interest of the innovator to sign ex ante a contract with the government if this contract specifies only a price for the innovation. On the other hand,

[5] Let β denote the discount factor corresponding to the bargaining periods, $w_1^R \equiv (1-\beta)W_1^R$ and $w_0^R \equiv (1-\beta)W_0^R$ denote the per-period welfares, and q_g and q_i denote the equilibrium offers when the government and the innovator make the offer. Then:

$$q_g = \beta q_i ,$$

and

$$w_1^R - \lambda q_i = w_0^R - \beta\lambda q_g .$$

Eq. (8) corresponds to the limit of q_g and q_i as β tends to 1.

[6] In a private context, the licensing fee is higher (lower) under a long-term contract if the marginal cost C' is concave (convex). For, if V denotes the value of the innovation for the buyer, the commitment price $q^* = C'(x^*)$ satisfies $\max [V - C'(x)]$, while the ex post licensing fee is $q = V/2$.

the innovator may agree to sign a contract that specifies a lump-sum payment and a price for the innovation, as the lump-sum payment may allow the regulator to compensate the innovator while not creating excessive incentives to innovate.[7] Secondly, as in Hart and Moore (1994), an innovator who has signed an ex ante contract might blackmail the government to force it to raise the price from q^* to q to complete the research, if she is indispensable for its completion.

Finally, we have assumed that the innovator does not sell short-term licenses to the agents while bargaining with the government. The possibility of short-term licenses, for example, makes the government more patient in the bargaining process. We have not yet studied the net effect.

Proposition 4. The government may (and does in the case of a quadratic cost function) pay a higher price for the innovation if it signs the contract ex post rather than ex ante. This phenomenon results from two effects, the 'internalization effect' and the 'limited liability effect'.

8. Summary

The purpose of this exploratory paper has been, first, to alert the reader to the negative impact of plain allowance markets on environmental innovations and, second, to suggest some improvements. Stand-alone spot markets enable the government to expropriate an innovation by offering a competing 'technology' (pollution permits) and by putting an arbitrary downward pressure on the licensing price. Advance allowances reduce expropriation but still create very suboptimal incentives for innovation. They have the further drawback that permits are inefficiently used when the innovation occurs. In this respect, options to pollute at a given striking price fare better than allowances because they create private incentives to phase out pollution in the case of innovation.

The paper then studied government procurement and showed that the second-best optimum can be implemented by an option allowance market cum licensing tax. Last, and surprisingly, ex post licensing by the innovator to the government may yield a higher licensing fee than an ex ante contract.

The limited scope of this paper has left many issues unexplored. For example, the role of a futures market as a guide for the agents' individual investments in pollution-abating technologies (which is the focus of our companion paper) was omitted from the analysis. Another desirable exten-

[7] However, such contracts may be unlikely to be observed in practice because of adverse selection considerations (the regulator being wary that the two-part contract could attract mediocre inventors).

sion would describe in more detail the microstructure of the innovation process (see Aghion and Tirole, 1994) and examine how financing, control rights on the process, property rights on the innovation and return from licensing would be optimally split among the several actors (innovator, government, users of the innovation and financiers). These, and the many other extensions, await further research.

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