Pollution Regulation and the Efficiency Gains from Technological Innovation

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Abstract

Previous studies suggest that emissions taxes are more efficient at stimulating the development of improved pollution abatement technologies than other policy instruments, such as (non-auctioned) tradable emissions permits. We present results from a competitive model that cast *some* doubt on the empirical importance of this assertion. For example, we find that efficiency in the market for "environmental R&D" under tradable permits is typically less than 6 percent lower than that under an emissions tax for innovations that reduce pollution abatement costs by 10 percent or less. However the discrepancy is more significant in the case of more major innovations.

We also find that the presence of R&D spillovers per se does not *necessarily* imply large inefficiency in the R&D market. For example, efficiency in the R&D market under a Pigouvian emissions tax is generally more than 90 percent of that in the first best outcome if the private benefit from innovation exceeds 50 percent of the social benefit. Thus the R&D spillover effect must substantially limit the private benefit from R&D in our analysis for there be a potentially "large" efficiency gain from additional policies -- such as research subsidies -- to stimulate innovation.

Key Words: emissions tax; tradable emissions permits; performance standard; R&D; efficiency effects; patents.

JEL Classification Nos.: Q28, O38.

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POLLUTION REGULATION AND THE EFFICIENCY GAINS FROM TECHNOLOGICAL INNOVATION

Ian W. H. Parry*

1. INTRODUCTION

Traditionally, economists have focused on the static efficiency impacts of pollution regulations.[1] These are determined by the environmental benefits and economic costs from instantaneous reductions in pollution, given the current state of technology. In a dynamic context however, the state of technology is endogenous. This means that pollution regulations can also affect efficiency through their impact on the incentives for technological innovation. This paper focuses on the efficiency gain from "environmental R&D" -- that is, R&D into improved pollution abatement technologies -- induced by alternative environmental policy instruments. We refer to this as the *R&D efficiency gain*.

The potential for an R&D efficiency gain arises because of two potential externality problems associated with environmental R&D. First, innovating firms are unlikely to take into account spillover benefits to other firms in an industry that might be able to adopt new abatement technologies. Second -- in the absence of regulation -- firms may lack incentives to adopt technologies that produce environmental benefits.

Previous studies have shown that emissions taxes are potentially more effective at stimulating environmental R&D than other instruments such as (non-auctioned) tradable emissions permits and performance standards.[2] The problem with tradable permits is that the diffusion of cleaner technologies drives down the equilibrium permit price. This reduces the private gains from adopting cleaner technologies, since these gains include the revenues from selling "spare" emissions permits.[3] The problem with a performance standard is that firms may not reduce the level of emissions per unit of output to the ex post optimal level, following the adoption of a cleaner technology. Again, this reduces the private benefit from adopting cleaner technologies. (These issues are discussed in more detail below).

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[1] See for example the survey in Cropper and Oates (1992).

[2] For analytical models see Milliman and Prince (1989), Downing and White (1986), Jung et al. (1996) and Parry (1996). Econometric studies find that environmental policies have had a significant effect on the incentives to invent and adopt cleaner technologies over time (for example Newell et al., 1996), and that these incentives are greater under emissions taxes and tradable emissions permits than command and control regulations (Jaffe and Stavins, 1995).

[3] However this problem could be avoided if the permits were auctioned by the regulatory agency (Milliman and Prince, 1989) or if the regulatory agency were willing to buy back permits at the initial market price (Parry, 1996).

In addition, previous studies have shown that even under an emissions tax (set at the Pigouvian level) the amount of environmental R&D may be suboptimal.[4] This is because an innovating firm may not be able to appropriate the full social benefits from a new technology when there are spillover benefits to other firms. This suggests there may be an important case for stimulating more innovation, either by raising the level of emissions tax or by using supplementary instruments such as research subsidies and prizes.

This paper investigates under what conditions there might be a potentially "large" R&D efficiency gain from using emissions taxes over other policy instruments and from stimulating additional innovation under an emissions tax. We begin by deriving the first-best efficiency gain from environmental R&D using a social planning model. We then derive the R&D efficiency gain in a decentralized version of the model under an emissions tax, a performance standard and tradable emissions permits, assuming the Pigouvian level of regulation is imposed. Simulations of the relative R&D efficiency gain in each case are then presented, using a wide range of values for the relevant parameters.

We find that efficiency in the R&D market is *not* necessarily much lower under tradable permits than emissions taxes, assuming environmental policies are set at ex ante optimal levels. This crucially depends on the potential size of innovations, since this determines whether the impact on the permit price will be substantial or not. For example, the R&D efficiency gain is typically less than 6 percent lower than that under the emissions tax for an innovation that reduces pollution abatement costs by 10 percent or less. It is around 10-40 percent lower for innovations that reduce abatement costs by 40 percent. The relative efficiency discrepancy between the emissions tax and performance standard is somewhat larger, although again is very sensitive to the potential size of innovation. Moreover, the efficiency differences between the policy instruments would be eliminated, more-or-less, if the instruments could be adjusted to their *ex post* Pigouvian levels following innovation.

We also find that the presence of R&D spillovers *per se* does not necessarily imply large inefficiencies in the R&D market. For example, if the private benefit from innovation is 50 percent or more of the social benefit, the R&D efficiency gain under the emissions tax is at least 90 percent of that in the first-best outcome. This is because a "common pool" effect tends to counteract the effect of imperfect appropriability. Competition for a given amount of innovation rent is excessive because firms do not take into account the impact of their research on reducing the likelihood that other firms will obtain imitation rents. However, in cases where the lack of appropriability leads to a more dramatic divergence between the private and social benefits from innovation, the efficiency gains from inducing additional environmental R&D can be more substantial.

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[4] See Biglaiser and Horrowitz (1995) and Parry (1995).

Our model is simplified in a number of respects to keep the analysis transparent and tractable. For example, we ignore heterogeneity among firms and the possibility of strategic behavior in the R&D market. Nonetheless the analysis does provide a useful starting point for assessing under what conditions the R&D efficiency gain from using emissions taxes over other environmental policy instruments, or using additional incentives to stimulate innovation, are likely to be empirically important or not.

The next section outlines the model and derives the first-best R&D efficiency gain from the social planner's optimization problem. The following three sections solve the decentralized version of the model under an emissions tax, performance standard and tradable emissions permits, and present the empirical results. Section 6 concludes and discusses some qualifications to the results.

2. THE SOCIAL PLANNING MODEL[5]

In this section we begin by describing the model assumptions. We then solve the social planner's optimization problem for the first-best level of production, waste emissions and environmental R&D. This enables us to derive the first-best R&D efficiency gain. Finally, we describe some additional assumptions necessary to solve the decentralized version of the model in subsequent sections.

A. Model Assumptions

Throughout the analysis we employ quadratic functional forms; that is, marginal benefits and marginal costs are assumed to be linear. This assumption (in general) enables us to solve the model analytically.[6]

We assume that a large number of identical firms produce a good X that is consumed by households (for example electricity). The inverse demand function for X is $P(X)$, where $P' < 0$ and $P'' = 0$. X is produced under constant returns to scale and the cost per unit of producing X is $c > 0$. Therefore the supply curve of X is perfectly elastic. We choose units of X such that each firm produces one unit.[7]

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[5] The analytical model used below shares some features of that in Parry (1995), which in turn merged a model of the R&D market by Wright (1983) with a model of an environmental externality. The model below differs from that in Parry (1995) by allowing for variability in the emissions to final output ratio, and in considering a wider range of policy instruments. Unlike Parry (1995), we also implement the model empirically.

[6] Our objective is to indicate approximate empirical magnitudes using explicit formulas. To empirically solve the model under non-quadratic functional forms would typically require numerical simulation techniques. This can provide more accuracy, but at the expense of less transparency.

[7] Allowing firms to have U-shaped average cost curves and to choose their level of output does not affect the results of the analysis.

The production of X involves the discharge of waste emissions. These emissions cause environmental damages that are external to the industry.[8] Production firms can reduce their emissions per unit of X by employing inputs in abatement activities.[9] We normalize emissions such that emissions per firm in the absence of abatement activities would be unity. Actual emissions per firm are then $1-\Delta e$ where Δe is the reduction in emissions per unit of X from abatement. The firm's abatement cost function takes the following quadratic form: $a\Delta e^2/2$, where the parameter $a > 0$. Thus the marginal cost of abatement is increasing (this is a typical empirical finding).

Industry emissions are $(1-\Delta e)X$. We assume that environmental damages are $h(1-\Delta e)X$, that is, proportional to total emissions, where the parameter $h > 0$ is marginal environmental damage. (The implications of convex environmental damages are briefly discussed in Section 6).

In addition to the production sector, there is an R&D sector where a large number of firms attempt to invent a new emissions abatement technology. If discovered and adopted this technology would reduce abatement costs in the production sector to $(1-r)a\Delta e^2/2$, that is by a proportionate amount r ($0 < r < 1$).[10] Following Wright (1983), we assume that each R&D firm conducts one independent R&D project, and the number of firms is M. The probability that the new technology will be discovered (by at least one firm) is given by the following quadratic function:

$$\pi(M) = \beta M\left\{1 - \frac{\beta}{4}M\right\} \tag{3.1}$$

where the parameter $\beta > 0$. The maximum value of $\pi(M)$ is unity and $\pi'(M)$ is declining. Thus, at lower levels of M an additional firm can significantly increase the probability of discovery. However as more firms enter the market the probability of discovery approaches one, so that an additional firm has less impact on increasing π.[11]

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[8] For example, the damages to human health, visibility and natural habitat associated with the six criteria pollutants regulated under the Clean Air Act or the damages to drinking water, fish stocks and recreational activities caused by pollutants regulated under the Clean Water Act.

[9] These activities may represent the installation of "end-pipe" abatement technologies such as "scrubbers" to trap air pollutants after fuel combustion or technologies to reduce the toxicity of solid waste. More generally, these activities may represent the substitution of cleaner inputs for dirty inputs in production (for example the substitution of natural gas for coal).

[10] This is a standard way to model an improved abatement technology (see for example Downing and White, 1986, and Milliman and Price, 1989). The technology may have some commercial value if it reduces production cost c (for example an energy-saving technology). We focus purely on the environmental implications of the discovery; that is we assume no effect on c.

[11] Specifying a function relating the probability of innovation to the quantity of R&D is a common approach to modeling the R&D market. More sophisticated models incorporate the possibility of more than one technology being invented (for example Biglaiser and Horrowitz, 1995) and that previous R&D experience may affect the

The total cost of R&D is given by $kM^2/2$, where the parameter $k > 0$. Therefore the marginal cost, or supply curve, of R&D is kM. This is upward sloping, representing the increasing scarcity of specialized inputs, such as scientists and engineers, at higher level of R&D.[12] Finally, we assume interior solutions for R&D throughout the analysis; that is, R&D is always positive, but below the level where $p(M) = 1$.

B. Socially Optimal Outcome

We now derive the state-contingent output and emissions levels, and the quantity of R&D, that maximizes expected social welfare.

(i) Output and Emissions

If the new technology is not discovered, social welfare in this state is maximized by:[13]

$$V_1^* = \underset{\{X_1,\Delta e_1\}}{MAX} \int_0^{X_1} P(X_1)dX_1 - \left\{cX_1 + (a/2)(\Delta e_1)^2 X_1 + h(1-\Delta e_1)X_1\right\}$$

That is, by choosing output and the emissions reduction per firm to maximize consumer benefit (the area under the demand curve), less the sum of production costs, abatement costs and environmental damages. This yields the conditions:

$$a\Delta e_1^* = h \tag{3.2a}$$

$$P(X_1^*) = c + (a/2)(\Delta e_1^*)^2 + h(1-\Delta e_1^*) = c + h\left\{1 - \Delta e_1^*/2\right\} = MC_1^* \tag{3.2b}$$

Equation (3.2a) defines the optimal emissions reduction per firm. This where the incremental abatement cost equals the reduction in environmental damages, per unit of X. From equation (3.2b), the optimal production of X is where the marginal benefit to consumers (the height of the demand curve) equals the marginal social cost of production, MC_1^*. This equals the cost of production, plus the abatement cost, plus the environmental damage from residual emissions, per unit of X.

Following the analogous procedure, maximized social welfare (V_2^*) in the state when the cleaner technology is discovered occurs when:

$$(1-r)a\Delta e_2^* = h \tag{3.3a}$$

$$P(X_2^*) = c + (1-r)(a/2)(\Delta e_2^*)^2 + h(1-\Delta e_2^*) = c + h\left\{1 - \Delta e_2^*/2\right\} = MC_2^* \tag{3.3b}$$

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productivity of current research. For a survey of R&D models see Carlton and Perloff (1990), chapter 20, and Tirole (1988), chapter 10.

[12] Again, allowing R&D to be variable at the firm level does not affect the results if firms have the same U-shaped average cost curve (Wright, 1983).

[13] The no discovery and discovery states are denoted by subscript "1" and "2" respectively.

From (3.2a) and (3.3a):

$$\Delta e_2^* = \Delta e_1^* / (1 - r) \tag{3.4}$$

that is, the optimal emissions reduction per firm with the new technology would be $(1 - r)^{-1}$ times the optimal emissions reduction with the old technology.

Figure 1 illustrates the possible equilibrium, where X_0^* would be optimal production if there were no possibility of abatement activity ($a = \infty$), and the marginal social cost of production would be $c+h$. Using (3.2) and (3.3), the optimal level of production in each state can be expressed:

$$X_1^* = X_0^* - (c + h - MC_1^*) / P' = \left\{1 + \frac{\eta \Delta e_1^*}{2}\right\} X_0^* \tag{3.5a}$$

$$X_2^* = X_0^* - (c + h - MC_2^*) / P' = \left\{1 + \frac{\eta \Delta e_1^*}{2(1 - r)}\right\} X_0^* \tag{3.5b}$$

where

$$\eta = -\frac{h}{X_0^* P'} \tag{3.6}$$

η is the (magnitude of the) elasticity of demand for X at X_0^*, with respect to the shadow price of environmental damages.

From Figure 1, the social benefit from a new technology that reduced the marginal social cost of production from MC_1^* to MC_2^* would be:

$$\Delta V^* = V_2^* - V_1^* = (MC_1^* - MC_2^*) X_1^* + (MC_1^* - MC_2^*)(X_2^* - X_1^*) / 2 \tag{3.7}$$

The first component in equation (3.7) is rectangle $MC_1^* tv MC_2^*$ in Figure 1, which is the reduction in social cost per unit of X, multiplied by optimal output in the no discovery state. The second term is triangle *tuv*, which is the welfare gain from the additional output in the discovery state. Substituting (3.2), (3.3) and (3.5) into (3.7) we can obtain:

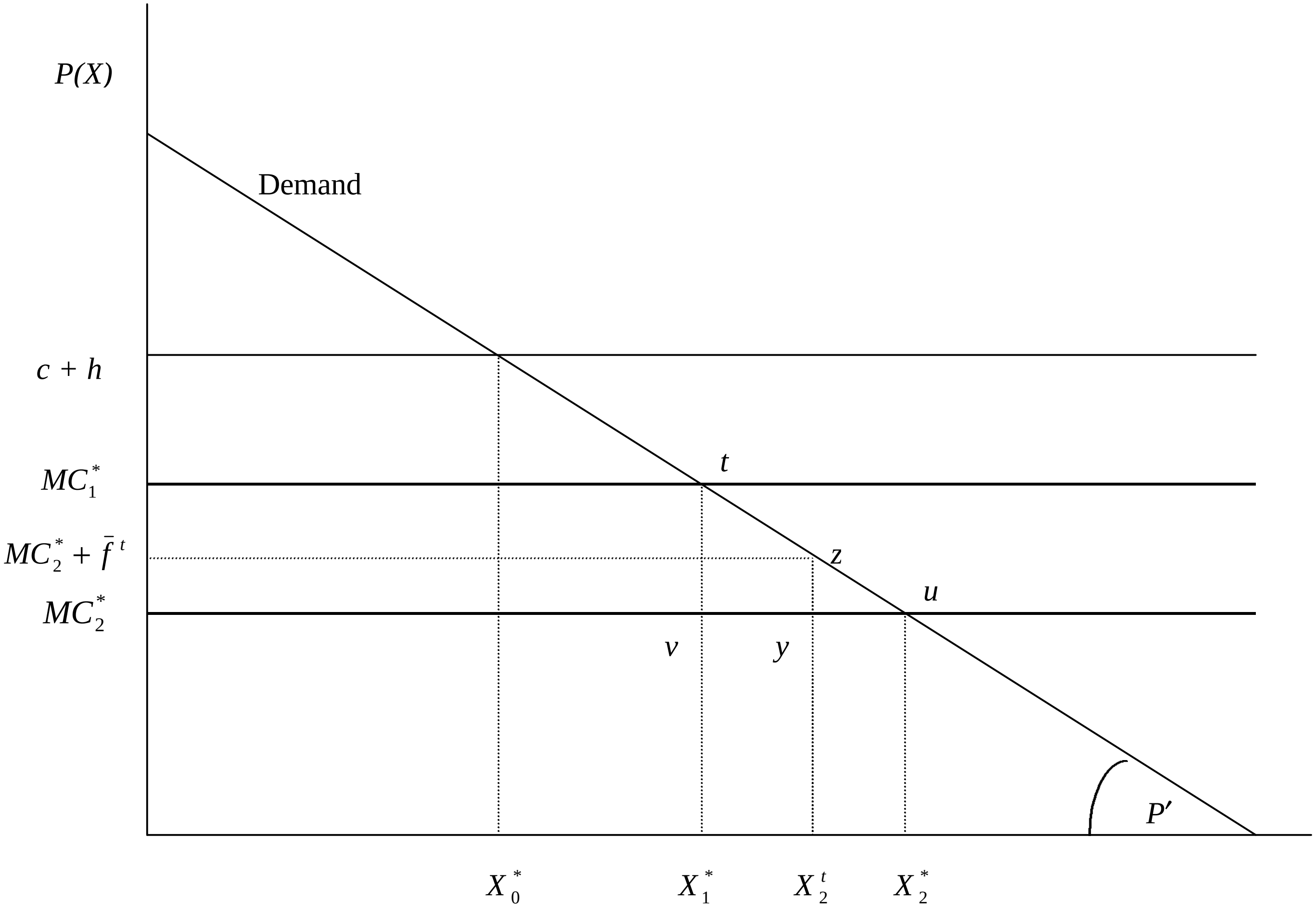
$$\Delta V^* = \left\{1 + \eta \frac{\Delta e_1^*}{4}\left[2 + \frac{r}{1 - r}\right]\right\} \frac{\Delta e_1^*}{2} \frac{r}{1 - r} h X_0 \tag{3.8}$$

(ii) <u>R&D</u>

The expected efficiency gain in the R&D sector is:

$$V(M) = \pi(M) \Delta V^* - kM^2 / 2 \tag{3.9}$$

Figure 1. Optimal Industry Output



This is the probability of discovering the new technology multiplied by the social benefit from the technology, less R&D costs. Maximizing this expression with respect to *M* gives:

$$\mathrm{p}'(M^*)\Delta V^* = kM^* \tag{3.10}$$

This equation equates the (expected) marginal social benefit and marginal social cost of R&D. Using (3.1) and (3.10) the socially optimal quantity of R&D is:

$$M^* = \frac{1}{\mathrm{b}}\left\{\frac{k}{\mathrm{b}^2\Delta V^*} + \frac{1}{2}\right\}^{-1} \tag{3.11}$$

Finally, substituting (3.11) into (3.9) gives

$$V(M^*) = \Delta V^*\left\{1 + \frac{2k}{\mathrm{b}^2\Delta V^*}\right\}^{-1} \tag{3.12}$$

This expression is the R&D efficiency gain in the first-best outcome.

C. Additional Assumptions in the Decentralized Market Model

The rest of this paper examines outcomes in a decentralized market version of the model. To do this requires some additional assumptions. First, we assume that the production and R&D markets are competitive, hence (in the absence of regulation) firm entry occurs until profits are zero. Thus, we do not consider the complications posed by non-competitive behavior when the number of production or R&D firms is relatively small.[14]

Second, we assume that R&D firms can appropriate (part of) the returns from innovation by obtaining a patent and then licensing the new technology to production firms. More generally, an innovating firm may use the technology itself and not license to other firms, thereby gaining monopoly rents. However when the product market is competitive, and the innovator does not face capacity constraints or increasing marginal costs, then the returns from licensing or producing with the technology itself are equivalent (Carlton and Perloff (1990), chapter 20). Following Wright (1983) we assume that if two or more firms discover the new technology then the patent is awarded at random to one of them.[15] Therefore the ex ante probability that an R&D firm will win the patent is $\mathrm{p}(M)/M$; that is the probability of the discovery being made, divided by the number of R&D firms. The amount of R&D is determined by:

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[14] In fact, Oates and Strassmann (1984) suggest that the empirical significance of non-competitive product markets for environmental policies may not be that large. Many R&D models in the Industrial Organization literature assume non-competitive behavior (see Tirole (1988) Ch.10 for a survey). However there are a plethora of different types of models and it would be somewhat ad hoc to use one of them in preference to all the others. Moreover, it makes some sense to start with the much more simple case of competition. Future investigations may then relax this assumption to assess whether this makes a significant empirical difference to the results or not.

[15] In patent races in the U.S. the patent is granted to the firm that can prove it made the discovery first.

$$\frac{\pi(M)}{M}F = kM \tag{3.13}$$

where F is the revenue from licensing the new technology to production firms. Equation (3.13) says that R&D firms will enter the market until the expected or average benefit per firm -- the probability of winning the patent times revenue from the patent -- equals the cost of the last firm.

Our third additional assumption is to incorporate an *imitation effect* into the analysis. Empirical evidence (for commercial innovations) suggests that the private returns to innovation are well below the social returns. In the case of patented technologies, this is because firms may develop their own imitations by "inventing around" a patented technology using, for example, information disclosed in the patent application.[16] However the patent holder is typically able to appropriate at least some rents, because imitation occurs only after a lag (Mansfield et al., 1981). We cannot include a lagged imitation effect into our one period model. Instead we assume that production firms *could* each imitate the new technology and these imitations would reduce their abatement costs in proportion by $\mu\rho$, where $0 \leq \mu < 1$. Although no imitation actually occurs in equilibrium, the *threat* of imitation limits the ability of a patent holder to appropriate the full social returns from innovation.

3. EMISSIONS TAX

We now compare the R&D efficiency gain under a Pigouvian emissions tax on emissions with that in the first-best outcome. Given our assumption of constant marginal environmental damages the Pigouvian tax does not change following innovation. Therefore (unlike the other policy instruments) we do not distinguish between cases where the policy maker can and cannot adjust the environmental policy over time. In subsection A, we discuss the qualitative differences between the first-best outcome and that under the emissions tax. Subsection B presents a quantitative comparison.

A. Model Solution

(i) Output and Emissions

Suppose the new technology is not discovered. The private (total) cost per production firm would be $C_1^t = c + a(\Delta e_1)^2/2 + h(1-\Delta e_1)$; that is, the sum of production cost, abatement cost and the tax paid on residual emissions.[17] Firms choose Δe to minimize C_1^t, which gives condition (3.2a). Thus $C_1^t = MC_1^*$; that is the marginal private cost equals the marginal social

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[16] For empirical studies on the imitation of patented commercial innovations see Mansfield (1985) and Levin et al. (1987).

[17] We use superscript "*t*", "*s*" and "*p*" to denote outcomes under an emissions tax, a performance standard and tradable emissions permits respectively.

cost of producing *X*. Production firms enter the market until price equals C_1^t, and therefore the socially efficient level of production in Figure 1, X_1^*, is induced.

Now consider the state when the new technology is available. If the patent holder charges a fee of *f* to license the technology, the private cost of a production firm adopting the technology is $C_2^t = c + (1-r)a(\Delta e_2)^2/2 + h(1-\Delta e_2) + f$.[18] Minimizing this expression with respect to Δe_2 gives condition (3.3a). Therefore the socially optimal amount of emissions per firm is induced. However, the private cost per production firm is:

$$C_2^t = MC_2^* + f \tag{4.3b}$$

that is, it exceeds the social cost per firm by the license fee. Equilibrium production is where price equals C_2^t, or analogous to (3.5):[19]

$$X_2^t(f) = X_0^* - (c + h - C_2^t)/P' \tag{4.5}$$

When choosing the license fee the patent holder is subject to a constraint. Private costs to production firms from producing with the licensed technology must not exceed those from producing with the imitation; if they do there will be no demand for the new technology and patent holder revenue would be zero. If a production firm used the imitation, private cost per firm would be $C_2^{t,I} = c + (1-\mu r)a(\Delta e_2)^2/2 + h(1-\Delta e_2)$. Minimizing this expression with respect to Δe and using (3.2a) we can obtain:

$$C_2^{t,I} = c + h\left\{1 - \frac{\Delta e_1^*}{2(1-\mu r)}\right\}$$

Equating this with C_2^t, and using (3.3b) and (4.3b), the maximum license fee constraint is:[20]

$$f \le \bar{f}^{\,t} = \frac{h\Delta e_1^*}{2}\frac{(1-\mu)r}{(1-\mu r)(1-r)} \tag{4.14}$$

The patent holder chooses *f* to maximize revenue $F^t = fX_2^t(f)$ subject to the constraint (4.14). It is straightforward to verify that the constraint in (4.14) is binding so long as:

$$\eta\frac{\Delta e_1^*}{1-r}\left\{\frac{r-(1+\mu r)/2}{1-\mu r}\right\} < 1 \tag{4.15}$$

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[18] More generally, patent holders may charge a fee per unit of emissions abatement. However this scheme would be privately (as well as socially) inefficient in the sense of reducing abatement below the optimal level. Per unit license fees are more likely when the patent holder is uncertain about the costs savings to firms from adopting the new technology.

[19] Since production firms are homogeneous, if it is profitable for one firm to license the technology, then it is profitable for all firms to license the technology.

[20] If there were no possibility of imitation ($\mu = 0$) the constraint on *f* is that private costs from licensing the new technology do not exceed those from continuing to use the original technology.

This condition is satisfied for the range of parameter values considered below. Therefore using (3.3b), (4.3b), (4.5) and (4.14), output under the emissions tax is:

$$X_2^t = \left\{1+\frac{\eta\Delta e_1^*}{2(1-\mu r)}\right\}X_0^* \tag{4.5b}$$

Comparing (3.5) and (4.5b), $X_1^* \leq X_2^t < X_2^*$. Therefore production in the discovery state would be *less* than the socially optimal level. This is because of a monopoly pricing effect associated with patents. It would be socially efficient to allow firms to adopt the cleaner technology free of charge. However, they have to pay a license fee that raises their costs and reduces the level of output. In terms of Figure 1, welfare from diffusing the cleaner technology is lower under the emissions tax than in the first-best outcome by triangle *zuy*, which has base $X_2^* - X_2^t$ and height $\bar{f}^t$. Using (3.5b), (4.5b) and (4.14), this has area:

$$\left\{\Delta e_1^* \frac{1-\mu}{1-\mu r}\frac{r}{1-r}\right\}^2 \frac{\eta h X_0^*}{8}$$

Subtracting this expression from ΔV^* in (3.8) gives the social benefit from diffusing the cleaner technology under the emissions tax:

$$\Delta V^t = \left\{1+\eta\frac{\Delta e_1^*}{4}\left[2+\frac{r}{1-r}\left(1-\left(\frac{1-\mu}{1-\mu r}\right)^2\right)\right]\right\}\frac{\Delta e_1^*}{2}\frac{r}{1-r}hX_0 \tag{4.8}$$

(ii) R&D

Multiplying (4.5b) by the expression in (4.14), patent holder revenue is:

$$F^t = \left\{1+\frac{\eta\Delta e_1^*}{2(1-\mu r)}\right\}\frac{\Delta e_1^*}{2}\frac{1-\mu}{1-\mu r}\frac{r}{1-r}hX_0 \tag{4.16}$$

From (3.1) and (3.13), the equilibrium quantity of R&D is:

$$M^t = \frac{1}{\beta}\left\{\frac{k}{\beta^2 F^t}+\frac{1}{4}\right\}^{-1} \tag{4.11}$$

Comparing (3.11) and (4.11), R&D may be above or below that in the first-best outcome. Firms enter the R&D market until the average benefit per firm, rather than the marginal benefit, equals the marginal cost.[21] Since the average probability curve, $\pi(M)/M$, lies above the marginal probability curve, $\pi'(M)$, this would generate an excessive amount of R&D if

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[21] Only if the R&D market were monopolistic rather than competitive, would the equilibrium be where *marginal* rather than *average* private benefit equals marginal cost.

$F = \Delta V^*$. This is because of an externality problem associated with competition for patent rents: R&D firms do not take into account the impact of their entry on reducing the probability that the other firms will win the patent. This has been referred to as the *common pool effect*, since it is analogous to the over-exploitation of common pool resources such as open-access fisheries.[22] However the private benefit from innovation, area $(MC_2^* + \bar{f}^t)zyMC_2^*$ in Figure 1, is below the social benefit from innovation in the first-best case, area $MC_1^* tuMC_2^*$. Essentially, this is because the threat of imitation reduces the maximum license fee below the reduction in social cost per firm, $MC_1^* - MC_2^*$.

Using (3.1) and (4.11), the efficiency gain from R&D under the emissions tax can be expressed:

$$V(M^t) = \pi(M^t)\Delta V^t - k(M^t)^2 / 2 = \left\{ \frac{\Delta V^t}{F^t} - \frac{1}{2} \right\} \left\{ \frac{k}{\beta^2 F} + \frac{1}{4} \right\}^{-2} \frac{k}{\beta^2} \qquad (4.12)$$

B. Parameter Values

The previous subsection illustrated three reasons -- the monopoly pricing effect, the common pool effect and the imitation effect -- why the R&D market under the emissions tax is potentially less efficient than in the first-best outcome. We now investigate under what conditions these imperfections are empirically important in our model by presenting some simulations on the R&D efficiency gain under the emissions tax $V(M^t)$, expressed as a proportion of that in the first-best case $V(M^*)$. To do this requires plausible values for five parameters. The ranges chosen for these parameters are necessarily somewhat arbitrary. *However,* we consider a wide range of parameter values, and -- with the exception of μ-- the results are not especially sensitive to alternative parameter values. That is, varying parameter values changes the R&D efficiency gain under the emissions tax and in the first-best case by approximately the same proportion.

We consider three scenarios for the potential proportionate reduction in abatement costs from the innovation: $r = 0.01$, 0.1 and 0.4. These cases span the range from a very minor innovation to a major innovation. η is defined with respect to environmental damages rather than the price of output and therefore is less than the elasticity of demand for X at X_0^*, conventionally defined. We consider a range of 0.1 to 2 for this parameter, with a benchmark value of 0.5. The optimal proportionate reduction in emissions per unit in the no discovery state, Δe_1^*, is equal to marginal environmental damage divided by the slope of the marginal abatement cost function. We assume a range of 0.05 to 0.5 for this "parameter", with a

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[22] For more discussion see Wright (1983). R&D may still be excessive when the R&D market is not competitive. This can occur when the rents from innovation come at the expense of pure profits of existing firms. See Dasgupta and Stiglitz (1980), Loury (1979), and Lee and Wilde (1980).

benchmark value of 0.2. The ratio $k / b^2 h X_0^*$ reflects the slope of the marginal cost of R&D relative to the slope of the marginal probability function (h and X_0^* are exogenous). We choose this “parameter” to imply the probability of discovering the cleaner technology in the first-best outcome lies between 0.35 and 0.9, with a benchmark case of 0.65. This range is (almost) the largest possible that is consistent with interior solutions under all the policy instruments considered. Finally, roughly speaking the private benefit from innovation is reduced below the social benefit in proportion to the imitation effect, represented by m We consider scenarios where imitation reduces the private benefit by up to 75 percent below the social benefit, and assume a 50 percent reduction in our benchmark case.[23] Condition (4.15), and similar conditions for the other policy instruments derived below, are satisfied for this range of parameter values .

C. Simulations

Table 1 presents our calculations of $V(M^t) / V(M^*)$ using these parameter values and equations (3.8), (3.12), (4.8), (4.12) and (4.16). The main point from this table is that imitation per se does not *necessarily* imply large inefficiency in the R&D market. In our benchmark case when the private benefit from innovation is 50 percent of the social benefit, the R&D efficiency gain is still 92-97 percent of that in the first-best outcome. The main reason for this is that the common pool effect counteracts the imitation effect. Indeed in some simulations -- denoted by * in the table -- the common pool effect dominates and R&D under the emissions tax exceeds that in the first-best outcome. In addition, when R&D differs from the socially optimal level the efficiency loss tends to be “small” relative to the total efficiency gain in the R&D market, because the incremental efficiency gain from R&D is declining. For example, if R&D were 25 percent less than in the first best case, the R&D efficiency gain is still around 94 percent of the first-best R&D efficiency gain. Nonetheless, when the imitation effect is substantial inefficiency in the R&D market can be more significant. For example, when the private benefits from innovation are 25 percent of the social benefits the R&D efficiency gain under the emissions tax falls to 63-79 percent of that in the first-best outcome (assuming benchmark values for other parameters).

An additional result of interest is that the relative efficiency loss from the monopoly pricing effect (triangle *zuy* in Figure 1), is very small. This is because it is a second order effect. In all the simulations the social benefit from diffusion of the new technology (area $MC_1^* tzy MC_2^*$) is at least 96 percent of that in the first-best outcome (area $MC_1^* tu MC_2^*$).

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[23] Estimates of the social rate of return vary widely across different case studies. In Mansfield’s (1977) study of 17 innovations, the median social rate of return is roughly twice the private rate of return. However, the social rates of return vary by a factor of more than 20.

Table 1. The R&D Efficiency Gain from an Emissions Tax
(relative to that in the first-best case)

		proportionate reduction in abatement cost		
		0.01	0.1	0.4
Benchmark case		.92	.94	.97
m	0	.93*	.93*	.91*
	.25	1.00*	1.00*	.95*
	.75	.63	.66	.79
$p(M^*)$	.35	.83	.85	.91
	.9	1.00*	1.00*	1.00*
h	.1	.92	.93	.98
	2.0	.94	.95	.96
Δe_1^*	.05	.81	.83	.90
	.5	1.00	1.00*	.96*

4. PERFORMANCE STANDARD

We now consider a performance standard. A performance standard specifies the maximum emissions per unit of production. In the current homogeneous firm model, it differs from an emissions tax in two respects. First, to maintain emissions abatement at the optimal level, the standard must be tightened in the event that the new technology is discovered (no adjustment in the emissions tax is required). In practice a regulatory agency can adjust an emissions standard over time in response to changing technology, but not in response to every individual innovation. Thus in subsection A we consider two cases which span the range of possibilities: a fixed performance standard and a flexible standard that adjusts to the ex post optimal level following innovation. Second, in the absence of a production control the number of firms producing X, and hence the total amount of pollution, would be inefficiently high because firms are not charged for their residual emissions (Spulber, 1985; Goulder et al., 1997). This creates a greater demand for innovation and would “distort” the comparison with other policy instruments. To avoid this problem, we assume that there is also a quota that limits production to the socially optimal amount. Subsection B presents the empirical results for the fixed and flexible performance standard.

A. Model Solution

(i) Fixed Standard

In the no discovery state, emissions per firm are constrained to the efficient level $1-\Delta e_1^*$, and the quota limits production to X_1^*. The private cost per firm, $C_1^s = c + a(\Delta e_1^*)^2/2$, is less than the social cost MC_1^* because firms are not charged for their residual emissions $1-\Delta e_1^*$.

In the discovery state the allowable level of emissions per firm remains at $1-\Delta e_1^*$. If a production firm were to license the new technology, the private cost to that firm would be $C_2^s = c + (1-r)a(\Delta e_1^*)^2/2 + f^s$. If instead a production firm used the imitation, the private cost would be $C_2^{s,I} = c + (1-\mu r)a(\Delta e_1^*)^2/2$. The maximum license fee (when $C_2^s = C_2^{s,I}$), is therefore (using (3.2a))

$$\bar{f}^s = \frac{h\Delta e_1^*}{2}(1-\mu)r \tag{5.14}$$

Using (5.14) and (3.5a), patent holder revenue, $\bar{f}^s X_1^*$, is:

$$F^s = \left\{1+\eta\frac{\Delta e_1^*}{2}\right\}h(1-\mu)r\frac{\Delta e_1^*}{2}X_0^* \tag{5.16}$$

Since emissions remain at $1-\Delta e_1^*$, the social cost per production firm using the new technology is:

$$MC_2^s = c + (1-r)a(\Delta e_1^*)^2/2 + h(1-\Delta e_1^*) = c + h\left\{1 - \frac{(1+r)\Delta e_1^*}{2}\right\}; \tag{5.3b}$$

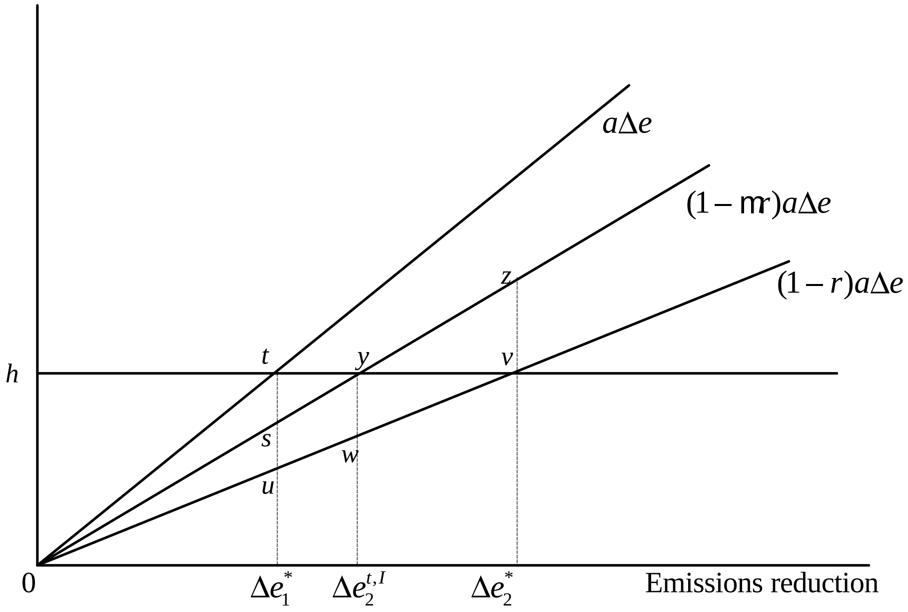
The social benefit from diffusion of the cleaner technology is $\Delta V^s = (Z_1^* - Z_2^s)X_1^*$; that is the reduction in social cost per firm times the number of firms, which remains at X_1^*. Using (3.2b), (3.5a) and (5.3b) this can be expressed:

$$\Delta V^s = \left\{1+\eta\frac{\Delta e_1^*}{2}\right\}\frac{\Delta e_1^*}{2}rhX_0^* \tag{5.8}$$

Figure 2 illustrates two important differences between the performance standard and the emissions tax. First, under the emissions tax the social gain per production firm from adopting the cleaner technology consists of triangle *0tu* plus triangle *tvu*. These are the reduction in abatement cost at the initial level of abatement and the gain from the additional emissions reductions from Δe_1^* to Δe_2^*, respectively. Under the fixed performance standard the social gain per firm only consists of triangle *0tu*. Second, under the emissions tax the private gain from using the cleaner technology rather than the imitation consists of triangle *0yw* plus triangle *yvw*. These are the reduction in abatement cost for an emissions reduction of $\Delta e_2^{t,I}$ and the private gain from increasing emissions reductions to Δe_2^* respectively. Under the performance standard the private gain is *0su*, since emissions reductions are fixed at Δe_1^*. Hence the willingness to pay for the cleaner technology, and patent holder revenue, are lower under the performance standard.

Finally, for a given quantity of patent holder revenue the level of R&D is determined in the same way as under the emissions tax. Hence the R&D efficiency gain is determined by equation (4.12), given the appropriate substitutions for F and ΔV.

Figure 2. Optimum Abatement per Firm



(ii) Flexible Standard

Now suppose that the required emissions reduction increases to Δe_2^*, and the level of production is restricted to X_2^*, in the case when the new technology is discovered. Following a similar procedure to that above, we can obtain:

$$\Delta V^s = \Delta V^* \qquad (5.8')$$

$$F^s = \frac{h\Delta e_1^*}{2}\frac{(1-\mu)r}{(1-r)^2}\left\{1+\frac{\eta\Delta e_1^*}{2(1-r)}\right\}X_0^* \qquad (5.16')$$

Equation (5.8′) says that the social benefit from diffusing the new technology equals that in the first-best case. This follows because both emissions and output are adjusted to their ex post optimal levels in the discovery state. Comparing (5.16′) with (4.16), patent holder revenue exceeds that under the emissions tax. This occurs for two reasons. First, the private gains from using the cleaner technology, as opposed to the imitation, are greater in Figure 2 by triangle *yzv* than under the tax, since the required emissions reduction in the discovery state is fixed at Δe_2^*. This raises the maximum license fee that production firms are willing to pay. Second, the equilibrium number of production firms is greater ($X_2^* > X_2^t$ in Figure 1).

B. Simulations

The upper half of Table 2 shows the R&D efficiency gain under the fixed emissions standard, expressed relative to that under the emissions tax (using equations (4.8), (4.12), (4.16), (5.8), (5.16), and the previous parameter ranges). These simulations suggest that the R&D efficiency gain may be significantly lower under the fixed performance standard than under the emissions tax. However, this result is very sensitive to the potential size of the innovation. The R&D efficiency gain under the performance standard is about 15-20 percent lower than under the tax, for an innovation that would reduce abatement costs by 10 percent. It is 1-3 percent and 46-71 percent lower for innovations that would reduce abatement costs by 1 percent and 40 percent respectively. The explanation for this is clear from Figure 2. The larger the reduction in (marginal) abatement costs, the greater is the size of triangle *tuv* relative to triangle *0tu*. Hence the greater is the social benefit from diffusion of the cleaner technology under the emissions tax relative to that under the performance standard. In addition, the larger the innovation, the larger the size of area *syvu* relative to area *0su*, hence the greater is patent holder revenue under the emissions tax relative to that under the performance standard. This implies lower efficiency under the performance standard (in cases when R&D is below the first-best level).

The lower half of Table 2 shows the R&D efficiency gain under the flexible performance standard expressed relative to that under the emissions tax (using equations (4.8), (4.12), (4.16), (5.8′) and (5.16′)). In general these estimates are very close to unity implying that the R&D efficiency gain under the flexible performance standard is almost identical to that under the emissions tax. This is because the social gain from diffusion is greater when the performance standard is flexible than when it is fixed. However, the flexible standard is more likely to generate an excessive amount of R&D because firms' willingness to pay for the new technology exceeds that under the emissions tax by triangle *yzv* in Figure 2. This is especially the case when the reduction in abatement costs -- and hence triangle *yzv* -- is "large" and when the imitation effect is weak.[24]

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[24] For example, when the proportionate reduction in abatement costs is 40 percent and there is no imitation effect, R&D under the flexible performance standard exceeds the first best level by 80 percent!

Table 2. The R&D Efficiency Gain from an Emissions Standard
(relative to that under the emissions tax)

		proportionate reduction in abatement cost		
		0.01	0.1	0.4
A. Fixed Standard				
Benchmark case		.98	.82	.37
m	0	.99	.85	.40
	.25	.98	.84	.43
	.75	.97	.77	.29
$p(M^*)$	.35	.98	.79	.33
	.9	.99	.87	.50
h	.1	.98	.81	.38
	2.0	.98	.81	.37
Δe_1^*	.05	.98	.79	.33
	.5	.99	.86	.46
B. Flexible Standard				
Benchmark case		1.00	1.02	1.02
m	0	.99	.94	.38
	.25	1.00	.99	.78
	.75	1.00	1.02	1.09
$p(M^*)$	.35	1.00	1.03	1.09
	.9	1.00	1.00	.88
h	.1	1.00	1.02	1.01
	2.0	1.00	1.02	1.01
Δe_1^*	.05	1.00	1.00	1.10
	.5	1.00	1.00	.89

5. TRADABLE EMISSIONS PERMITS

We now examine the efficiency impact of tradable emissions permits in the R&D market. Unlike in the previous cases, the equilibrium conditions are non-linear and obtaining analytical solutions would be very complicated. Instead we characterize the equilibrium conditions and solve the model computationally. Analogous to the previous section, we consider cases where the quantity of permits is fixed at the ex ante Pigouvian level and where the quantity of permits is adjusted to the ex post Pigouvian level if the cleaner technology is discovered. As discussed below, we regard the former assumption as probably the more realistic.

A. Equilibrium Conditions

(i) Fixed Permits

Suppose emissions are limited by the Pigouvian quantity of permits, that is X_1^* firms are each given $1-\Delta e_1^*$ emissions permits. In the no discovery state production and emissions are optimal and the permit price equals marginal environmental damages, *h*. If these firms could adopt the new technology, the marginal abatement cost curve would pivot down to $(1-r)a\Delta e$ in Figure 2. Therefore the privately optimal level of emissions abatement would increase above Δe_1^* (at the initial permit price). This means that firms have “spare” emissions permits. These permits can be sold to “entrants”; that is, firms who previously could not produce *X* because they had no emissions permits.[25] The private cost of an entrant licensing the new technology would be $C_2^p = c + (1-r)a(\Delta e_2)^2/2 + q_2(1-\Delta e_2) + f$, where q_2 is the permit price and $q_2(1-\Delta e_2)$ is the cost of purchasing the enough permits to cover residual emissions. The net private cost of an initial permit holder is $C_2^P - q_2(1-\Delta e_1^*)$; that is, lower than the cost to an entrant by the rents from the initial (exogenous) permit endowment.

Minimizing C_2^P, the privately optimal emissions reduction for both entrants and permit holders is defined by:

$$(1-r)a\Delta e_2 = q_2 \tag{6.3a}$$

Hence:

$$C_2^p = c + q_2(1-\Delta e_2/2) + f \tag{6.17}$$

Entrants come into the market until profits are zero. Thus $P(X_2) = C_2^p$, or analogous to (4.5)

$$X_2^p(f) = X_0^* - (c+h-C_2^p)/P' \tag{6.5}$$

If production firms used the imitation instead of licensing the cleaner technology, their private production costs (gross of any permit rents) would be $C_2^{p,I} = c + (1-\mu r)a(\Delta e_2)^2/2 + q_2(1-\Delta e_2)$.

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[25] In a more general setting firms may use spare permits to increase their own production rather than selling to entrants. In both cases, innovation leads to a decline in the permit price.

Minimizing this expression, and equating with that for C_2^p, we can obtain the maximum license fee constraint:[26]

$$\bar{f}^p = \Delta e_2 \frac{q_2}{2}\left\{\frac{r(1-m)}{1-mr}\right\} \tag{6.14}$$

Finally, there is the following additional constraint:

$$(1-\Delta e_2)X_2^p = (1-\Delta e_1^*)X_1^* \tag{6.18}$$

This equation says that total emissions equals the quantity of emissions permits.

Equations (6.3a), (6.17), (6.5), (6.14) and (6.18) could be solved analytically for the endogenous variables X_2^p, Δe_2, q_2, C_2^p and $\bar{f}^p$. However this produces very complex formulas because the system is non-linear.[27] Instead, we present the numerical solutions to the model in subsection B, which are solved computationally. Analogous to (3.7), the social gain from diffusion of the cleaner technology is:

$$\Delta V^p = (MC_1^* - MC_2^p)X_1^* + \{(MC_1^* + C_2^p)/2 - MC_2^p\}(X_2^p - X_1^*) \tag{6.7}$$

where $MC_2^p = c + (1-r)a(\Delta e_2^p)^2/2 + h(1-\Delta e_2^p/2)$ is the marginal social cost of production. ΔV^p is the reduction in social cost from the initial X_1^* firms in the market, plus the efficiency gain from the additional output.[28] Finally, the privately optimal level of R&D, and the R&D efficiency gain, are again determined by equations (4.11) and (4.12), except that ΔV is defined by equation (6.7), and $F^p = \bar{f}^p X_2^p$.

(ii) Flexible Permits

Now suppose that the quantity of permits is adjusted to the ex post optimal amount, $(1-\Delta e_2^*)X_2^*$, if the technology is discovered (prior to diffusion). The equations characterizing the equilibrium are the same as in the fixed permit case, except that (6.18) now becomes:

$$(1-\Delta e_2)X_2^p = (1-\Delta e_2^*)X_2^* \tag{6.18′}$$

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[26] We assume that the patent holder cannot discriminate by charging different fees to initial permit holders and entrants.

[27] This is because the level of emissions abatement depends on the equilibrium permit price, which is endogenous. Under the emissions tax and performance standard the level of emissions abatement depends only on exogenous parameters.

[28] The latter is the area under the demand curve (a trapezoid with average height $(MC_1^* + C_2^p)/2$ and base $X_2^p - X_1^*$) less the area under the marginal social cost curve (a rectangle with height MC_2^p and base $X_2^p - X_1^*$).

Table 3. The R&D Efficiency Gain under Tradable Emissions Permits
(expressed relative to that under the emissions tax)

		proportionate reduction in abatement cost		
		0.01	0.1	0.4
A. Fixed Permits				
Benchmark case		1.00	.95	.73
m	0	1.00	.98	.82
	.25	1.00	.97	.79
	.75	1.00	.92	.63
$p(M^*)$	.35	.99	.94	.68
	.9	1.00	.99	.88
h	.1	1.00	.94	.63
	2.0	1.00	.99	.91
Δe_1^*	.5	1.00	.99	.91
	.05	1.00	.94	.59
B. Flexible Permits				
Benchmark case		1.00	1.00	1.00
m	0	1.00	1.01	1.04
	.25	1.00	1.00	1.02
	.75	1.00	1.00	.99
$p(M^*)$	.35	1.00	.99	1.00
	.9	1.00	1.01	1.03
h	.1	1.00	1.01	1.01
	2.0	1.00	1.00	.99
Δe_1^*	.05	1.00	1.00	.99
	.5	1.00	1.01	.94

B. Simulations

The upper panel in Table 3 shows calculations of the R&D efficiency gain under the fixed permits policy, expressed relative to that under the emissions tax. All of the entries are less than or equal to unity; that is the R&D efficiency gain under tradable permits is less than under the emissions tax, or at least never exceeds it. However, the entries are larger than those in the upper panel of Table 2; that is the efficiency gain exceeds that under the fixed performance standard. These results are due to two asymmetries. First, the reduction in social cost per firm from adopting the new technology under the permit policy is between that under the emissions tax and the fixed performance standard. That is, firms increase abatement after adopting the cleaner technology, but not all the way to Δe_2^* in Figure 2. This is because the permit price falls below *h* as permit holders sell spare permits to entrants (and emissions abatement is proportional to the permit price in (6.3a)). Second, the willingness to pay for licensing the new technology, and hence patent holder revenue, is lower under tradable permits than under the emissions tax. This is because the fall in permit price reduces the private gains to production firms from adopting the new technology and selling emissions permits.

However the discrepancy between tradable permits and the emissions tax is only empirically “significant” for major innovations, when the fall in permit price is more substantial. For an innovation that reduces abatement costs by 10 percent or less, the R&D efficiency gain is only up to around 6 percent lower under tradable permits than under the emissions tax. However, it is 10-40 percent lower for an innovation that reduces abatement costs by 40 percent.

The lower panel of Table 3 shows the results for the flexible policy when the quantity of permits is reduced prior to diffusion of the cleaner technology. In this case the R&D efficiency gain is very similar to that under the emissions tax. Again, diffusion of the cleaner technology causes a fall in the permit price. However the initial permit price is greater than in the fixed permits case. This implies greater revenues for the patent holder, and a higher level of emissions abatement with the cleaner technology.

In general, the case of fixed emissions permits is probably more realistic than that of flexible emissions permits. The existing programs for controlling sulfur dioxide and nitrogen oxides set the quantity of allowable emissions over a 15-year time horizon. It is unlikely that the announced targets will be renegotiated during the intervening years. Similarly, if the U.S. adopts a tradable permits program to reduce carbon dioxide emissions the quantity of permits allocated each year is likely to be fixed in advance over a long time horizon.

6. CONCLUSION

This paper analyzes the welfare effect in the market for environmental R&D induced by alternative environmental policy instruments. The induced welfare gain is greater under an emissions tax than tradable emissions permits. However, we find that the empirical significance of this discrepancy crucially depends on the potential size of innovation. For an innovation that reduces abatement costs by 10 percent or less, the R&D efficiency gain is only up to around 6 percent lower under tradable permits than under the emissions tax. However, it is 10-40 percent lower for an innovation that reduces abatement costs by 40 percent. The efficiency discrepancies between an emissions tax and a fixed performance standard are somewhat larger, although again they are very sensitive to the potential size of innovations.

The possibility that new, cleaner production technologies will be imitated by other firms can reduce the private benefits from innovation below the social benefits. This suggests that inducing more environmental R&D -- for example by research subsidies or tightening environmental regulations beyond the Pigouvian level -- may significantly improve efficiency in the R&D market. The above results cast *some* doubt on this assertion. We find that efficiency in the R&D market is generally more than 90 percent of that in the first-best outcome, even when imitation limits private benefits to 50 percent of the social benefits from innovation. This is because the common pool effect -- by which competition for innovation rents is excessive -- tends to offset the effects of imitation. Thus in our analysis the threat of imitation has to be substantial before research subsidies can potentially produce “large” efficiency gains in the R&D market.

Our analysis does not examine the choice between R&D policy instruments. However our results underscore that the potential efficiency gain from additional incentives to stimulate environmental R&D is highly sensitive to the discrepancy between the private and social benefit from innovation. This suggests that a policy that subsidizes all environmental R&D at the same rate -- such as the existing R&D tax credit -- is potentially inefficient. A more efficient policy might be to target research prizes at new emissions abatement technologies for which it is particularly difficult to appropriate spillover benefits to other firms.

Our analysis provides a useful starting point for assessing under what circumstances there might be significant inefficiency in the R&D market under alternative environmental policies. However, there are many ways the analysis might be extended to examine how robust the empirical results are. The model employs quadratic functional forms. Allowing for more general functional forms may affect the quantitative results to some extent, although this is unlikely in the case of more minor innovations. We assumed the environmental damage function is linear. Under a convex damage function the private benefits from innovation under the Pigouvian emissions tax can exceed the social benefits. This is because marginal environmental benefits from diffusing a cleaner technology are declining, while marginal private benefits, in terms of reduced tax payments, are constant. Thus the possibility of R&D exceeding the first-best level appears to be more likely under convex damages.[29] The analysis does not investigate the implications of heterogeneity among firms or the empirical significance of possible strategic behavior in the R&D market. Nor do we allow for transaction costs when analyzing tradable emissions permits. These transactions costs may reduce the returns to innovation and hence the incentives for environmental R&D (Parry, 1996). Our analysis also ignores the possibility that technological innovation may arise from learning by doing, rather than deliberate investments in research activity.[30]

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[29] For more discussion of this see Parry (1995).

[30] See Goulder and Mathai (1997) on the significance of this distinction.

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