Instrument Choice for Environmental Protection When Technological Innovation is Endogenous

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Abstract

This paper presents an analytical and numerical comparison of the welfare impacts of alternative instruments for environmental protection in the presence of endogenous technological innovation. We analyze emissions taxes and both auctioned and free (grandfathered) emissions permits.

We find that under different sets of circumstances each of the three policies may induce a significantly higher welfare gain than the other two policies. In particular, the relative ranking of policy instruments can crucially depend on the ability of adopting firms to imitate the innovation, the costs of innovation, the slope and level of the marginal environmental benefit function, and the number of firms producing emissions. Moreover, although in theory the welfare impacts of policies differ in the presence of innovation, sometimes these differences are relatively small. In fact, when firms anticipate that policies will be adjusted over time in response to innovation, certain policies can become equivalent.

Our analysis is simplified in a number of respects; for example, we assume homogeneous and competitive firms. Nonetheless, our preliminary results suggest there is no clear-cut case for preferring any one policy instrument on the grounds of dynamic efficiency.

Key Words: technological innovation, externalities, environmental policies, welfare impacts

JEL Classification Numbers: Q28, O38, H23

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Carolyn Fischer, Ian W. H. Parry, and William A. Pizer*

1. INTRODUCTION

Policy makers must often choose amongst alternative policy instruments for protecting the environment. A key consideration affecting this choice is the impact of different policies on firm incentives to develop cleaner production technologies.[1] Over the long run, the cumulative effect of technological innovation may greatly ameliorate what in the short run can appear to be serious conflicts between economic activity and environmental quality (Jaffee and Stavins, 1995; Kneese and Schultz, 1975). This effect is especially pertinent in the context of global climate change, where governments have so far been unwilling to implement measures to substantially reduce emissions of greenhouse gases due to the potential economic costs of these measures.

In environmental economics a strand of literature, mainly theoretical, has explored the effects of environmental policies on technological innovation.[2] Several early studies in this literature showed that emissions taxes and emissions permits generally provide more incentives for technological innovation than "command and control" policies (such as performance standards and technology mandates) in a single-firm setting.[3] However many innovations are applicable to more than a single firm. Indeed at the heart of most R&D models in the industrial organization literature is the spillover benefits of innovation to other firms, and the inability of innovators to fully appropriate the rents from innovation. Thus, more recent studies in environmental economics have expanded the earlier models to incorporate the diffusion of new technologies to other firms in the industry.

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[1] A number of other factors affect this choice. For example, the ease of monitoring and enforcement, political feasibility, and the expected costs of policy instruments in the presence of uncertainty, firm heterogeneity and pre-existing tax distortions. For a review of the literature see Cropper and Oates (1992).

[2] Innovation incentives are frequently listed as an important consideration in the choice among environmental policy instruments (see e.g. Stavins, 1998; Bohm and Russell, 1985). However the amount of analysis of this issue--particularly empirical analysis--is surprisingly limited.

[3] See e.g. Downing and White (1986), Magat (1978) and Zerbe (1970).

The most comprehensive study of innovation in a multi-firm setting was Milliman and Prince (1989) (hereafter MP).[4] An important finding in their analysis was that--when policies are fixed at their "Pigouvian" levels over a period of time--incentives for innovation are greater under an emissions tax than under free (grandfathered) emissions permits, and higher still under auctioned emissions permits (see also Jung et al., 1996). Two effects underlie these results.

First, the amount of emissions abatement is greater after innovation under the emissions tax than under emissions permits. Innovation reduces the (marginal) cost of emissions abatement, which induces more emissions abatement under a tax, while under permits the industry-level amount of emissions by definition remains constant. Since firms reduce emissions by a larger amount under the tax, they are willing to pay more for innovations that reduce the costs of abatement. We refer to the industry-level reduction in abatement costs brought about by innovation as the *abatement cost effect*. Thus the abatement cost effect is larger under the emissions tax than under emissions permits.

The second effect arises from the impact of innovation on reducing the equilibrium permit price. To the extent that firms purchase permits to cover their emissions--as they do under auctioned permits--they gain from the fall in permit price. We refer to the reduction in payments on firm emissions caused by innovation as the *emissions payment effect*. This effect is absent under a fixed emissions tax and (in the aggregate) free permits. In MP the emissions payment effect is generally sufficient to raise the overall incentives for innovation under auctioned permits above those under the emissions tax.

Our paper differs from MP in three main respects. First, we alter some of the assumptions regarding the process of adoption and the spillover mechanism. MP assume that innovators can appropriate a constant fraction of the private gains to all firms in the industry from a new technology. In our analysis, we assume a competitive equilibrium where non-innovating firms pay a royalty for the new technology. The royalty level is endogenously determined by the desire of the innovator to attract payment from the marginal, non-innovating firm.[5] An important consequence of this assumption under a permit system is that the innovator cannot appropriate any of the emission payment effect accruing to non-innovators because the marginal firm has no effect on the equilibrium permit price. As a result, the extra incentives for innovation from auctioning permits rather than grandfathering them are typically lower in our analysis than in MP.

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[4] Other studies following MP have examined different aspects of the innovation process. For example Jung et al. (1996) and Biglaiser and Horrowitz (1995) consider environmental policies in a setting where firms differ in abatement costs and their willingness to pay for new technologies. Jaffe and Stavins (1995) find some econometric evidence for the superiority of market-based environmental policies at promoting innovation over command and control policies. For more discussion of the literature see Kemp (1997) and Ulph (1998).

[5] Indeed in our analysis the rate of appropriation of the overall industry gains from a new technology--which is obviously crucial for innovation incentives--is endogenously determined under all policy instruments, rather than being exogenous as in other studies.

Second, we provide a numerical--as well as analytical--comparison of policy instruments. Thus, we investigate the types of situations where the gains from using one instrument over others may be important and when they are not. Our analysis focuses on emissions taxes and auctioned and free emissions permits.[6] For the most part we assume that these policies are set at their (ex ante) Pigouvian levels--the standard recommendation from static analyses.[7]

Third, previous studies have tended to focus on the impact of policies on the demand for innovation. However, from a welfare perspective, more innovation is desirable only if the benefits outweigh the costs. Our analysis explicitly models the costs of using environmental policies to induce innovation; therefore, we are able to examine the overall impacts of policies on social welfare.

In contrast with some earlier studies our results do not suggest a general preference for auctioned permits over emissions taxes--and emissions taxes over free permits--either on the criterion of welfare gains or the induced amount of innovation. Instead, our tentative conclusion is that a more pragmatic approach to instrument choice in the presence of induced innovation may be appropriate. Under different sets of circumstances, we find that each of the three policies may generate a substantially higher welfare gain than the other two policies. In particular, the relative welfare ranking of policy instruments can crucially depend on four important factors: the ability of adopting firms to imitate the innovation, the cost of innovation, the shape of the environmental benefit function, and the number of firms producing emissions. In certain situations, however, these welfare differences are small enough to be of little practical relevance for the choice of policy instruments. Thus, an evaluation of the circumstances specific to a particular pollutant seems to be required in order to judge whether a case for one instrument over the other two instruments can be made on dynamic efficiency grounds.[8]

To give some flavor of our results, we find that when innovators can effectively appropriate a large fraction of the rents from innovation, an emissions tax may induce a significantly greater amount of innovation than free and auctioned permits, due in part to the larger abatement cost effect under the tax. Assuming marginal environmental benefits are

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[6] These policy instruments are generally advocated by economists over command and control policies on the grounds of their static efficiency properties (see for example Stavins, 1998). A free tradable emissions program was implemented in the U.S. in 1990 to reduce sulfur emissions. All three policy instruments have been proposed as a means to achieving the limits on carbon emissions agreed at the recent conference in Kyoto.

[7] Static models that assume the state of technology is exogenous do not capture the welfare gain from innovation. In this sense they understate the overall welfare gains from environmental policies. However, the optimal level of environmental regulation in the presence of innovation is not necessarily greater than the Pigouvian amount. For more discussion of this see Parry (1995).

[8] Some of our results complement a recent study by Parry (1998). He showed that the welfare gain from using an emissions tax over free emissions permits is only likely to be significant in the case of "major" innovations. Our analysis generalizes that in Parry (1998) in a number of respects. We provide a much more comprehensive comparison of policy instruments. In addition we broaden the choice of policy instruments to include auctioned emissions permits, we vary the number of firms producing emissions, and we allow for convex as well as linear environmental benefits. Our analysis also reconciles the results from earlier studies.

relatively flat, this greater amount of innovation is socially desirable and welfare is also significantly greater under the tax. However when appropriation is weak (due to the availability of imitation technologies) the emissions payment effect at the innovating firm becomes relatively more important, and both the innovation level and welfare gains can be highest under auctioned permits. The welfare gain from induced innovation is also more likely to be greatest under emissions permits when the marginal environmental benefit curve is steeply sloped relative to the marginal abatement cost curve. Moreover, we find that the welfare discrepancies between policies are only significant when the amount of innovation over the period for which policies are fixed is large enough to reduce abatement costs by a significant amount (around 10 percent or more). In this connection, the flexibility of policy instruments over time is important. If policies can be adjusted at regular intervals (and firms anticipate this) the welfare discrepancies between instruments are less important.

A number of important caveats are in order. For example, we mainly assume environmental policies are fixed at today's (pre-innovation) Pigouvian levels. As already mentioned, innovation incentives can differ when firms anticipate frequent policy adjustments in response to innovation. In addition, our assumption of a Nash equilibrium in the market for new technologies may or may not be more realistic than the constant appropriations rate approach in MP. Clearly, joint ventures or some other form of cooperation or bargaining between innovators and non-innovators are possible. However, we do believe that our approach provides an important competitive-equilibrium benchmark that is amenable to future extensions while also providing policy guidance based on numerical simulations. The results can then be used to gauge the quantitative importance of incorporating more complex features, such as imperfectly competitive behavior.

The rest of the paper is organized as follows. Section 2 develops an analytical framework that decomposes the determinants of innovation incentives under alternative policy instruments. This framework is used to explain our numerical results, which are presented in Section 3. Section 4 concludes and suggests extensions for future research.

2. THEORETICAL ANALYSIS

In this section, we first develop the basic model of induced technological change. Then we compare in general terms the differences between different environmental policies with respect to their impacts on innovation and on welfare.

A. The Basic Model

We model a three-stage process of innovation, diffusion and emissions abatement involving a fixed number of *n* identical, competitive firms.[9] One of these firms is an

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[9] The industrial organization literature on innovation has tended to focus on strategic models involving a small number of firms where monopoly rents, timing and preemption are important (see e.g. the survey in Tirole, 1988). While appropriate for major R&D industries such as pharmaceuticals, these studies may be less appropriate where environmental issues are concerned. Major pollutants like sulfur dioxide, nitrogen oxides, particulates and carbon

innovator. In the first stage, the innovating firm decides how much to invest in R&D to develop an emissions abatement technology. In the second stage, the other n-1 firms decide whether to adopt this technology in return for a royalty fee. Alternatively, they can use an imitation technology that is not fully equivalent to the original innovation. In the third stage, all n firms choose emissions abatement to minimize costs given an emission tax or a permit price. The environmental policy is set prior to innovation, although implementation (including any auctioning of permits) takes place in the last stage. The model is best solved backwards.

(i) Abatement Cost Minimization

The abatement cost function for a firm in the third stage is $C(a,k)$, where a is firm-level emissions abatement and k represents the state of technology for reducing emissions.[10] Abatement costs are assumed to be increasing and convex in a and decreasing in k with diminishing returns to technology: $C_a>0$, $C_{aa}>0$, $C_k<0$, $C_{kk}>0$, $C_{ak}<0$, $C_a(0,k)=0$. Technological innovation (k) is determined in the first stage and therefore is exogenous in the third stage. An augmented state of technology (higher k) reduces the slope of the marginal abatement cost function.[11]

Let t denote the "price" of emissions. Under an emissions tax this is simply the tax rate. Alternatively it represents the equilibrium permit price under an emissions permit policy. Firms are competitive in the market for emissions; i.e., they take the emissions price as given when making abatement decisions.

In the third stage each firm solves

$$m(k,t) = \min_a \{C(a,k) + t(e-a)\}, \tag{2.1}$$

where e is what emissions would be in the absence of abatement. Firms choose emissions abatement to minimize the sum of (i) abatement costs and (ii) tax payments on actual emissions, or alternatively the cost of purchasing (or forgoing sales) of emissions permits. This cost minimization yields the following first order condition:

$$C_a(a,k) = t\,. \tag{2.2}$$

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dioxide are produced by large numbers of firms. See Oates and Strassmann (1984) for a defense of the competitive assumption in models of environmental policy.

[10] Abatement reduces emissions per unit of output and represents the substitution of cleaner inputs for polluting inputs in production, or the installation of end-of-pipe clean-up technologies. In practice emissions also fall as industry output contracts in response to higher pollution abatement costs. For simplicity we do not incorporate this effect. For many pollutants this may be a reasonable approximation because abatement costs are typically only around 2 percent of total production costs (Robison, 1985). Indeed, Goulder et al. (1998) find that around 98 percent of NO_X emissions reductions come from firms reducing emissions per unit of output and only 2 percent from reductions in industry output.

[11] An increase in k may represent, for example, a new process for blending cleaner fuels in production, or a more effective technology for "scrubbing" air pollutants or cleaning water pollutants. The impact of successive increases in innovation on reducing abatement costs is declining, since there is a limit on the ability to reduce abatement costs (costs cannot become negative).

In other words, marginal abatement costs equal the price of emissions.

(ii) The Technology Adoption Choice

Typically innovators can only partially appropriate the spillover benefits to other firms from new technologies. In particular, other firms may use the new information to develop alternative technologies to the original innovation. We represent imperfect appropriation by assuming that the new innovation is patented but other firms can (imperfectly) imitate around the patent. Thus in the second stage non-innovators decide whether to pay a fixed-fee royalty *Y* for licensing the technology (*k*) developed in the first stage. Alternatively, they can use an imitation that improves their technology level by sk rather than *k*, where $0 \leq s \leq 1$. A firm will adopt the patented technology if its costs (including the royalty payment) are no higher than costs with the imitation.[12]

Each firm makes its decision of whether to adopt given the adoption decisions of all the other firms and the prevailing price of emissions. We assume the royalty is set such that in the resulting Nash equilibrium, all firms adopt the original innovation rather than use an imitation.[13] Thus, the maximum royalty that the innovator can charge just leaves the last adopting firm indifferent between the new technology and the imitation:[14]

$$Y = m(k,t) - m(sk,t). \tag{2.3}$$

Thus, while in equilibrium no one chooses to imitate, the *threat* of imitation limits the ability of the innovator to appropriate the social benefits from innovation.[15]
From (1) and (3), the maximum royalty can be expressed:

$$Y(k) = \left\{C(a^{s}, sk) - C(a^{1}, k)\right\} + t(k)(a^{1} - a^{s}), \tag{2.4}$$

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[12] For simplicity, we assume zero costs to imitation. Allowing for positive imitation costs would raise the willingness to pay for the patented technology and hence the rate of appropriability. Thus, incorporating imitation costs would be equivalent to lowering the value of s in our model. In addition we could assume that the alternative technology was also invented and patented by one firm. However allowing for multiple (and competing) patented technologies would have the same impact on reducing innovation incentives as imitation (or s) does in our model (Bigliaser and Horrowitz, 1995).

[13] We ignore the possibility that pricing the technology such that only some portion of non-innovating firms adopt is the profit-maximizing outcome.

[14] We prohibit the possibility of price-discrimination in royalties according to the order of adoption, since in that case every firm would want to be the last to adopt.

[15] Allowing for the possibility of imitation is one way to introduce imperfect appropriation into the model. An alternative approach would be to allow for firm heterogeneity and the cost reduction from adopting the innovation to differ across firms. The innovator cannot charge different royalties to different firms and therefore would be unable to appropriate the full social benefits from the innovation (see Bigliaser and Horrowitz, 1995). Imperfect appropriability also arises when one firm's R&D in one period raises the productivity of another firm's R&D in future periods. Also the assumptions that new technologies are patented and licensed to all firms are not crucial. Often, when the number of potential users of a new technology is small, innovators may choose not to patent a new technology. Our assumptions simply enable us to represent imperfect appropriability, and in Section 3 we consider a wide range of possible scenarios for the appropriation rate.

where superscripts σ and 1 denote the solution to condition (2.2) for a firm with technology level σk and k respectively. From equation (2.4), the willingness to pay for adopting the patented technology rather than using the imitation consists of two components. First, the savings in abatement costs from using the better technology over the imitation is $C(a^{\sigma},\sigma k)-C(a^{1},k)$. Second, tax payments (or payments for emissions permits) on emissions net of abatement with the patented technology $(t(k)(e-a^{1}))$ are less than the corresponding payments if the imitation were used $(t(k)(e-a^{\sigma}))$. Thus, using the patented technology over the imitation reduces these payments by $t(k)(a^{1}-a^{\sigma})$.

Our assumption of adopting firms being competitive in the market for emissions implies that no one firm believes its abatement and adoption decisions can affect price of emissions. However, changes in (marginal) abatement costs aggregated over all firms can affect the price of emissions, and our innovator does recognize this implication of technological diffusion. In the case of fixed permits, this adjustment occurs through changes in the permit price; thus, we write $t = t(k)$. Under a fixed emissions tax, the price of emissions does not change with aggregate abatement cost reductions (although we also briefly consider a case where the tax rate is adjusted in response to innovation). To the extent that emissions prices fall due to aggregate marginal cost reductions, adopting firms will benefit from lower payments on their inframarginal emissions. However, since any one firm can enjoy this benefit whether it adopts or not, given an equilibrium where every other firm is adopting, the innovator cannot appropriate these gains. Still, any adjustments in the price of emissions continue to affect the maximum royalty, since it affects the relative value of the imitation option.

Differentiating (2.4) with respect to k gives the marginal change in individual royalty payments:

$$Y'(k)=\sigma C_{k}(a^{\sigma},\sigma k)-C_{k}(a^{1},k)+t'(k)(a^{1}-a^{\sigma})\,. \qquad (2.5)$$

(iii) <u>The Innovation Decision</u>

We assume that innovation results from investments in R&D activity by one firm.[16] The cost of the R&D necessary for technological innovation is $F(k)$, where $F'>0$, $F''\geq 0$. In the first stage the innovator chooses R&D (or, equivalently, the amount of technological innovation) to maximize profits:[17]

$$\pi(k)=(n-1)Y(k)-C(a^{1},k)-F(k)-t(k)(e-a^{1}-\bar{e})\,. \qquad (2.6)$$

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[16] Other studies have explored the implications of innovation by more than one firm. In those settings, innovation may be socially excessive. This is because firms do not take into account the potential effect of their research efforts on reducing the likelihood of innovation rents at other firms (see Wright (1983) for a good discussion).

[17] Thus we simplify by assuming that innovation is continuous rather than discrete. "Innovation" in our analysis effectively represents the aggregate amount of innovation over a given period, and in this sense it is more reasonable to regard it as a continuos variable. An alternative formulation would be to assume that firms invest in R&D to increase the probability of successfully inventing a discrete technology (see e.g. Wright, 1983; Parry, 1998).

Innovator profits equal royalties from the other *n*- 1 firms minus the sum of own abatement costs, innovation costs and payments on own emissions, either in the form of tax payments or permit purchases. $\bar{e}$ is the (exogenous) permit allocation of the innovating firm under the free permits policy ($\bar{e}$ = 0 for the emissions tax and auctioned permits policies).[18]

Maximizing (2.6) with respect to *k* gives

$$F'(k) = (n-1)Y'(k) - C_k(a^1, k) - t'(k)(e - a^1 - \bar{e})\,. \tag{2.7}$$

Substituting (2.5) in (2.7) gives the following condition that determines the privately optimal amount of innovation:

$$\begin{aligned} F'(k) = \quad & - \underbrace{nC_k(a^1, k^1)}_{abatement\,cost\,effect} + \underbrace{(n-1)\sigma C_k(a^\sigma, \sigma k)}_{imitation\ effect} \\ & - \underbrace{t'(k)(e - a^1 - \bar{e})}_{emissions\ \ payment\ effect} + \underbrace{(n-1)t'(k)(a^1 - a^\sigma)}_{adoption\ price\,effect} \end{aligned} \tag{2.8}$$

Equation (2.8) equates the marginal cost and marginal private benefit of innovation, where the latter is decomposed into four components. First, the (marginal) *abatement cost effect* is the increased willingness to pay for the new technology across all firms due to the impact of (incremental) innovation on reducing firm abatement costs. Second, the (marginal) *imitation effect* is the reduction in the willingness of non-innovators to pay for the new technology, due to the impact of (incremental) innovation on increasing the possibility of abatement cost-reducing imitation.

The third and fourth components are present when emissions prices adjust to changes in marginal abatement costs, e.g., permit policies or policies adjusted *ex post*. The (marginal) *emissions payment effect* represents the reduction in payments for permits to cover the innovator's (infra-marginal) emissions, net of current permit holdings, due to the effect of innovation on reducing the permit price. Under auctioned permits, the innovator must cover all inframarginal emissions (e- a^1) and the corresponding reduction in payments can be a significant additional incentive to innovate. Under free permits, if the permit allocation $\bar{e}$ is less (greater) than emissions ($e - a^1$), the innovator is a net buyer (seller) of permits. Thus, by driving down the emissions price, innovation produces a private gain (loss) for the innovator if he is a net buyer (seller) of permits. We simplify by assuming that all firms receive the same permit allocation. Therefore, since in our symmetric equilibrium all firms produce the same amount of emissions, no buying or selling of permits actually occurs and, correspondingly, no emissions payment effect exists under free permits.[19] Although non- innovators who

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[18] $\bar{e}$ does not appear in equation (2.1) or (2.3), since firm decisions about emissions and technology adoption do not affect the price of emissions, and hence the rents obtained from permit allocations.

[19] More generally, if the innovator is a net buyer of permits, the amount of induced innovation will lie between the amount under our free and auctioned permit cases. If the innovator is a net permit seller, innovation will be below that in our free permit case.

are net buyers of permits also gain from an emissions payment effect, the innovator cannot appropriate this benefit, which accrues *regardless* of any one firm's choice to adopt the patented technology or the imitation. In other words, non-innovators free ride on the fall in permit price.[20]

The final component in equation (2.8) is the *adoption price effect*. Under free or auctioned permits, if a non-innovator were to use the imitation instead of the patented technology, it would have higher emissions and would pay $t(k)(a^1 - a^s)$ for the additional permits. By reducing the permit price, innovation reduces these extra payments and hence the royalty that non-innovators will pay for the new technology. Again, no corresponding effect exists under an emissions tax, unless the policy maker reduces the emissions tax in response to innovation.[21] We summarize the determinants of the incentives for innovation under alternative policies in Table 1.

Table 1: Determinants of the Incentives for Innovation

	Emissions tax	Free permits	Auctioned permits
abatement cost effect	+	+	+
imitation effect	–	–	–
emissions payment effect	0[a]	0	+
adoption price effect	0[a]	–	–

[a] Our main focus is on a fixed emissions tax. In the case when marginal environmental benefits are declining and the Pigouvian tax is adjusted downwards in response to innovation, the emissions payment effect is positive and the adoption price effect is negative, as with auctioned permits.

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[20] In contrast MP effectively assume that innovators appropriate an (exogenous) fraction of the emissions payment effect at other firms. This assumption seems more applicable when the number of non-innovating firms is relatively small. In this case the decision of non-innovators about whether to adopt the patented technology or the imitation may affect the equilibrium permit price. In addition the innovator could bargain with all other firms as a group and threaten not to license the new technology to the group unless non-innovators pay for part of the emissions payment benefit. With fewer firms there is also greater scope for collusion over innovation strategies and sharing the (private) industry-wide benefits from innovation. Note that in these cases the appropriable fraction of the emissions payment effect at other firms will be complex and difficult to estimate empirically. It will depend, among other things, on the number of firms and the form of imperfect competition.

Our assumption of Nash equilibrium implicitly implies that firms have rational expectations about the final equilibrium permit price. If this is not the case, some licensing of the new technology may occur at disequilibrium prices (that is, before complete diffusion of the new technology). However so long as non-innovators are price-takers in the permit market the innovator is still unable to appropriate the emissions payment effect at other firms.

[21] It is possible that an innovating firm will be an outside supplier. That is the firm is engaged in developing new technologies but does not produce pollution itself. In this case there is no emissions payment effect at the innovating firm, and auctioned permits would be equivalent to free permits in our analysis.

(iv) The First-Best Outcome

In order to investigate the welfare properties of these policies, we first need to define outcomes in the first-best or social planning version of the model. We assume that environmental benefits from emissions abatement by the *n* firms is *B(na)* where $B'>0$ and $B'' \leq 0$ and *a* continues to represent firm-level emission abatement. Social welfare equals environmental benefits, less abatement costs across the *n* firms, less innovation costs:

$$W = B(na) - nC(a,k) - F(k)\,. \tag{2.9}$$

Maximizing this expression with respect to *a* and *k* gives

$$C_a(a^*,k^*) = B'(na^*)\,, \tag{2.10}$$

and

$$F'(k^*) = -nC_k(a^*,k^*)\,. \tag{2.11}$$

In other words, Equation (2.10) shows that a social planner would equate firm-level marginal abatement costs per firm with marginal environmental benefits. In Equation (2.11), the planner equates the marginal cost of innovation with the marginal benefit in terms of reducing abatement costs across all firms.

B. Comparing Policy Instruments

We now compare the impacts of alternative policies on innovation and welfare. For the most part we assume that policies are fixed at their "Pigouvian" levels, since this is the standard recommendation from static analyses.[22] We illustrate the important points using Figures 1 and 2. These figures show the gains from innovation at the innovating firm (upper panels) and the royalty received from non-innovators (lower panels), under the tax (Figure 1) and permit policies (Figure 2). $C_a(a,0)$, $C_a(a,\mathrm{s}k)$ and $C_a(a,k)$ are the marginal cost of abatement prior to innovation, with the imitation, and with the patented technology respectively.

(i) Innovation Incentives

Under the emissions tax, firms reduce emissions until the tax rate equals marginal abatement costs. Therefore, abatement per firm increases as marginal costs shift down, depicted in Figure 1 by a^0, a^t_s and a^1 with the original technology, the imitation and the patented technology, respectively. The innovator gains the full abatement cost effect for itself, the shaded area 0*hj* in the top panel. However, non-innovators, although they realize the same cost savings, are only willing to pay the shaded area 0*lj* to adopt the patented technology.

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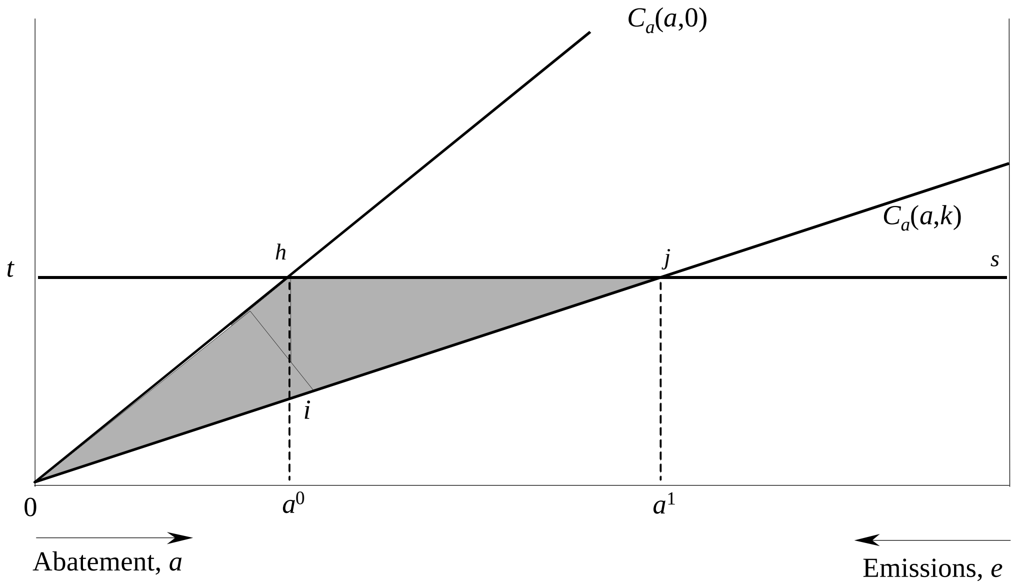
[22] That is, policies are set to equate the marginal environmental benefits and marginal abatement costs prior to innovation.

Figure 1: Appropriable Gains to Innovation with a Tax

(a) From the Innovator



(b) From a Non-Innovator

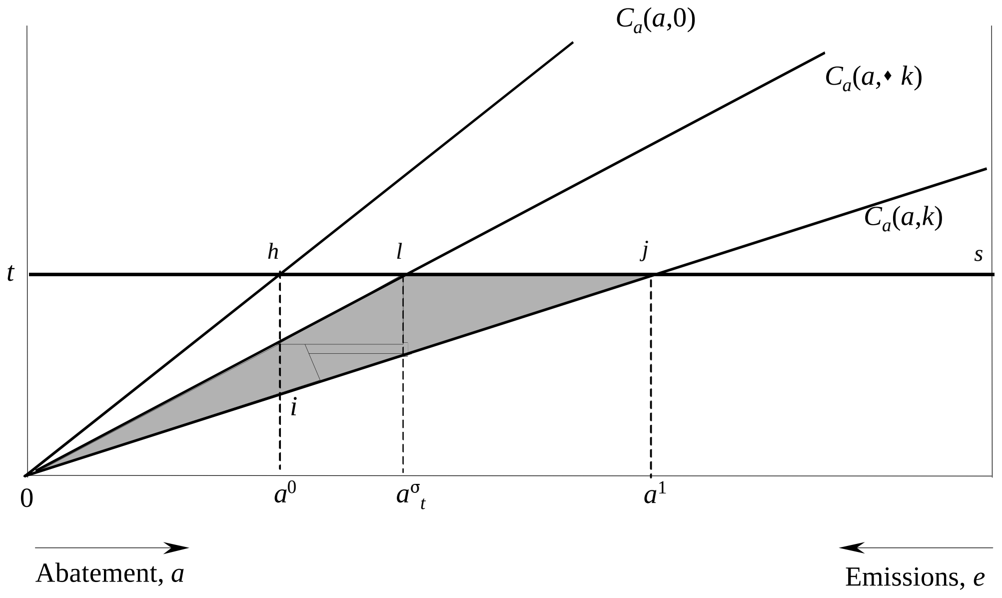
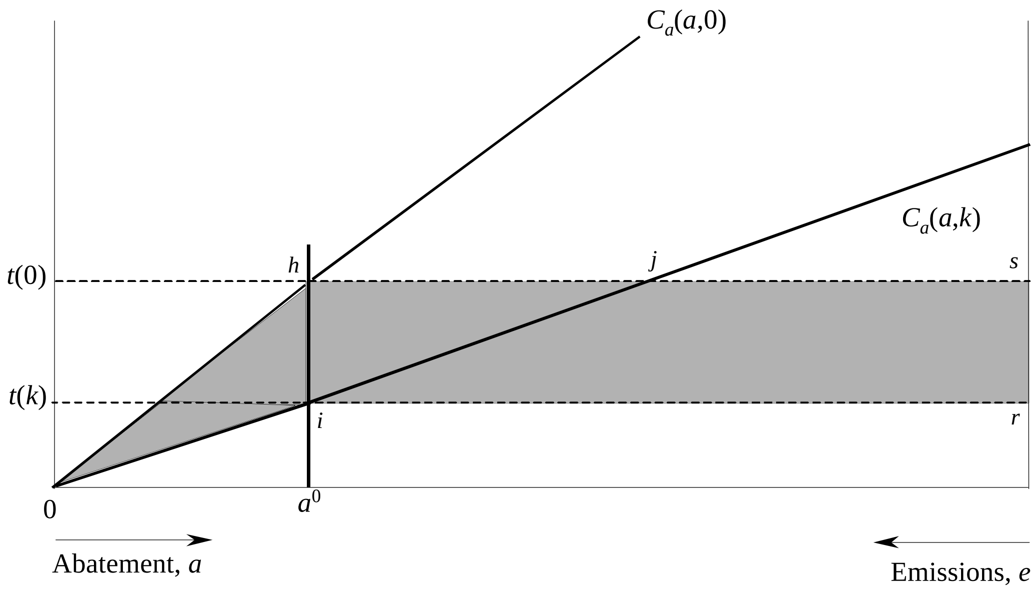
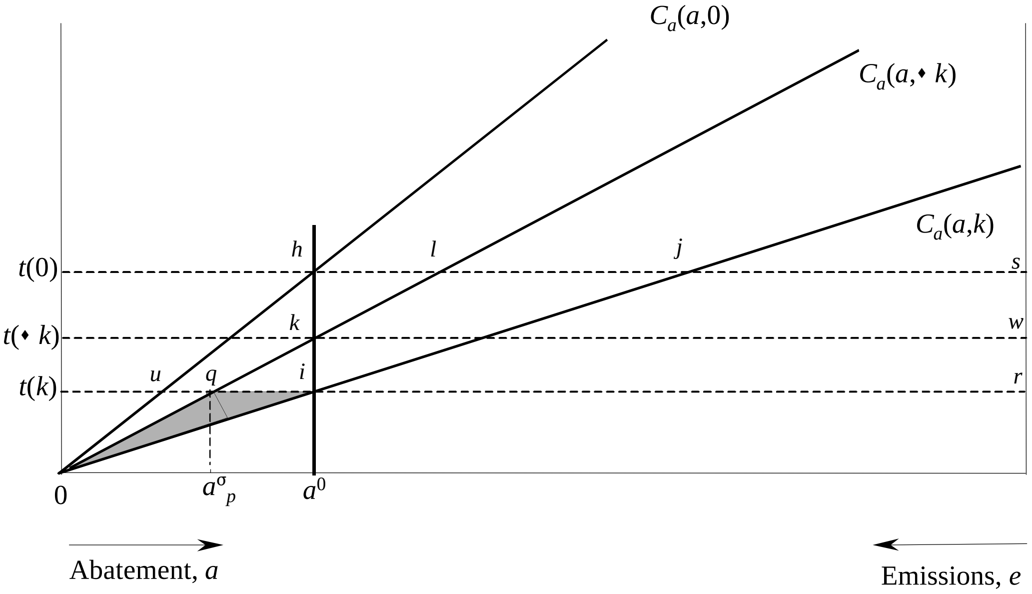


Figure 2: Appropriable Gains to Innovation with Auctioned Permits

(a) From the Innovator



(b) From a Non-Innovator



This area equals the benefit from using the patented technology over the original technology *less* the benefit from using the imitation over the old technology. Overall, the innovator gets *n* times the abatement cost effect, 0*hj*, less (*n*-1) times the imitation effect, 0*hl*.[23]

Now suppose a fixed quantity of auctioned, tradable permits limits industry emissions to $n(e- a^0)$. With no innovation the equilibrium permit price would be *t*(0) in Figure 2 (equaling the ex ante Pigouvian tax in our baseline). If all firms adopt the patented technology, the permit price falls to *t*(*k*), since emissions per firm remain at $e–a^0$.[24] Since abatement levels do not increase as costs fall, the abatement cost effect for permits, 0*hi*, is lower than that for taxes, 0*hj*. However, here the innovating firm also gains from its emissions payment effect, *hsri*. Together these direct gains exceed those for the innovating firm under the emissions tax by area *ijsr*. On the other hand, the innovator extracts a smaller royalty than under the emissions tax, due to the combination of the lesser abatement cost effect (net of the imitation effect) with the adoption price effect. Suppose a non-innovator were to use the imitation rather than the patented technology; it would reduce abatement to a_p^s (where marginal abatement costs equal the new equilibrium permit price) and then purchase $a^0 - a_p^s$ extra emissions permits. Thus, the non-innovator is willing to pay only the shaded area 0*qi* in Figure 2b to acquire the patented technology, which is smaller than that with the tax by area *qlji*. Overall, the total private benefit from innovation under auctioned permits is *n* times *0hi* (the abatement cost effect), plus *hsri* (the emissions payment effect), less (*n*–1) times 0*hk* (the imitation effect), less (*n*–1) times *kqi* (the adoption price effect).[25]

Thus, in theory, whether innovation incentives are highest under the emissions tax or auctioned permits is ambiguous. This determination depends crucially on the strength of the imitation effect, and hence the ability to appropriate the gains to non-innovators. Suppose imitation were perfect (s=1), so that the innovator does not appropriate any of the gains to other firms in the lower panels of Figures 1 and 2. Innovation incentives are greater under auctioned permits by area *ijsr* in Figure 2a. Suppose instead that no imitation is possible (s=0). In this case the innovator would extract (*n*–1) times area *hjiu* more in royalties from non-innovators under the emissions tax than under emissions permits. This extra gain is likely to dominate area *ijsr* in Figure 2a when the number of non-innovators is significant. In short, we would expect there to be some critical imitation rate below which an emissions tax provides the most incentive for innovation and above which auctioned permits provides the most incentive.

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[23] To be more precise, the effects as described in equation (2.8) are all on the margin; in these figures, the marginal abatement cost effect is 0*j* and the imitation effect is s times 0*l*.

[24] In equilibrium the permit price must equal marginal abatement costs. If, for example, it was above marginal abatement costs, then all firms would try to increase abatement to sell emissions permits, and this would reduce the permit price.

[25] At the margin, under auctioned permits, 0*i* is the abatement cost effect, $t'(k)ir$ the emissions payment effect, s times 0*q* the imitation effect, and $t'(k)qi$ the adoption price effect.

Finally, suppose that permits were given out for free. In this case the incentives for innovation are less than under auctioned permits since the emissions payment effect at the innovating firm (rectangle *hsri*) is absent. Free permits therefore also induce less innovation than the emissions tax, since both the abatement cost effect and the royalty received from non-innovators is smaller.

Table 2 summarizes these results. Innovation under the emissions tax is less than the first-best amount (due to the imitation effect), except possibly when marginal environmental benefits are declining. Innovation under free permits is always less than under auctioned permits or the tax. Under auctioned permits, innovation could be greater or less than under the tax, depending on the relative strength of the emissions payment effect.

Table 2: Relative Incentives for Innovation

Level of policy instruments[a]	Marginal environmental benefits	Innovation under emissions tax relative to first-best innovation	Innovation under auctioned permits relative to innovation under emissions tax	Innovation under free permits relative to innovation under emissions tax
1. Ex ante Pigouvian policies	constant	less	greater or less	less
	declining	greater or less	greater or less	less
2. Ex post Pigouvian policies	constant	less	same	same
	declining	greater or less	same	less

[a] Our main focus is on ex ante Pigouvian policies.

(ii) Welfare Effects

High levels of innovation are not always indicative of welfare maximization. Innovation is costly and therefore only desirable to the extent that the marginal gains from innovation exceed the cost. In particular a social planner will weigh the decrease in abatement costs, net of any change in the optimal abatement level, against the innovation cost. While decentralized policies provide similar incentives to innovate, they are potentially distorted by the imitation, emission payment, and adoption price effects, as well as policy stickiness. As a result, the welfare ranking of the different policies is even more ambiguous than the ranking of innovations incentives, particularly when the slope of marginal benefits is taken into account.

Suppose first that marginal environmental benefits are constant and equal to t in Figure 1 (or $t(0)$ in Figure 2). The total social benefit from innovation (gross of innovation costs) in the first-best outcome is n times triangle $0hj$. Society gains both from reducing abatement costs at the ex ante optimal abatement level a^0 and from additional environmental benefits (net of costs) from increasing abatement to a^1. These gains exceed the private benefit from innovation under the Pigouvian emissions tax by the amount of the imitation effect aggregated over the (*n*-1) firms. As a result, the induced amount of innovation under the tax is less than the socially optimal level. However, given the amount of innovation, emissions abatement is optimal, since the emissions tax (and hence marginal abatement costs) equals marginal environmental benefits.

As discussed above, innovation under free permits is less than under the emissions tax and hence even further below the socially optimal amount. In addition, the ex post abatement level is also sub-optimal since abatement does not increase as marginal abatement costs fall. Therefore, welfare is unambiguously lower than under the emissions tax, when marginal environmental benefits are constant.

As shown in section 3, welfare is typically lower under auctioned permits than under the emissions tax with constant marginal environmental benefits. The exception is the case when innovation is greater under auctioned permits than under the emissions tax, *and* the welfare gain from this extra innovation more than outweighs the welfare loss from sub-optimal (ex post) abatement levels.

Now suppose marginal environmental benefits decline monotonically, and therefore are lower at a^1 than a^0 in Figure 1. Thus, starting with Pigouvian tax *t*, given any positive amount of innovation, the emissions abatement under a tax will be socially excessive, because marginal abatement costs will exceed marginal environmental benefits. In addition, innovation may now exceed the first-best amount, if the excessive demand for innovation from the abatement cost effect more than outweighs the negative influence of the imitation effect.

Under free emissions permits innovation is necessarily below the socially optimal amount. This is because emissions abatement is less (not greater) than ex post optimal levels, and because of the imitation effect. Insufficient innovation is also likely under auctioned permits, except possibly when the emissions payment effect is relatively strong. Overall welfare may be greater under any of the three policies, depending on which policy induces abatement and innovations levels that are closer to first-best levels. As illustrated below, this crucially depends on the relative slope of the marginal environmental function and the strength of the imitation effect.

(iii) Policy Adjustment

Finally, we consider very briefly what happens when policies are perfectly flexible and are adjusted to the new Pigouvian levels following innovation.[26] Suppose the tax, or quantity of permits, are adjusted such that emissions abatement is optimal given the ex post state of technology. When the innovator anticipates this policy adjustment, taxes and auctioned permits become functionally equivalent policies. When marginal environmental benefits are constant, free permits are equivalent as well. Ex post abatement levels, and hence

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[26] We do not consider optimal (second-best) policies because they would be difficult to implement in practice. To estimate optimal policies would require information on the costs and benefits of both innovation and pollution abatement.

the abatement cost effect, are identical under all policies. In addition, the quantity of permits is reduced to prevent the emissions price from falling and hence there are no emissions payment or adoption price effects. However, innovation is still below the first-best level in each case to the extent that there is an imitation effect.

When marginal environmental benefits are declining, abatement does not expand as much relative to the constant marginal benefits case, and the abatement cost effect becomes smaller on the margin. At the same time, the emissions price falls under each policy following innovation. The resulting adoption price effect causes appropriable gains to fall even more. For the tax and auctioned permits, where the innovator is liable for his or her own inframarginal emissions, the emissions payment effect provides some added inducement to innovate. However, this effect is absent under free permits, causing innovation to be lower for this policy.

Thus, the welfare discrepancies between policies would tend to disappear if policies could be continuously adjusted to their Pigouvian levels in response to every new innovation (except in the case when the emissions payment effect is significant and leads to less innovation under free permits). In practice, policy instruments are not perfectly flexible--they can only be adjusted at discrete points in time. Nonetheless, in general, the smaller the amount of innovation during the period for which policies are fixed, the smaller is the relative welfare discrepancy between policies.

3. NUMERICAL ANALYSIS

We now explore the quantitative importance of the results in Section 2 by specifying functional forms for the previous model and solving numerically. This procedure is described in Subsection A. Subsection B presents the simulation results of the numerical model. Subsection C summarizes some tentative policy lessons from our findings.

A. Functional Forms and Model Calibration

We assume the following functional forms:

$$nC(a,k) = e^{-k}\,\frac{(an)^2}{2} \tag{3.1}$$

$$F(k) = f\,\frac{k^2}{2} \tag{3.2}$$

$$B(an) = ban - \frac{\mathsf{a}}{2}(b-an)^2 \tag{3.3}$$

where k is the innovation level, a is the emissions abatement level for each firm, n is the number of firms and f, b and a are parameters.

Equation (3.1) specifies emission abatement costs with $C(a,k)$ representing the abatement costs at a single firm. The costs of abatement decline exponentially with innovation, k. Thus, it becomes increasingly difficult to generate additional reductions in abatement costs through innovation as abatement costs fall towards zero. For a given state of technology, emissions abatement costs are quadratic.[27] Equation (3.2) specifies the costs of innovation. These costs are also quadratic and the parameter *f* determines the slope of the marginal cost of innovation.[28] Finally, equation (3.3) specifies environmental benefits from emissions abatement. When $\alpha=0$, marginal environmental benefits are constant, and when $\alpha>0$, marginal environmental benefits are declining.

Equations (3.1)–(3.3) can be combined to form an expression for welfare that is analogous to equation (2.9):

$$W(an,k) = B(an) - nC(a,k) - F(k) = ban - \frac{\alpha}{2}(b-an)^2 - e^{-k}\frac{(na)^2}{2} - \frac{f}{2}k^2 \qquad (3.4)$$

The numerical model maximizes this expression by solving first order conditions analogous to equations (2.10) and (2.11), yielding the first-best outcome a^* and k^*. Writing the optimal abatement level in the absence of innovation as a_0, we define the welfare gain from innovation as:

$$W(a^* n, k^*) - W(a_0 n, 0) - F(k^*)$$

That is, environmental benefits net of abatement costs with innovation ($a = a^*$, $k = k^*$), less environmental benefits net of abatement costs with no innovation ($a = a^0$, $k = 0$), less innovation costs.[29]

To obtain the outcomes under alternative policies, we first note that the cost function per firm defined by (3.1), namely $C(a,k) = ne^{-k}a^2/2$, can be used to solve for firm-level abatement in response to a tax or permit price *t* and at a particular innovation level *k*:

$$a(k,t) = \frac{t}{ne^{-k}}$$

Using this expression, we write out the profit function for the innovator. From (2.4) and (2.6) this is:

$$\pi(k) = -nC(a,k) + (n-1)C(a^{\sigma}, \sigma k) - t(k)(e - a - \bar{e}) + (n-1)t(k)(a - a^{\sigma}) - F(k) \qquad (3.5)$$

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[27] We normalize the slope of the industry-wide marginal abatement cost function to unity. That is, the second derivative of aggregate costs *nC(a, k)* with respect to aggregate abatement *na* is one (when *k* = 0). We normalize costs in this way so that the socially optimal level of aggregate abatement and innovation is independent of the number of firms. Otherwise, in our examination of the effect of market size on policy choice, it would be difficult to vary the number of firms without simultaneously affecting the degree to which optimal innovation shifts the marginal abatement cost curve.

[28] The assumption of increasing marginal costs from innovation seems plausible, due to the increasing scarcity of specialized inputs, such as scientists and engineers, at higher levels of research activity. However, our results are not sensitive to assuming constant marginal costs of innovation.

[29] This welfare gain corresponds to *n* times area 0*hj* in Figure 1, less innovation costs.

where $a^{s} = a(sk, t(sk))$ and $a = a(k, t(k))$. As before, s is the degree to which other firms can imitate the innovation, *e* is the uncontrolled emission level, and $\bar{e}$ is the number of permits freely given to each firm. For the emissions tax, *t* is a constant and set equal to $B'(a_0 n)$ where $B'(a_0 n) = C_a(a_0, 0)$; this marginal benefit defines the Pigouvian tax prior to innovation (see Figure 1). Under permits the quantity of abatement is fixed at a_0, and the permit price is endogenously determined. $\bar{e}$ equals $e - a_0$ in the case of free permits, and is zero for the other two policies. We substitute (3.1)–(3.3) into (3.5) and the profit functions under alternative policies are maximized numerically to determine the innovation level *k*. The welfare gain from innovation under each policy, $W(na, k) - W(na_0, 0) - F(k)$, is then computed and expressed as a fraction of the welfare gain in the first-best outcome (thus, the relative welfare gain cannot exceed unity).

In this model, the relative welfare impacts of alternative policies depend on five important parameters: (i) the extent of imitation, s; (ii) the innovation cost parameter *f*; (iii) the initial level of abatement/environmental benefits, *b*; (iv) the relative slope of the marginal environmental benefit curve, a; (v) the number of firms, *n*. We begin by creating a benchmark scenario. The choice of initial parameter values for this benchmark is necessarily somewhat arbitrary. However we subsequently explore how each parameter affects the welfare ranking of alternative policies, under a wide range of assumed values.

We begin by assuming a flat marginal environmental benefit curve, a = 0, and we set *b* = 0.2 to imply an optimal emissions reduction of 20 percent before innovation.[30] The parameter *f* is chosen to imply that innovation in the first-best outcome would reduce abatement costs by 20 percent over the period (*f* = 0.11).[31] We assume *n* = 100 to approximate a competitive market (thus the innovator's emissions are small relative to total emissions). Finally, we begin by considering all possible values for s $(0 \leq s \leq 1)$ and subsequently a "high imitation" case (s = 0.25) and a "low imitation" case (s = 0.75).[32]

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[30] This translates further into a_0 = 0.2 under the permit policies ($\bar{e}$ = 0.8 for free permits) and *t* = 0.2 under the emissions tax. The assumption of flat marginal environmental benefits appears to be a reasonable approximation for a number of pollutants including sulfur dioxide (Burtraw et al., 1997) and carbon dioxide (Pizer, 1998).

[31] It is very difficult to estimate ex ante the costs of developing cleaner production technologies. Instead, we assume different scenarios for the amount of innovation (in the first-best case), and infer the value of *f* that would generate these innovation levels.

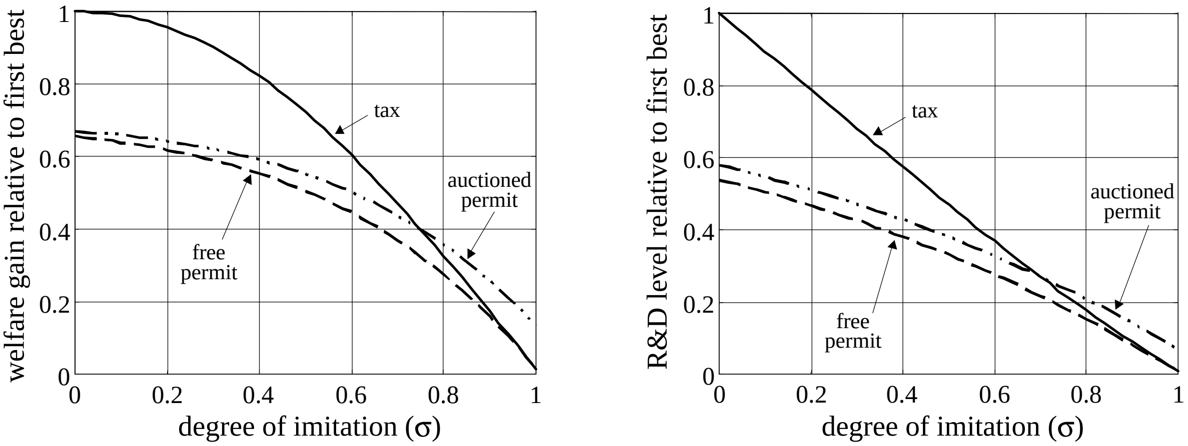
[32] Under the emissions tax the innovator appropriates approximately 1–s of the private benefits to other firms from innovation. The appropriation rate is somewhat less than 1–s under auctioned emissions permits, since the benefits to other firms include the (non-appropriable) emissions payment effect. Studies for commercial (or non-environmental) innovations suggest that appropriation rates vary considerably over different types of innovations, with an average rate of around 50 percent. See Griliches (1992) and Nadiri (1993).

B. Numerical Results

(i) Benchmark Results: The Role of the Imitation Effect

Our first simulations highlight the role of the imitation effect. The left-hand panel of Figure 3 compares the welfare gain from innovation under each policy instrument, expressed relative to that in the first-best outcome, using our benchmark parameter values. These relative welfare gains are shown as a function of the imitation rate, varying from 0 to 100 percent.[33] The right hand panel indicates the corresponding amount of innovation under each policy, again expressed relative to the first-best amount of innovation. Figure 3 displays several noteworthy features.

Figure 3: Benchmark Simulations of Alternative Policies



First, and not surprisingly, the absolute amount of, and welfare gain from, innovation under each policy falls dramatically as the imitation effect increases. For example, under the emissions tax the amount of, and welfare gain from, innovation declines from 100 percent of the first best levels when $s = 0$ to practically zero percent when $s = 1$. A stronger imitation effect reduces the ability of the innovator to capture the benefits of innovation to other firms.[34]

Second, however, the *relative* performance of policy instruments also critically depends on the imitation effect. With no imitation ($\sigma = 0$), taxes provide a much greater incentive to innovate than free or auctioned permits in our benchmark scenario: innovation under free and auctioned emissions permits is less than 60 percent of that under the emissions

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[33] When there is no imitation (s=0), the innovator appropriates 100 percent of the private gains from innovation to other firms under the emissions tax and free permits, and somewhat less than 100 percent under auctioned permits (see previous footnote). When there is perfect imitation (s=1), the innovator obtains none of the benefits to other firms under all policies.

[34] As mentioned earlier when more than one firm conducts R&D, competition for innovation can be excessive. Parry (1998) discusses to what extent this effect may mitigate the negative incentives from imperfect appropriation.

tax. Essentially, the emissions tax induces additional emissions abatement as (marginal) abatement costs fall, while emissions permits do not. With more abatement over which to garnish cost savings under the tax, the abatement cost effect is larger and the willingness to pay for improved abatement technologies is greater. Under our benchmark assumptions of flat marginal environmental benefits, this additional abatement is also socially efficient.

As the potential for other firms to imitate increases, the innovator appropriates less of the abatement cost effect of other firms. This imitation effect has a disproportionate impact under the emissions tax since the abatement cost effect is larger under this policy. As a result, this policy loses its relative advantage, as all policies underprovide innovation. Furthermore, the emissions payment effect from auctioned permits becomes relatively more important when the innovator appropriates very little from other firms. Indeed, at some rate of imitation, innovation and welfare are highest under auctioned permits. However in absolute terms any gain from using auctioned permits over other instruments is never very substantial in our benchmark scenario. Figure 3 illustrates a counter-example to previous theoretical studies which appear to imply a general preference for auctioned permits over other instruments on the grounds of innovation incentives.[35]

(ii) <u>The Implications of Declining Marginal Environmental Benefits</u>

Figure 4 illustrates the welfare implications of declining marginal environmental benefits. On the horizontal axes we vary the (magnitude of the) slope of the marginal environmental benefit curve between one tenth and ten times the slope of the marginal abatement cost curve. We do this by pivoting the marginal environmental benefit curve about the initial Pigouvian abatement level of 20 percent (a^0 in Figures 1 and 2). The level of policy instruments--and hence the induced amount of innovation and abatement--are constant in this exercise: varying marginal environmental benefits affects first-best outcomes but not the policy-induced outcomes. The left and right hand panels in Figure 4 correspond to our low and high imitation scenarios respectively.

The left-hand panel illustrates that the relative slope of the marginal environmental benefit function crucially influences the welfare ranking of alternative policies. When the marginal environmental benefit curve is flatter than the marginal abatement cost curve ($a<1$), welfare is significantly higher under the tax; when marginal environmental benefits are relatively steep ($a>1$), welfare is higher under the permit policies, possibly by a dramatic

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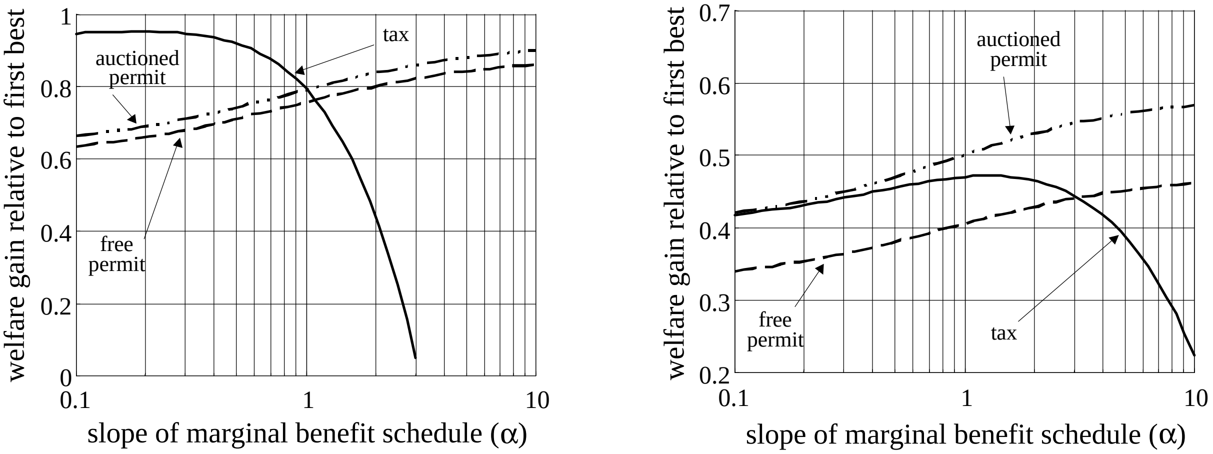
[35] It should be noted that while policy rankings according to innovation level and welfare are the same in Figure 3, this is not always the case. Since welfare depends on both abatement and innovation level, as shown in (3.2), one policy might induce the right level of innovation and another the right level of abatement. In our benchmark case, the tax always induces the correct level of abatement since marginal environmental benefits are equal to the tax rate. In order for a permit scheme to have a higher welfare gain than a tax scheme, not only must the innovation level under a permit scheme be closer to the socially optimal level, but it must be closer by a margin large enough to offset the incorrect abatement level under the permit scheme. This explains why, in our scenario, innovation is higher under auctioned permits when $s>0.70$, but welfare is greater under auctioned permits only when $s>0.73$.

amount. The emissions tax is better than permits at approximating the marginal environmental benefit curve when this curve is relatively flat. Thus, the extra emissions abatement and willingness to pay for abatement technologies under the tax is socially efficient in this case. However, when the marginal environmental benefit curve is relatively steep, innovation and emissions abatement under the permit policies, though sub-optimal, are still closer to the first-best levels than under the emissions tax. Under the emissions tax, the abatement cost effect is "too large," and more than compensating for the imitation effect in the left-hand panel. Thus, innovation and ex post abatement levels are both socially excessive.

Figure 4: Effect of Marginal Benefit Slope on Welfare Gains



(low imitation scenario, σ = 0.25) (high imitation scenario, σ = 0.75)

In the high imitation scenario the incentives for innovation are sub-optimal under all policies and the welfare gain curves are shifted down (the right hand panel of Figure 4). Again, as the marginal environmental benefit curve becomes steeper it becomes more likely that welfare is higher under permits than under the tax.[36] Auctioned emissions permits induce a more substantial welfare gain over free permits in this case. This result reflects the relative importance of the emissions payment effect at the innovating firm when the innovator appropriates only a small amount of the benefits to other firms.[37]

Figure 4 illustrates the potential danger from ranking environmental policies based on how much innovation they induce, rather than their overall welfare impact. When the imitation

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[36] However, note that welfare under taxes exceeds that under free permits over a wider range of values for a in the right hand panel than the left-hand panel. Even when marginal environmental benefits are relatively steep and abatement is excessive under the emissions tax, up to a point this policy may still be more efficient overall than free emissions permits. This is because the greater incentives for innovation under the tax, due to the higher abatement cost effect, now serves to mitigate the inadequate incentives due to high imitation (in contrast in the low imitation scenario this higher abatement cost effect is more likely to induce excessive innovation).

[37] Indeed auctioned permits perform slightly better than the emissions tax even when marginal environmental benefits are relatively flat. In this case abatement under the tax is closer to the first-best level. However, innovation is closer to the first-best level under auctioned permits because of the emissions payment effect.

effect is relatively weak, as in the left panel, the emissions tax induces the most innovation. However, when the marginal environmental benefit curve is steeper than the marginal abatement cost curve the emissions tax produces the smallest welfare gain. This result is reminiscent of Weitzman's (1974) result concerning instrument choice in the presence of uncertainty: steep marginal benefits favor permits. The reason is the same: when marginal costs are shifting after policy has been set--either due to random shocks or to innovation--the policy that most closely mimics the relative slope of the marginal benefit curve will perform better.

(iii) Alternative Scenarios for Innovation Costs

Figure 5 illustrates how the cost of innovation affects the relative welfare ranking (returning to our benchmark assumption of flat marginal environmental benefits). As the costs of innovation (*f*) increase both the amount of innovation under each policy and the downward shift in the marginal abatement cost curve decline. This reduces the relative importance of the larger abatement cost effect and willingness to pay for abatement technologies under the emissions tax. Consequently, the relative welfare discrepancy between the tax and permits policies is smaller as firms in the low imitation scenario (the left-hand panel of Figure 1). As the amount of induced innovation becomes very small the welfare impacts of the policies almost converge.[38] Conversely, when the potential for innovation is large there is a much greater welfare discrepancy between the tax and emissions permits.[39]

In the right-hand panel of Figure 5, the stronger imitation effect reduces the amount of, and hence the welfare gain from, innovation under all three policies. The proportionate reduction in welfare is greater under the emissions tax, because the imitation effect is relatively more important under this policy due to the higher level of abatement. Auctioned permits typically induce the highest welfare gain in this high imitation scenario, since the emissions payment effect is relatively more important.[40]

As discussed in Section 2, all the policies would induce the same welfare gain if they could be instantly adjusted to their ex post level in response to innovation (at least when

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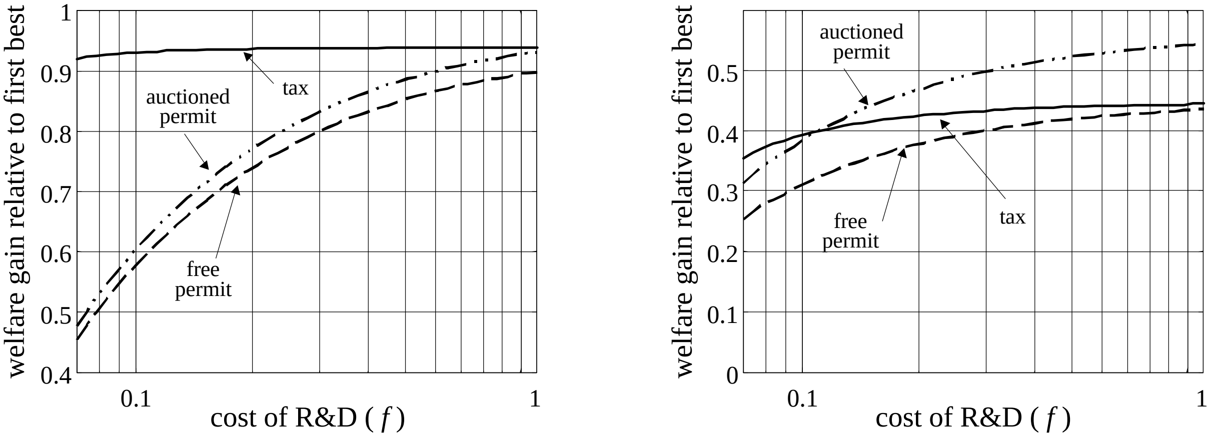
[38] Nordhaus (1997) makes the point that the amount of induced innovation is likely to be small if emissions are tied directly to input usage and if the price change in the polluting input is small. For example, in the case of carbon dioxide abatement is directly related to reduced energy use. Since energy is already priced in the marketplace, firms already have an incentive to find energy (and carbon) saving innovations. Government policies to reduce carbon dioxide emissions simply add to this incentive. Therefore without substantial increases in the price of energy, he argues it is unlikely that induced innovation will be large.

[39] For example, in our benchmark, f=0.11, optimally inducing a 20 percent reduction in abatement costs. When f=0.07, innovation reduces abatement costs by nearly 35 percent under the tax, and the induced welfare gain is twice as large as under emissions permits. When $f = 1$, on the other hand, innovation reduces abatement costs by less than 3 percent under all policies.

[40] Note that the amount of innovation need not be large in order for there to be important welfare discrepancies among policies. When f=1 welfare is 20 percent higher under auctioned permits than under the tax and free permits in the right hand panel of Figure 5. The discrepancy would be even larger if marginal environmental benefits were declining. Thus concern about proper policy choice in the presence of innovation need not focus on large amounts of innovation.

marginal environmental benefits are constant). In practice, policy instruments can only be adjusted at discrete points in time rather than on a continuous basis. "Innovation" in our analysis effectively represents the cumulative amount of innovation over the period for which environmental policies are fixed (at their Pigouvian levels). At least for the emissions tax and free emissions permits, Figure 5 indicates that the welfare discrepancies between policy instruments are less significant when there is less innovation. Thus, in practice the welfare loss from using free emissions permits over an emissions tax may not be very important if little innovation is occurring.

Figure 5: Effect of R&D Costs on Welfare Gains

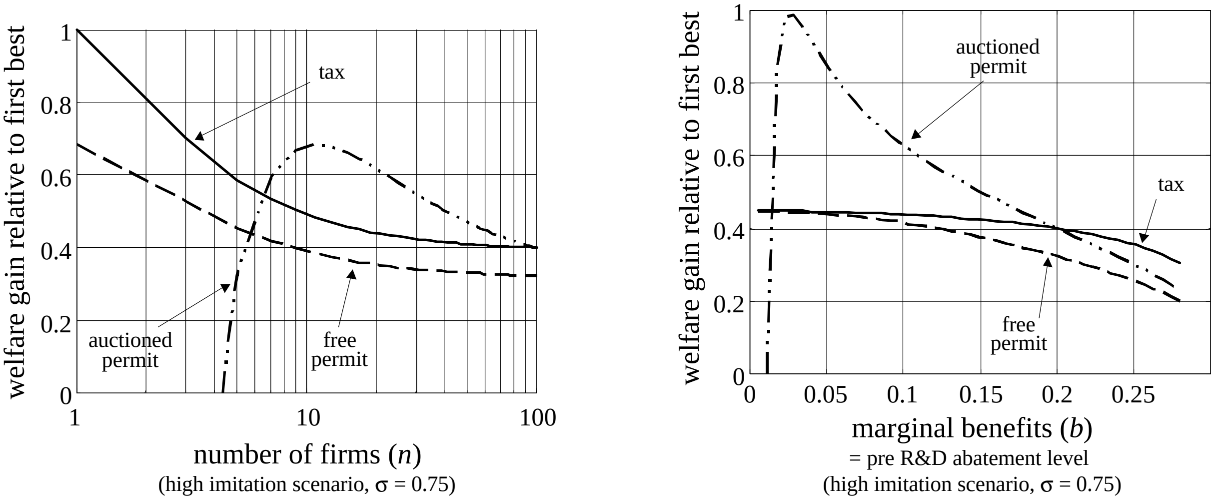


(low imitation scenario, σ = 0.25) (high imitation scenario, σ = 0.75)

(iv) <u>Number of Firms and Benefit Level</u>

Figure 6 highlights the importance of both market size (left panel) and the level of environmental benefits/initial abatement (right panel). Both panels show cases where the emissions payment effect under auctioned permits becomes large relative to the other determinants of innovation incentives, leading to dramatically higher levels of innovation and, in the extreme, too much innovation. With only a few firms, the emission payment effect becomes large because the innovator is purchasing a significant fraction of the auctioned permits. We also observe that innovation and welfare rise for both taxes and free permits since the imitation effect is smaller when there are fewer firms to imitate. The initial level of abatement/marginal environmental benefits works in a slightly different way. Rather than affecting the size of the emissions payment effect, this variation changes the abatement cost effect: when abatement and benefits are low, the abatement cost effect is necessarily small. The emissions payment effect then becomes *relatively* more important and can, in the extreme, induce too much innovation. At high initial abatement/environmental benefit levels, we see effects similar to the effect of low innovation costs: considerable innovation and an increasing preference for taxes under the benchmark assumption of flat marginal benefits.[41]

Figure 6: Effect of Number of Firms and Benefit Level on Welfare Gain



(v) Further Sensitivity Analysis

Varying each parameter individually as we have done above may obscure some important interactions among parameter combinations. For the interested reader we provide Table 3 in the appendix that illustrates the implications of varying all parameters simultaneously. For each parameter we consider "high" and "low" values, and for each combination of parameter values we show both innovation and welfare under each policy relative to the corresponding levels in the first-best outcome.

There are several points in this table worth noting that have not already been mentioned. For example, so far we have only seen situations where either taxes or auctioned permits are preferred. Consider the case of high imitation, steeply sloped marginal environmental benefits, low innovation costs, a small number of firms, and high benefits/abatement, as shown in the last line of Table 3 (case #32). Free permits outperform both taxes and auctioned permits. In this situation, auctioned permits lead to too much innovation while taxes lead to too much abatement. We can also see those situations where the emissions payment effect generates far too much innovation, namely when there are a small number of firms and a small level of initial abatement (cases #3, 7, 11, 15, 19, 23, 27, and 31). As noted in the last section, each of these situations by

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[41] These results are obviously interdependent as discussed below. At higher initial levels of abatement, a small number of firms will not necessarily lead to an excessive emissions payment effect. Similarly, with a large number of firms, low initial abatement will not as easily diminish the abatement cost effect to the point where it is dwarfed by emissions payment effect. In the case of market size, the results may also be sensitive to our assumption that innovators behave competitively. This assumption is less plausible when the number of firms producing emissions is very small.

themselves generates a relatively large emissions payment effect. Together, the consequences are extremely adverse. Finally, we can see cases where taxes induce far too much innovation: when marginal benefits are steep and innovation incentives are large (low innovation costs and high abatement/benefit levels). A relatively weak imitation effect induces more than twice the first-best amount of innovation and leads to large negative welfare consequences (cases #14 and #16). If the imitation effect is relatively strong this is not as much of a problem since the innovation level is already too low.

C. Lessons for Policy

The above discussion illustrates that no unambiguous case can be made for preferring one environmental policy instrument over other instruments in the presence of endogenous technological innovation. Under certain circumstances (i.e. combinations of parameter values) one policy instrument can perform significantly better than the other instruments, while under other circumstances that instrument may be significantly worse than the other instruments. Nonetheless, we can still draw some rough policy guidelines.

First, in cases where imitation opportunities are low and diffusion is wide, what matters is inducing the optimal level of emissions abatement over time. If marginal environmental benefits are relatively flat an emissions tax is the most efficient instrument for this. If marginal environmental benefits are steep relative to the marginal cost of emissions abatement then free or auctioned permits are the more efficient policies.

Second, when imitation rates are high and gains to adopters are hard to appropriate, auctioned emissions permits may induce the highest welfare gain. However, the danger exists that this policy may induce excessive innovation when the number of polluters or the initial abatement level is small.

Third, the welfare discrepancies between policies are generally less important when less innovation is performed during the period for which policy instruments are "sticky". Conversely, if policy instruments can be adjusted at regular intervals over time in response to innovation, the choice of specific policy instrument will matter less. However, while regular adjustment will ensure greater ex post efficiency, some innovation incentives risk being compromised when the innovating firm rationally expects the policy adjustments. Essentially, endogenous policy adjustments create an adoption price effect which, in aggregate, can outweigh the emissions price effect to the innovating firm and reduce innovation incentives. In some cases, the extra innovation incentive of a fixed tax can outweigh the ex post efficiency loss from over-abatement and provide a higher welfare gain than the adjusted policy. However, our initial simulations indicate that this improved performance is slight compared to the gains from adjusted taxes or auctioned permits when the naive policies are performing poorly.

4. CONCLUSION

In this paper we present an analytical and numerical comparison of the welfare impacts in the innovation market induced by emissions taxes and both free and auctioned emissions permits. Contrary to earlier theoretical work we do not find a general preference for auctioned permits over emissions taxes, and emissions taxes over free permits, on the grounds of their incentives for innovation. Under different circumstances, either auctioned permits or taxes can induce larger amounts of innovation but, more importantly, *any* of the three policies can have significantly greater welfare gains than the other two policies. In particular, the relative ranking of policy instruments can crucially depend on a number of key factors: the scope for imitation, the costs of innovation, the relative level and slope of the marginal environmental benefit function, and the number of firms producing emissions. Thus, a more pragmatic approach to instrument choice, one that evaluates the circumstances specific to a particular pollutant, appears to be more appropriate.

For practical purposes, sometimes the welfare discrepancies between policy instruments are not very important. This situation is more likely the smaller the amount of innovation that occurs during the period for which the level of regulation is fixed. Thus, the intertemporal flexibility of policy instruments is important. The welfare discrepancy between the most and least efficient policies may be quantitatively unimportant, if policies can be adjusted at regular intervals in response to innovation. However, policy adjustments, when expected, may trade off ex post abatement efficiency against some ex ante innovation incentives.

Our analysis ignores a number of complications that might be worth exploring in future research. We abstract from heterogeneity in the willingness of firms to pay for cleaner technologies and the possibility of strategic behavior. We also assume the innovation process is deterministic. In reality, the fruits of innovation investments can be highly uncertain.[42] Our analysis compares policies on welfare grounds. Sometimes (particularly when environmental benefits are highly uncertain) the policy objective may be to minimize the cost of stabilizing environmental quality at a target level. This alternative criterion may affect the appropriate choice of policy instrument. We also assume that technological innovation results exclusively from deliberate investments in innovation activity. More generally, firms may "learn by doing" and become more efficient at pollution abatement as they gain more experience over time.[43] Finally, if pollution damages depend on the stock of pollution rather than the annual flow, the relative timing of and policy emphasis on innovation versus abatement activities may be an important issue.

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[42] For a discussion of how uncertainty over the costs and benefits of R&D may affect the relative efficiency of research (as opposed to environmental) policies see Wright (1983).

[43] Goulder and Mathai (1998) model technological innovation arising from both R&D investments and learning by doing in the context of optimal carbon taxes. Although there are some subtle differences between these two formulations, they find that in practice there is little difference between the optimal tax in each case.

APPENDIX

Table 3: Interaction of Alternative Parameter Values

case	imitation level	MB slope	innovation costs	number of firms	MB level	optimal shift in MC	welfare (relative to 1st best)			innovation level (relative to 1st best)		
							tax	auction	free	tax	auction	free
1	low	low	high	high	low	0.02	0.94	0.95	0.89	0.75	0.87	0.70
2	low	low	high	high	high	0.25	0.93	0.57	0.56	0.73	0.43	0.41
3	low	low	high	low	low	0.02	0.97	-22.69	0.92	0.83	5.70	0.78
4	low	low	high	low	high	0.25	0.97	0.20	0.60	0.82	1.15	0.47
5	low	low	low	high	low	0.06	0.94	0.87	0.81	0.75	0.77	0.63
6	low	low	low	high	high	0.77	0.99	0.13	0.13	0.95	0.16	0.15
7	low	low	low	low	low	0.06	0.97	-14.31	0.85	0.83	4.55	0.71
8	low	low	low	low	high	0.77	0.99	0.11	0.14	0.96	0.41	0.18
9	low	high	high	high	low	0.02	0.93	0.97	0.91	0.77	0.89	0.72
10	low	high	high	high	high	0.19	0.72	0.76	0.73	0.98	0.58	0.55
11	low	high	high	low	low	0.02	0.96	-23.25	0.95	0.85	5.85	0.80
12	low	high	high	low	high	0.19	0.63	0.26	0.79	1.10	1.55	0.64
13	low	high	low	high	low	0.06	0.92	0.93	0.86	0.80	0.82	0.67
14	low	high	low	high	high	0.41	-15.90	0.59	0.58	2.62	0.44	0.42
15	low	high	low	low	low	0.06	0.93	-15.30	0.91	0.89	4.87	0.76
16	low	high	low	low	high	0.41	-15.88	0.48	0.64	2.67	1.15	0.51
17	high	low	high	high	low	0.02	0.44	0.65	0.43	0.25	0.42	0.25
18	high	low	high	high	high	0.25	0.39	0.35	0.30	0.21	0.20	0.17
19	high	low	high	low	low	0.02	0.75	-20.90	0.72	0.50	5.52	0.48
20	high	low	high	low	high	0.25	0.69	0.29	0.49	0.44	1.10	0.33
21	high	low	low	high	low	0.06	0.43	0.61	0.40	0.25	0.39	0.23
22	high	low	low	high	high	0.77	0.16	0.09	0.08	0.14	0.09	0.08
23	high	low	low	low	low	0.06	0.74	-13.63	0.67	0.49	4.47	0.45
24	high	low	low	low	high	0.77	0.39	0.11	0.13	0.38	0.41	0.14
25	high	high	high	high	low	0.02	0.45	0.67	0.44	0.26	0.43	0.25
26	high	high	high	high	high	0.19	0.47	0.46	0.40	0.29	0.27	0.23
27	high	high	high	low	low	0.02	0.75	-21.42	0.74	0.51	5.66	0.49
28	high	high	high	low	high	0.19	0.74	0.38	0.65	0.59	1.47	0.44
29	high	high	low	high	low	0.06	0.46	0.65	0.43	0.27	0.42	0.25
30	high	high	low	high	high	0.41	0.51	0.40	0.35	0.39	0.25	0.21
31	high	high	low	low	low	0.06	0.75	-14.57	0.72	0.52	4.78	0.48
32	high	high	low	low	high	0.41	-0.28	0.49	0.56	1.05	1.14	0.40

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