On the Implications of Technological Innovation for Environmental Policy

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Abstract

This paper draws on a number of recent studies to shed light on several policy issues raised by the impact of environmental policies on technological innovation. First, to what extent does induced innovation raise the overall net benefits to society from environmental policies? Second, how does induced innovation affect the appropriate choice among alternative environmental policy instruments? Third, how does it affect the optimal stringency of environmental regulations? Fourth, should environmental policies be supplemented with additional policies to promote innovation, such as research contracts or prizes for new technologies?

Key Words: environment, technological innovation, pollution control, instrument choice

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Ian W.H. Parry *

1. Introduction

In recent years, economists have expanded the traditionally static analysis of environmental externalities to take into account the influence of environmental policies on the development of cleaner production technologies. This new research raises a number of important policy questions. First, how does the impact on technological innovation affect the overall net benefits to society from environmental policies? Second, how does the role of innovation affect the appropriate choice among different environmental policy instruments, such as tradable emissions rights and pollution taxes? Third, does it also affect the optimal stringency of environmental regulations? Fourth, should environmental policies be combined with additional policies targeted directly at promoting innovation, such as research subsidies or prizes for new technologies? This paper offers some preliminary thoughts on these policy questions based on pulling together a selection of recent studies. It is *not* a survey of the literature on environmental policy and technological change: this has been carefully reviewed elsewhere (e.g., Jaffe et al. 2000, Kemp 1997).

The next section sketches, heuristically, how the traditional Pigouvian model of pollution externalities might be extended to incorporate abatement cost-reducing innovation. Section 3 presents a framework for roughly assessing the magnitude of the welfare gains from induced innovation relative to the welfare gains from Pigouvian pollution control, under different

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scenarios for the speed of innovation and the initially optimal level of abatement. Section 4 discusses the choice among environmental policy instruments when technological change is endogenous. Sections 5 and 6 discuss the optimal stringency of environmental policies and the possible use of additional research stimulants. Section 7 discusses further issues and some complications in a developing country context. The final section provides some tentative policy conclusions.

Before beginning, a caveat is in order. There are other criteria on which to judge the success of environmental policies, besides their impact on economic efficiency. In particular, technological innovation may produce very substantial benefits over a period of decades by alleviating unpalatable short-run trade-offs between economic activity and the environment.[1] Therefore even if, when discounted back to the present, the savings in pollution control costs over time from innovation turn out to be fairly modest, the role of innovation may still be of primary concern to policymakers if their main objective is to ameliorate the conflicts between economic and environmental interests for future generations. For the purposes of this paper however, the focus is purely on the economic efficiency effects of environmental policies.

2. Incorporating Technological Innovation into the Pigouvian Model

Traditionally, economists have evaluated environmental policies using the static Pigouvian analysis in which the state of technology for reducing pollution is taken as given. In this framework, there is usually an upward sloping marginal cost curve for abating economy-wide emissions of a particular pollutant shown by MAC in Figure 1, where we denote the proportionate emissions reduction by a on the horizontal axis. This curve typically reflects some combination of the extra costs to firms from using cleaner but more expensive inputs in the production process, the costs of operating end-of-pipe technologies for treating waste emissions,

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[1] It is conceivable that, by the middle of the century, improvements in fuel efficiency, the spread of hybrid (electric and gasoline) vehicles, and fuel cells, will have greatly reduced pollution emissions from driving, thereby making it easier to satisfy air quality standards in regions like Los Angeles or to limit greenhouse gas emissions from transportation.

and the efficiency cost of reduced final production. The curve comes out of the origin when firms are competitive, there are no prior regulations, and the costs of pollution are external to firms.[2]

In addition, there is a marginal benefit (MB) curve drawn as flat in Figure 1 (declining marginal benefits are discussed later). This curve reflects the environmental gains from incremental reductions in pollution, such as the health benefits from cleaner air. The optimum amount of pollution abatement is a^* in Figure 1 where MB and MAC intersect, and the welfare gain achieving this abatement is triangle 0*bx*, the area between MB and MAC and between zero abatement and a^* (this assumes that abatement is less than 100%, $a^*<1$).[3]

In practice, the state of technology for pollution control is not exogenous and over time will change in response to environmental policies. If firms are penalized for producing waste emissions, they have incentives to come up with improved techniques for pollution control, so they can lower the future costs of emissions mitigation. Thus the MAC curve in Figure 1 will tend to move downwards over time in the presence of environmental policies. Consider a two-period setting where R&D into cleaner production methods is conducted in period one and pollution abatement by firms occurs in period two (we consider more periods later). R&D is costly: it involves the opportunity cost of the time of scientists, engineers, and so on, and the cost of capital inputs such as research labs.

Suppose that R&D yields technologies that, when used by firms in period two, will push down the marginal abatement cost curve to MAC′ in Figure 1. Optimal abatement would now be a' where MAC′ intersects MB. Thus, the maximum welfare gain from pollution control is now triangle 0*bw*, an increase in welfare of triangle 0*xw* over the situation with no technological

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[2] For simplicity, assume that firms are homogeneous. We note the implications of heterogeneous firms in the Appendix.

[3] We abstract from a number of complications that have been discussed elsewhere such as uncertainty over control costs, the costs of monitoring and enforcing pollution controls, and interactions with pre-existing tax distortions in the economy (see e.g. Kopp and Pizer 2001 for a review).

change. This additional welfare gain consists of the reduction in abatement costs at the originally optimal level of abatement (triangle 0*xv*) plus the welfare gain from increasing abatement from *a** to *a´*(triangle *xwv*).

Figure 2 sketches the welfare gain in the research (denoted by *R*) market. MC is the marginal cost (or supply) curve for R&D.[4] MSB denotes the marginal social benefit from R&D. The benefit from R&D is the benefit from the (expected) downward shift in the MAC curve resulting from a given amount of research effort, where the benefits are discounted back to period one. The optimum amount of R&D is *R** in Figure 2, where MSB and MC intersect. Suppose that MAC′ in Figure 1 represents the technology resulting from the optimal amount of research *R**. Then the height of the MSB curve at *R** in Figure 2 equals the marginal increase in area 0*bw* in Figure 1 that would result from a marginal increase in R&D, times the discount factor. MSB is drawn as downward sloping due to diminishing returns from research: additional amounts of research have a smaller and smaller effect on shifting down the MAC curve after the low-lying fruit has been picked.[5] The potential welfare gain from achieving *R** is given by triangle *xyz* in Figure 2, the area between MSB and MC between zero and *R**.

3. On the Magnitude of the Welfare Gains from Induced Innovation

Knowing the magnitude of the potential welfare gains from induced innovation would be particularly useful. It would reveal to what extent previous cost/benefit studies based on exogenous technology models might have understated the overall welfare gains from environmental policies (for a review of technology-constant cost and cost/benefit studies see

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[4] MC has a positive intercept because the opportunity cost of an incremental amount of labor or capital input is positive. We have drawn the curve as upward sloping, representing the increasing scarcity of specialized inputs into the R&D process, such as scientists with industry-specific knowledge.

[5] In theory, the marginal benefit from research could actually be increasing in places: although research may have a smaller and smaller impact on shifting down the MAC curve, the cost savings from a given downward shift in the MAC curve are higher at higher amounts of abatement. As discussed in Parry et al. (2000), in a dynamic context this means that the optimal amount of research could initially be increasing over time.

Morgenstern 1997, Jack 2001). Moreover, whether the welfare gains from induced innovation are large or not affects how important a consideration innovation incentives should be in the design of environmental policies, and whether theoretical differences between the innovation incentives provided by different policy instruments have much practical relevance or not.

However, estimating the potential welfare gains from induced innovation is a formidable problem. In particular, the costs of successfully discovering new technologies that will cut future abatement costs by a given amount are not known ex ante.[6] Nonetheless, we can still lay out a theoretical framework that shows the relative size of the welfare gains from innovation under different scenarios for the speed of innovation and the initially optimal level of abatement. The rest of this section describes such an approach, based on Parry, Pizer, and Fischer (2000), henceforth PPF. There are some limitations to this approach (see below), but it is still useful as a preliminary step to understanding the factors that determine the gains from innovation. For the interested reader, we provide more details on model assumptions, and how they might affect the results, in the Appendix.

An Upper Bound for the Social Benefits from Innovation. As noted above, the Pigouvian welfare gain from internalizing the pollution externality is initially 0bx in Figure 1, and assuming linearity this has area $ba^*/2$. We now consider an infinite horizon model where, without any technological innovation, the marginal benefit and marginal cost curves would be the same as those in Figure 1 across all future periods (see the Appendix for more discussion of this assumption). If the pollution externality were internalized in the current and all future periods, the present discounted value of the Pigouvian welfare gains, denoted PV^P, would be $ba^*/2r$, where r is the social discount rate.

We can do some “back-of-the-envelope” calculations to put an upper bound on the social benefit from innovation, when expressed relative to PV^P. Consider the most favorable (and

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[6] Ex post, after a new technology has emerged, it can still be difficult for the analyst to trace all the costs of the successful and unsuccessful attempts to invent the technology. Moreover, even if historical cost studies were accurate, the estimates might not be a reliable guide to the cost of further improvements in the state of technology.

highly unrealistic) scenario where new technologies completely eliminate the costs of pollution control, and these technologies can be invented and adopted instantaneously without cost. In this scenario, technological innovation leads to benefits in each period of trapezoid 0*xyu* in Figure 1, which has area $a^*b/2 + (1-a^*)b$.[7] The present discounted value of these benefits would be $(a^*b/2 + (1-a^*)b)/r$.

Using these formulas, the discounted benefit from innovation expressed relative to PV^P is simply $1+2(1/a^* - 1)$. This ratio equals 19 when the Pigouvian abatement level a^* is 0.1; it equals 3 when the Pigouvian abatement level is 0.5; and it equals 1.5 when the Pigouvian abatement level is 0.8. Thus, the discounted benefits from innovation cannot swamp the discounted Pigouvian welfare gains, if the optimal abatement level is initially fairly high. In addition, the relative benefits from innovation decline with a^*. If a^* is relatively close to the origin in Figure 1, this represents a situation where the marginal abatement cost curve is steep relative to the marginal environmental benefit curve, and there is a lot of potential for innovation to improve welfare by reducing abatement costs. Conversely if a^* is close to 1, the Pigouvian welfare gain is already large, and there is limited scope to increase this welfare gain by a given proportionate amount though moving the MAC curve downwards.

But these simple calculations may greatly overstate the relative size of the benefits from innovation. Most likely it takes a long time, perhaps decades, to accumulate and disseminate enough know-how to completely eliminate pollution, without raising the overall cost of producing products.[8] Moreover, to obtain the welfare gains from innovation we need to subtract the present value of the costs of R&D from the discounted stream of innovation benefits.

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[7] Pollution is reduced by 100% in all periods with no abatement costs implying benefits in each period of rectangle 0*byu* in Figure 1, or an improvement over the initial situation of 0*xyu*.

[8] This means that for a whole range of future periods the marginal abatement cost curve will be at a position such as MAC′ in Figure 1, that is, somewhere between MAC and the horizontal axis, and the optimal abatement level will be a', between a^* and 1. The benefits from innovation in that period will be triangle 0*xw* in Figure 1, which is smaller than trapezoid 0*xyu*, hence the present value of the benefits from innovation will be below 0*xyu*/*r*.

Scenarios for the Welfare Gains from Induced Innovation. As shown by PPF the size of PV^I/PV^P, where PV^I denotes the discounted welfare gains from innovation, boils down to three summary statistics or parameters. First, the initial Pigouvian abatement level a*, which summarizes the height of the marginal environmental benefit curve relative to the (initial) marginal abatement cost curve. Second, the speed at which innovation reduces abatement costs by a given proportion (on the optimal path for innovation). This reflects different assumptions about the costs of the R&D necessary to secure a given reduction in abatement costs.[9] Third, the discount rate, because the benefits from R&D occur in the future while the costs are upfront.

Table 1 shows calculations of PV^I/PV^P from PPF using a generic (rather than pollutant-specific) model (see Appendix for more details of the model). The first column shows values for a* ranging from 0.1-0.6 (emissions reductions of 10-60%). The next column gives PV^I/PV^P when abatement costs are reduced by 50% in 10 years, and ultimately by 100% (when the optimum amount of R&D is done over time). PV^I is about three times PV^P when the Pigouvan abatement is initially 0.1; it is about the same size as PV^P when the Pigouvian abatement level is initially 0.4, and it is 80% of PV^P when the Pigouvian abatement level is initially 0.6. But if it takes 20 years to halve abatement costs because R&D is more costly (third column), PV^I is always smaller than PV^P. For example, PV^I is 46% and 41% of PV^P when the Pigouvian abatement level is initially 0.4 and 0.6 respectively. If it takes 40 years for innovation to halve abatement costs then PV^I is only about 16% of PV^P (fourth column). In short, for PV^I to be as large as PV^P requires not only that abatement costs be substantially reduced through innovation fairly quickly (50% in 10 years), but also that the initial Pigouvian level of abatement is fairly modest.[10] By omitting induced innovation, traditional cost/benefit analyses may have

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[9] The higher the intercept of the marginal cost of R&D in Figure 2, or the steeper the slope of this curve, the smaller is PV^I for two reasons. First, the costs of R&D are greater. Second, the discounted benefits from innovation are also smaller, since the optimal pace of innovation is diminished.

[10] Interestingly, during the first decade of the sulfur-trading program, which reduced emissions by 50%, abatement costs seem to have been roughly halved (Burtraw 1996). However, not all of this cost reduction was due to innovation—a significant portion was due to deregulation of the railroads, which reduced the price of transporting low sulfur coal.

significantly understated the overall welfare gains from environmental policies. However, they may still have captured the most important component of the welfare gain.

Limitations. Several caveats should be borne in mind. First, this approach tells us nothing about the *absolute* welfare gains from innovation. In particular, the absolute welfare gains from innovation increase with the initial level of abatement a^* because there is more abatement over which to garner cost savings, even though the welfare gains relative to PV^P fall. Thus, in absolute terms, the welfare gains from induced innovation are still larger for major environmental problems (when a^* is large) compared with minor environmental problems (when a^* is small).[11] Second, for convenience we have only focused on the case when pollution control is optimal: in practice pollution is often sub-optimal, and the relative welfare gains from innovation may be somewhat different. Third, the results may be somewhat sensitive to different assumptions about functional forms, discount rates, and so on (see Appendix). Nonetheless, the above discussion is still useful as a first pass in understanding how different factors determine the magnitude of the welfare gains from induced innovation.

A couple of papers have attempted to assess the efficiency gains from technological innovation that might be induced by carbon control policies (Nordhaus 1998; Goulder and Mathai 2000). In both cases, the efficiency gains turn out to be fairly small relative to the welfare gains from emissions control

[11] Moreover, for a given a^*, the welfare gains from induced innovation will be larger in industries where abatement costs are larger relative to GDP.

4. The Choice of Environmental Policy Instrument

This section discusses various distortions in the market for environmentally focused R&D and the implications for the welfare effects of pollution taxes and grandfathered and auctioned emissions permits.[12]

Imperfections in the Research Market. The industrial organization literature identifies at least two potentially important sources of distortion in R&D markets. First, when a firm's innovation is general rather than firm specific, this leads to spillover benefits to other firms if the other firms can copy, or develop their own variants, of the technology. The public good characteristic of knowledge means that innovators may be unable to fully appropriate the social benefits of new technologies, which include the spillover benefits to other firms. Firms can apply for a patent and, if awarded, this prevents other firms from legally copying the new innovation without the consent of the patent holder. This creates monopoly power for the innovator, although it is sometimes in the innovator's interest to license out the new technology to other firms in return for a royalty fee (e.g., Carlton and Perloff 1990, pp. 676-679).

However the effectiveness of the patent system is often limited by the possibility that other firms can invent around the patent by developing their own imitations that are sufficiently differentiated from the original technology so as not to be precluded by the patent. The possibility of imitation limits the monopoly rents earned by the patent, or the amount that patent holders could charge for licensing the original technology (e.g., Mansfield et al. 1981, Levin et al. 1988). Moreover, because patents require that all the information about a new technology be disclosed, innovators may prefer not to patent, to keep this information from rival firms (at least

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[12] More traditional "command and control" approaches to curbing pollution are still in widespread use. However the inefficiencies of these policies have been recognized, and market-based approaches have been adopted in more recent policy initiatives, such as the sulfur-trading program, and are being seriously considered for controlling emissions of carbon and nitrogen oxides. The theoretical and econometric literature is limited, but it does suggest that the incentives for innovation are much weaker under command and control policies than under market-based approaches (Jaffe and Stavins 1995, Downing and White 1986, Milliman and Prince 1989). For example, under a technology forcing standard firms are not rewarded for developing new technologies that will not be part of the standard.

in the short term). Not surprisingly, appropriation rates differ considerably for different types of new technologies depending, for example, on whether they are firm specific or general. On average, innovators appear to appropriate very roughly 50% of the full social benefit from new technologies (e.g., Griliches 1992, Nadiri 1993).

A second imperfection, which works in the direction of too much R&D, is the “common pool” problem (e.g., Dasgupta and Stiglitz 1980, Wright 1983, Mankiw and Whinston 1986). A firm may not take into account the effect of its R&D on lowering the likelihood that other firms will obtain innovation rents—for example, as one firm puts more effort into developing a patentable technology, this reduces the probability the patent will go to another firm.[13] Nonetheless, empirical evidence for commercial (non-environmental) innovations seems to suggest that on balance positive externalities associated with technology spillovers dominate the common pool effect, leading to social rates of return to R&D that are substantially higher than the private rates of return (Griliches 1992, Mansfield 1996).[14]

Emissions Taxes. Again, suppose the Pigouvian emissions tax *b* is imposed in Figure 1. If there were no imperfections in the research market, the tax would induce the optimal amount of R&D, R^* in Figure 2. To see this, note that firms will initially reduce emissions by a^* in Figure 1, at which point the cost of reducing emissions by one more unit equals the benefit in terms of avoided tax payments. Suppose firms now adopt technologies that push the marginal abatement cost curve down to MAC′ in Figure 1. The private benefit to firms from adopting these technologies is triangle $0xw$.[15] But the social benefit from shifting the marginal abatement cost

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[13] The problem is analogous to the over-exploitation of a fishery: individual fishermen do not take into account their effect on depleting the stock of fish and hence reducing the expected catch of other fishermen.

[14] Another reason why R&D may be suboptimal is that lenders have less information about the prospective benefits and costs of R&D projects than firms seeking funding: externally funded R&D may be lower than when there is no information asymmetry (e.g., Hubbard 1998).

[15] This equals the reduction in abatement costs at the original level of abatement (triangle $0xv$) plus the benefit from increasing abatement to a' (triangle xwv), which equals the reduced tax payments ($xwa'a^*$) net of the additional abatement costs ($vwa'a^*$).

curve down to MAC′ is also area 0*xw* (see above). In addition, the supply curve for R&D reflects both the marginal private and the marginal social cost of research inputs. Therefore, since the private and social benefits from innovation coincides, and similarly for the costs, the emissions tax induces the optimal amount of innovation.

However, if the imperfect appropriability effect outweighs the common pool effect, the marginal private benefit (MPB) from R&D under the Pigouvian emissions tax will lie below MSB in Figure 2, and R&D will be suboptimal at a point like R_0. Conversely, if the common pool effect dominates, R&D will be too high. Are the resulting welfare losses likely to be large in magnitude or not?

Parry (1998) uses a model similar to a static version of that outlined above, to get at this issue. The results are summarized in Table 2. Here we consider scenarios when the proportionate reduction in abatement costs at firms adopting a new technology is 0.01, 0.10, or 0.40. We also consider scenarios when an innovating firm appropriates between 25% and 100% of the total benefits to polluting firms from adopting the technology. In addition, in these benchmark simulations the initial optimized pollution abatement is 20%.

The middle set of columns shows R&D under the Pigouvian emissions tax expressed relative to the first-best level of R&D. When the appropriation rate is 50% R&D is 72%–87% of the first-best amount—R&D is suboptimal because the imperfect appropriability effect more than offsets the common pool effect. However, the emissions tax still captures 92%–98% of the first-best efficiency gain (i.e., the gain when innovation is socially optimal). Only when the appropriation rate is around 25% are the efficiency losses more substantial—in this case the welfare gain from innovation under the emissions tax is 63%–79% of that when innovation is socially optimal (and R&D is only 39%–54% of first-best levels).[16] The main point here is that

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[16] The relative efficiency gain is triangle *vwz* divided by triangle *xyz* in Figure 2. Assuming linearity, this means that, even if R&D under the tax is, say, only 50% of the first-best level, the welfare gain under the emissions tax is still 75% of the first-best welfare effect. Note that when the appropriation rate is 100%, R&D under the emissions tax is 26% higher than the first-best amount of R&D, due to the common pool effect.

the welfare losses under an emissions tax may not be that large under certain situations (though they might be under others), implying that we may not *necessarily* have to worry about buttressing emission taxes with additional policies to stimulate R&D, such as research subsidies and prizes.

One other point is worth noting. The results in Table 2 are not very sensitive to varying the initial level of Pigouvian abatement, the proportion of firms in the industry that can potentially use the new technology, and the extent of innovation, that is, the resulting reduction in firm abatement costs. Each of these factors affects the returns to innovation in obvious ways but, since the social and private returns to innovation change in roughly the same proportion, there is not much effect on the welfare gain under the emissions tax *relative* to the first-best welfare gain.

Grandfathered Permits. Now suppose the government induces the initial Pigouvian abatement level by issuing a fixed amount of tradable emissions permits equal to $1-a^*$ in Figure 1, and these permits are grandfathered (given out for free) to existing firms. Under this policy, abatement is fixed at a^* in Figure 1 and does not increase in response to a lowering of marginal abatement costs. Thus, the private benefits to firms from adopting cleaner technologies consist only of the reduction in abatement costs, triangle $0xv$—unlike under the emissions tax, triangle xwv is not obtained (e.g., Milliman and Prince 1989, Fischer, et al. 1998, Keohane 1999). Note that if the quantity of emissions permits could be instantly adjusted to the new Pigouvian level following innovation, then innovation and welfare would be the same under emissions permits and emissions taxes. Although regulatory agencies can periodically adjust the emissions cap, they cannot do this in response to every single innovation. The difference between emissions taxes and emissions permits (set at Pigouvian levels) therefore depends on the amount of innovation that would occur during the period for which the quantity of permits is fixed.

Table 3 shows calculations from Parry (1998) of the amount of R&D, and the welfare gain from R&D, under the ex ante Pigouvian quantity of emissions permits, expressed relative to

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those under the Pigouvian emissions tax. The main point here is that, even though innovation is lower under emissions permits, whether this makes much difference in terms of welfare depends on whether innovation would produce a large or a small reduction in abatement costs over the relevant period. When innovation reduces abatement costs by only 1%, there is essentially no difference between the policies. If innovation reduces abatement costs by 10%, permits still achieve 87%–94% of the welfare gains under the emissions tax. But if innovation reduces firm abatement costs by 40%, permits only achieve 49%–67% of the welfare gains under the emissions tax. The intuition is straightforward from Figure 1: the larger the downward shift in the marginal abatement cost curve, the larger the size of triangle *xwv* relative to triangle 0*xv*, hence the smaller the private benefits from innovation under emissions permits relative to those under the emissions tax.[17]

Auctioned Emissions Permits. Now suppose that emissions permits are auctioned by the government rather than given out for free. An additional effect on innovation incentives comes into play. From Figure 1, prior to innovation, firms must pay rectangle *xyua** to the government to purchase permits for their emissions of 1–*a**. Following innovation that reduces the marginal abatement cost curve to MAC′, the permit price falls and the amount spent on purchasing permits falls to *vzua**, or by rectangle *xyzv*.

This effect provides additional innovation incentives to the extent that an innovator can appropriate rectangle *xyzv*. If polluting firms are competitive, and the innovator is an outside supplier, the innovator will be unable to capture any of rectangle *xyzv*. Polluting firms are price-takers: their decision of whether to adopt the new technology or not has no impact on the equilibrium permit price. Individual firms free ride on the fall in permit price when all firms adopt the technology together, and are unwilling to pay anything to the innovator for the fall in

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[17] The relative welfare effects of the two policies are not very sensitive to varying the proportion of polluting firms that adopt the new technology, or varying the initial level of abatement, so long as abatement is not initially close to 100% (Parry 1998). These parameters affect the private returns to innovation in roughly the same proportion under the two policies.

permit price. In this case, whether the government auctions permits or gives them away for free has no effect on the amount of innovation or social welfare (Fischer et al. 1998, Keohane 1999).

But if the innovating firm is also a polluter, it benefits by rectangle *xyzv* times the share of its emissions in total industry emissions—Fischer et al. (1998) call this the "emissions payment effect". This effect is generally of relatively minor importance if there are spillover benefits to a large number of other polluting firms. But if the number of polluting firms is limited, the innovator's share of total industry emissions is larger. Also, innovation and welfare can be notably higher under auctioned permits than under emissions taxes or grandfathered permits.[18]

Declining Marginal Environmental Benefits. The assumption of constant marginal environmental benefits seems reasonable for some pollutants; for example, harm to human health is the most important component of the damages from air pollution, and health effects appear to increase in a roughly linear fashion with ambient pollution concentrations (Burtraw et al. 1997). But declining marginal environmental benefits seem plausible in some cases, such as when there are thresholds in the assimilative capacity of the environment.

Consider a highly extreme case when the MB function in Figure 1 is vertical at a^* rather than flat. When innovation shifts the marginal abatement cost curve down to MAC′, it is now optimal to keep pollution abatement at a^* rather than increasing it to a'. This is achieved under emissions permits hence, if there were no imperfections in the research market, the optimal amount of R&D would be induced under permits. In contrast, research would be excessive under an emissions tax, since the private benefits from innovation exceed the social benefits by triangle *xwv*. However, matters are more complicated when we allow for imperfect appropriability. Assuming this effect dominates the common pool effect, welfare can still be higher under the emissions tax when the MB curve is relatively steep, because the excessive private gains from

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[18] In Milliman and Prince (1989) and Jung et al. (1996) innovators appropriate a portion of the benefit to other firms from the emissions payment effect, hence innovation is relatively high under auctioned permits in their analyses. This is certainly plausible when we relax the assumption of competition, and allow for collusion over research strategies.

innovation under the emissions tax can partly compensate for imperfect appropriability (e.g., Fischer et al. 1998).

5. The Optimal Stringency of Environmental Regulation

At first glance, it might seem that the optimal stringency of environmental policy is increased when we add the net benefit from induced innovation to the net benefit from reducing a pollution externality. However there are a number of subtle points here.

The optimal stringency of a policy instrument depends on the marginal welfare effects rather than the total welfare effects. Indeed, in theory it is possible that the optimal pollution tax is *below* the Pigouvian tax if the Pigouvian tax would generate an excessive amount of research (Parry 1995). However, if we assume that the imperfect appropriability effect dominates the common pool effect, then research would be suboptimal under the Pigouvian tax, and up to a point raising the pollution tax above the Pigouvian level would improve welfare. But there are a number of caveats to bear in mind. First, raising the pollution tax above the Pigouvian level generates excessive pollution abatement, and the theoretically optimal tax trades off the resulting welfare loss against the welfare gain from more innovation (and similarly for setting a more stringent emissions cap). Second, the optimal tax is difficult to estimate because it depends on the potential for innovation to reduce future abatement costs—the greater the potential for abatement-cost reducing innovation the greater the theoretically optimal tax. However, the potential for innovation is very difficult to assess ex ante. Finally, a potentially more efficient way to stimulate more innovation is to target the research market directly, rather than indirectly increasing pollution abatement above the Pigouvian level.[19]

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[19] Several papers have discussed the implications of induced innovation for the optimal taxation of carbon (see e.g., Goulder and Mathai 2000 and the references therein). This is a complicated problem because carbon dioxide is a stock pollutant, and therefore innovation can change the slope, as well as shift, the optimal time profile for carbon taxes. Goulder and Mathai (2000) find that allowing for induced innovation has ambiguous effects on the optimal carbon tax in each period, depending on whether innovation results from R&D or learning-by-doing, and whether the policy objective is to maximize welfare or minimize the costs of controlling atmospheric carbon dioxide concentrations.

6. Research Policy Instruments

There are a number of policy instruments that can be used to directly stimulate R&D. First, patents can be awarded for new technologies, which is the main way of promoting more innovation in the United States.[20] Second, the government also can increase innovation by subsidizing R&D ex ante, through research contracts or research tax credits.[21] A third option is to award prizes ex post for new technologies, although historically this policy has rarely been used in the United States. Unfortunately, there is not much quantitative work on the relative economic efficiency of these policy instruments. But we can at least identify some of their efficiency properties (see Wright 1983 and Carlton and Perloff 1990, Ch. 20, for more discussion).

If there were no uncertainty over the costs and benefits of R&D, then the optimal amount of R&D could be induced by awarding appropriate prizes ex post, or by issuing the appropriate amount of research contracts ex ante.[22] There is no imperfect appropriability problem under these policies since innovators obtain their rewards from the government, rather than trying to obtain rents from other firms. New discoveries are made public and any firm can make use of new knowledge free of charge. Patents generally do not induce the efficient outcome: they induce too little R&D if the imperfect appropriability effect dominates the common pool effect, and too little diffusion of new technologies due to the monopoly power conferred by patents.

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[20] Almost any invention, whether commercial or environmental in nature, is potentially eligible for a patent. In 1996, 211,600 patent applications were made in the United Sates, of which 58% were issued (*Statistical Abstract of the United States* 1998, pp. 557). Patents confer monopoly rights over new technologies for 17 years.

[21] About 30% of the $206 billion spent on R&D in 1997 was directly funded by the government (*Statistical Abstract of the United States* 1998, Table 988). The tax expenditure for the R&D tax credit was about $2.6 billion in 1998 (OMB 2000, Table 5.2).

[22] The optimal prize is somewhat less than the social benefit of a new technology, however. Setting the value of the prize equal to the social benefit would induce too much research because of the common pool problem (e.g., Carlton and Perloff 1990, Ch. 20).

In practice, however, there is also imperfect information. Firms know more about the costs and expected benefits of their own R&D than the government. This makes it difficult for the government to set the optimal prize for new technologies, or to issue the optimal amount of research contracts. If, for example, the government underestimates R&D costs or overestimates the benefits from innovation, it will give out an excessive amount of research contracts, or will award prizes that generate too much R&D.

In contrast, the government does not need to know the costs and benefits of R&D in order to operate the patent system. If firms anticipate large payoffs from developing a particular new technology, they will go ahead with the research project because, if successful, they expect large rents, and whether the government knows about the benefits of the technology development is irrelevant.[23] Wright (1983) shows that any one of the three policies might be more efficient, depending on the relative importance of imperfect appropriability, asymmetric information, and the common pool effect. In short, if imperfect appropriability is the most important problem, research contracts and prizes can be preferable on efficiency grounds, while patents are more efficient if asymmetric information is a more important problem.[24]

7. Further Discussion

The above discussion provides a framework for analyzing some of the issues for environmental policy raised by technological innovation. But we have abstracted from a number of complications.

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[23] Moral hazard may also be a problem with research contracts. Firms receive the funding up front, and the government may be unable to monitor whether the firm puts in as much research effort as it is supposed to. However, this may be less of a problem if firms care about their reputation for producing successful research projects, because they are concerned about future funding possibilities.

[24] Another policy option would be to encourage joint research ventures among firms by, for example, removing the threat of anti-trust prosecutions if firms openly collude over research strategies (rather than pricing strategies). To some extent, this would allow firms to internalize technology spillovers. However joint ventures may not be feasible when a large number of firms can benefit from new technologies.

Environmental policies are rarely set to achieve the Pigouvian level of abatement in practice. A possible reason is dispute over the benefits from reducing pollution, which are often difficult to quantify, or policy may be determined as the outcome of competition among interest groups, rather than from benevolent government behavior (e.g., Becker 1983). It would be useful to explore how the socially optimal amount of innovation changes when environmental policies are set above or below levels that internalize pollution externalities.

The discussion in Section 3 may understate the welfare gains from innovation for a couple of reasons. First, the calculations do not take into account non-environmental spillovers: for example, if firms adopt energy saving technologies, they may lower the costs of producing products, in addition to lowering the costs of satisfying emissions limitations. However, to the extent that innovations produce benefits to firms even in the absence of pollution controls, these benefits may be partially internalized. Second, the discussion only considers innovation that results from costly R&D, while some, perhaps more incremental, innovation may occur for "free" through learning-by-doing (e.g., Goulder and Mathai 2000). For example, as firms begin to blend cleaner fuels into the production process, they may develop better blending techniques over time simply with practice.

However, we may have overstated the welfare gains from innovation in one respect. Increased R&D into environmentally focused technologies may divert resources from other commercial R&D, such as efforts to discover new products and more efficient production techniques (Nordhaus 1998 and Goulder and Schneider 1999). If the (marginal) social benefit from alternative types of R&D exceeds the (marginal) private benefit, then there will be an indirect efficiency loss from crowding out. In other words, the social opportunity cost of research inputs to develop pollution control technologies may be significantly larger than assumed above.

Finally, we note some reasons why the analysis may differ in a developing country context. Regulatory pressure to control pollution in developing countries is often weak due to a lack of political will, but also because pollution may be produced by large numbers of small-scale businesses in the informal sector that are difficult to monitor. This lack of regulatory pressure is the main impediment to innovation and diffusion of cleaner production technologies.[25] In addition the inputs required for R&D projects, for example scientists and engineers, are much more scarce than in industrial countries. Moreover, even if firms were to develop cleaner production techniques, it is much more difficult to enforce patent rights in developing countries.

This means that new technologies may be more likely to be imported from industrial countries rather than developed at home, and to this extent inducing the optimal amount of R&D may be less of a concern for environmental policy design in developing countries. However another issue that, due to poorly functioning capital markets, the diffusion of improved pollution control techniques may be slowed down if small-scale firms are unable to obtain funds for new investments. In our framework this would tend to reduce the relative size of PV^I.

8. Policy Conclusions

Although the caveats mentioned above should be borne in mind, we can still draw some preliminary policy lessons. First, aside from some special cases, the welfare gains from induced innovation may be less than the welfare gains from pollution control (at least for policies set at Pigouvian levels). This does not mean that innovation is unimportant: the welfare gains from induced innovation could still be substantial in absolute terms, and over the long term innovation can greatly reduce the costs of environmental protection. But, at least from an efficiency perspective, innovation should not necessarily be the overriding consideration in policy design.

Second, an efficiency argument might be made for emissions taxes over emissions permits on the grounds of innovation incentives, but in practice the welfare difference between the policies may not be very large, unless a very substantial amount of innovation occurs during

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[25] Implementing tradable emission permit systems is impractical when a lot of pollution is produced by unmonitored firms in the informal sector, though some permit trading schemes have been proposed for firms in the formal sector in Chile, Mexico and Kazakhstan. To date, emissions fees have been more common than permit systems in developing countries, for example in China, Lithuania and Poland. See Blackman and Harrington (1998) for a review of market-based environmental policies in developing countries.

the period for which the quantity of emissions permits is fixed. In special cases, for example when innovators or firms engaged in joint research ventures account for a sizeable share of industry pollution, the incentives for innovation can be greater under auctioned emissions permits than under other policies.

Third, in principle, a case can be made for setting more stringent regulations than required to internalize pollution externalities, if induced innovation would be suboptimal under the Pigouvian level of regulation (the imperfect appropriability effect outweighs the common pool effect). But probably a better approach is to use policy instruments that target the distortions in the research market more directly.

Fourth, in cases where imperfect appropriability is not a serious problem, there seems little justification for supplementing Pigouvian environmental policies with research subsidies and/or technology prizes, particularly if the private sector has much better information on the costs and benefits of research projects than the government. But in cases where appropriability is weak, such as new technologies that are applicable to large numbers of firms and are easy to imitate even if patented, additional research stimulants may have a valuable role.

Appendix: Further Discussion of the Welfare Gains from Innovation

Here we provide more detail on the assumptions underlying the model in Section 3, and how the welfare gain from induced innovation depend on various parameters and model specifications.

In the PPF model, a social planner chooses the amount of pollution control, and the amount of research (R), in each period across an infinite horizon to minimize the discounted sum of environmental damages, abatement, and research costs. R&D augments a knowledge stock (K) over time, and the costs of future pollution abatement decline as the knowledge stock expands. The marginal abatement cost curve in a particular period is proportional to $(1-K)^2$, where K is initially zero and when $K=1$ abatement costs are completely eliminated. K is the sum of research across all previous periods, where the cost function for research in a particular period is $f_1R+f_2R^2$. For simplicity, there is no uncertainty over the benefits from R&D.[26]

Discount rate. A higher (lower) discount rate reduces (increases) the discounted welfare gains from innovation because the costs from R&D occur up front while the benefits in terms of reduced abatement costs occur in the future. The figures in Section 3 are based on a discount rate of 5% (a figure defended by Nordhaus 1994), however there is much controversy over the appropriate value (e.g. Portney and Weyant 1999). Using a lower discount rate increases the range of outcomes under which the welfare gains from innovation exceed the Pigouvian welfare gains. For example, in PPF when innovation reduces abatement costs by 50% in 20 years and the initial Pigouvian abatement level is 40%, PV^I/PV^P increases from 0.46 to 1.32 when the discount rate is reduced from 5% to 2%.

Functional Forms. If research costs include a fixed component rather than being purely variable this has ambiguous effects on PV^P. If it takes time to construct research facilities this will delay the date at which new technologies come on line. On the other hand, once fixed costs have been incurred the marginal cost of research may be very low implying that research projects can be completed quickly.

PPF assume that marginal abatement costs decline, but at a diminishing rate, with more knowledge accumulation and that, in any given period, it is increasingly costly to add to the knowledge stock. If abatement costs decline at a faster (slower) rate with knowledge accumulation, this has the same effect as reducing (increasing) the costs of R&D. In other words, it reduces (increases) the time taken to achieve a given reduction in abatement costs on the optimal path.

The results in Section 3 are based on a model where marginal abatement costs are linear. It is plausible that marginal abatement costs are convex rather than linear, in which case the Pigouvian welfare gains are larger, implying a lower value for PV^I/PV^P.

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[26] The results discussed in Section 3 are based on numerical solutions to this theoretical model. Ideally, it would be useful to econometrically test the model assumptions.

Exogenous changes in the marginal benefit and marginal abatement cost curves. The marginal environmental benefit function, rather than being constant, may change over time as, for example, the number of elderly people, who are most sensitive to air quality, increases. The effect of this is similar to the effect of changing the discount rate. If marginal environmental benefits were increasing at say 1% per annum, this would have approximately the same effect as reducing the discount rate from 5% to 4%.

The discussion in Section 3 assumes that the marginal cost of a given percentage reduction in emissions is constant over time. This might be a reasonable approximation, even if the polluting industry is expanding over time with growth in the size of the economy. But if there is technological innovation for non-environmental reasons, for example firms are developing energy saving technologies to reduce production costs the marginal cost of percentage emissions reductions could be falling over time. This effect would increase the discounted Pigouvian welfare gains, and reduce PV^I/PV^P.

Firm heterogeneity. Finally, the analysis above assumes that polluting firms are homogeneous. In principle, firm heterogeneity makes no difference to the discussion of the welfare gains from innovation in Sections 2 and 3, so long as the aggregate marginal abatement cost function is the same and responds in the same way to innovation. In practice however, firm heterogeneity can make it more difficult for innovators to capture the social benefits from innovation (Biglaiser and Horrowitz 1995), that is, it can compound the imperfect appropriability effect.

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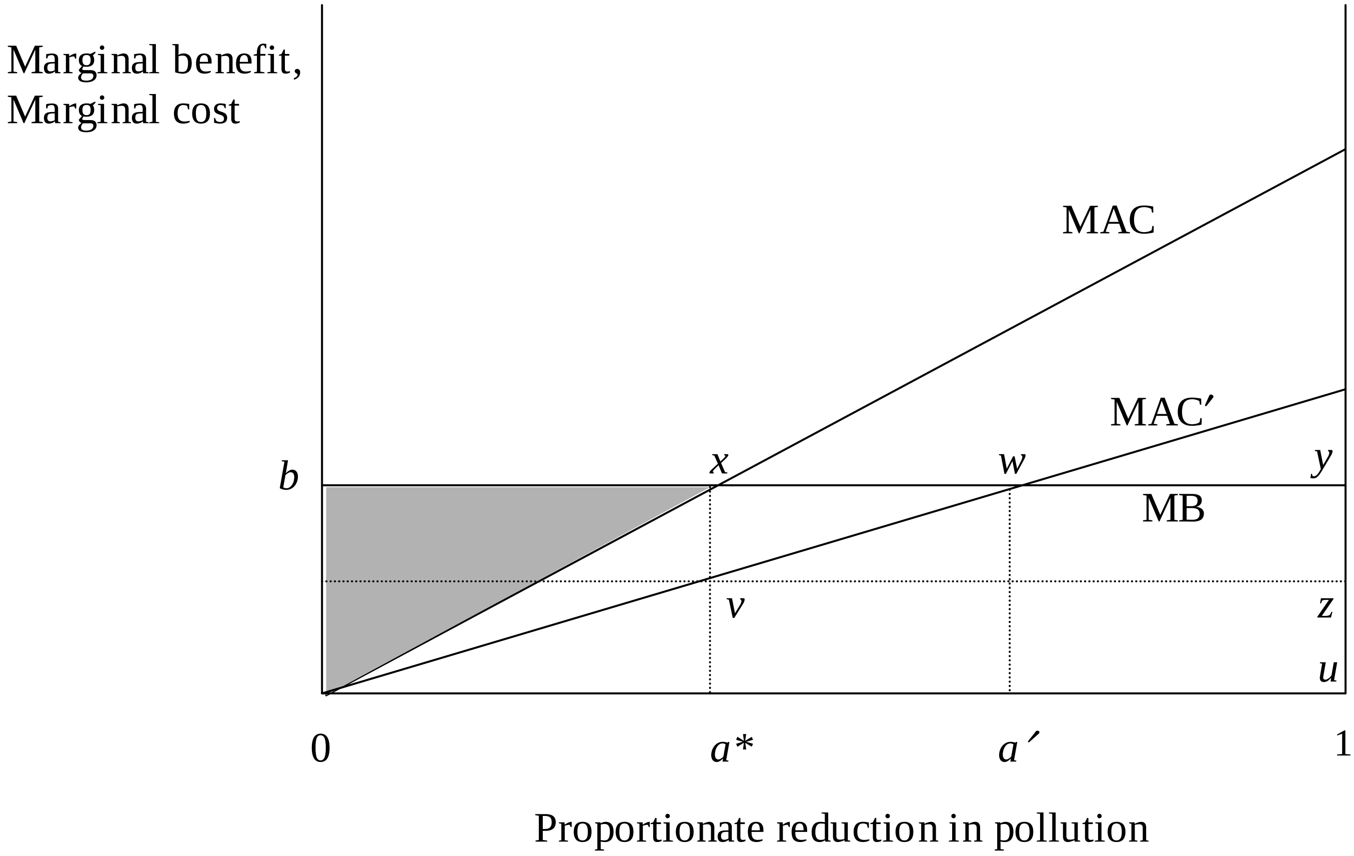
Figure 1


Marginal benefit,
Marginal cost
MAC
MAC′
b
x
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y
MB
v
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1
Proportionate reduction in pollution

Table 1: Ratio of Welfare Gains from Innovation to Welfare Gains from Pollution Control, PV^I/PV^P

Pigouvian abatement (proportionate emissions reduction)	Time lag until abatement costs halve		
	10 years	20 years	40 years
0.1	2.98	0.88	0.16
0.4	1.07	0.46	0.16
0.6	0.79	0.41	0.17

Source: Parry, Pizer and Fischer (2000).

Table 2. Efficiency gain under the Pigouvian Emissions Tax Relative to First-Best Efficiency Gain

		R&D relative to first-best level			Efficiency gain from R&D under emission tax relative to first-best efficiency gain		
Proportionate reduction in abatement costs		0.01	0.1	0.4	0.01	0.1	0.4
Appropriation rate	100%	1.26	1.26	1.26	.93	.93	.93
	75%	1.01	1.03	1.09	1.0	1.0	.95
	50%	.72	.75	.87	.92	.94	.98
	25%	.39	.42	.54	.63	.66	.79

Source: Parry (1998).

Table 3. Efficiency gain under Emission Permits Relative to that Under the Emissions Tax

		R&D relative that under the emissions tax			Efficiency gain from R&D under emission permits relative to that under the emissions tax		
Proportionate reduction in abatement costs		0.01	0.1	0.4	0.01	0.1	0.4
Appropriation rate	100%	.99	.92	.63	1.0	.94	.67
	75%	.99	.92	.62	.99	.92	.61
	50%	.99	.91	.61	.99	.89	.55
	25%	.99	.91	.59	.99	.87	.49

Source: Parry (1998).