How Important is Technological Innovation in Protecting the Environment?

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Abstract

Economists have speculated that the welfare gains from technological innovation that reduces the future costs of environmental protection could be a lot more important than the "Pigouvian" welfare gains over time from correcting a pollution externality. If so, then a primary concern in the design of environmental policies should be the impact on induced innovation, and a potentially strong case could be made for additional instruments such as research subsidies.

This paper examines the magnitude of the welfare gains from innovation relative to the discounted Pigouvian welfare gains, using a dynamic social planning model in which research and development (R&D) augments a knowledge stock that reduces future pollution abatement costs.

We find that the discounted welfare gains from innovation are typically smaller—and perhaps much smaller—than the discounted Pigouvian welfare gains. This is because the long-run gain to innovation is bounded by the maximum reduction in abatement costs and, since R&D is costly, it takes time to accumulate enough knowledge to substantially reduce abatement costs. Only in cases when innovation substantially reduces abatement costs quickly (by roughly 50% within 10 years) *and* the Pigouvian amount of abatement is initially modest, can the welfare gains from innovation exceed the welfare gains from pollution control. These results apply for both flow and stock pollutants, and for linear and convex environmental damage functions.

Our results suggest that spurring technological innovation should not be emphasized at the expense of achieving the optimal amount of pollution control. More generally, our results appear to have implications for a broad range of policy issues. They suggest that the welfare gains from innovation that reduces the costs of supplying any public good (defense, crime prevention, infrastructure, etc.) may be fairly small relative to those from providing the optimal amount of the public good over time.

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How Important is Technological Innovation in Protecting the Environment?

Ian W.H. Parry, William A. Pizer, and Carolyn Fischer[1]

1. Introduction

When firms are not charged for the harm their activities do to the environment, two types of resource misallocation can occur. As is well known from the Pigouvian model, at a point in time firms' pollution levels will exceed the socially optimal amount. It also is important to recognize that the state of technology is endogenous over the long run. If firms do not have to worry about pollution control, they lack incentives to engage in innovative activities that might lead to cleaner production technologies for future periods. This problem is compounded by the usual R&D externality: even if firms do invent new abatement technologies, they may be unable to capture all the spillover benefits to other firms due to the public good nature of knowledge. In short then, there is both a static and a dynamic source of market failure.

This paper is about the relative importance of the dynamic resource misallocation. More specifically, we measure the welfare gains from achieving the socially optimal innovation of cleaner technologies over time, relative to the welfare gains from reaching the optimal amount of pollution control—the "Pigouvian" welfare gains—with technology held constant. This question crucially bears on the appropriate design of measures to tackle environmental problems in a variety of different respects.

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First, it is helpful for policymakers to know what is at stake in terms of economic welfare from policy intervention to address specific environmental problems—whether a strong case for policy intervention can be made or not depends on whether the potential welfare gains are large or not. Part of this welfare gain consists of the potential to address externality distortions in the market for environmentally-focussed R&D. Since existing studies usually take the state of technology as exogenous (e.g., the survey in Cropper and Oates (1992)), they ignore this opportunity to improve welfare and understate the potential efficiency gains from environmental policies.

Second, the size of the welfare gain from induced innovation can bear directly on the appropriate choice of environmental policy instrument. As demonstrated in earlier studies, different environmental policy instruments are likely to induce different amounts of R&D (e.g., Milliman and Prince (1989), Jung *et al*. (1996), Parry (1998), Fischer *et al*. (1999)). Therefore, the welfare effects of policies that are equivalent (under certain conditions) in a static, partial equilibrium framework—such as emissions taxes, grandfathered permits, and auctioned permits—can differ when technological innovation is endogenous. However, whether these differences are likely to matter much in practice depends on how significant the welfare gains from innovation are, relative to the Pigouvian welfare gains.[2] A related point is that technological innovation may affect the optimal stringency of environmental regulations.[3] Again though, whether the optimal deviations from the Pigouvian rule matter much in practice depends on the relative economic importance of induced innovation effects.

Finally, if in the presence of environmental policies the patent system is not especially effective at enabling innovators to capture the full social benefits from new abatement

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[2] In a competitive setting, Fischer *et al*. (1999) find that there is no clear-cut ranking between emissions taxes, free tradable emissions permits, and auctioned permits. Under certain conditions concerning the potential for innovation, the degree to which non-innovating firms can imitate new technologies, and the degree of convexity of the pollution damage function, any one of these three instruments may induce a larger welfare gain than the other two. For example, they find that emissions taxes tend to induce larger welfare gains when marginal environmental damages are relatively constant and the potential for imitating new technologies is limited.

[3] For example, Parry (1995) shows that the second-best optimal pollution tax may exceed marginal environmental benefits when, despite patents, innovators are unable to appropriate the full benefits to other firms from new technologies. On the other hand, competition for a given amount of innovation rent can be socially excessive, in the same way that competition can lead to the overuse of natural resources. This “common pool” effect tends to dampen the optimal pollution tax.

technologies, additional measures to stimulate R&D may be justified. Examples include research subsidies, tax credits, or technology prizes. The case for introducing these supplementary measures, and the optimal amount of rewards involved, depends on the potential welfare gains from additional innovation.

In fact, in the long run technological innovation seems to be at the heart of resolving a number of problems with seemingly irreconcilable conflicts between economic activity and the environment. For example, governments have so far been unwilling to accept the economic costs that would be necessary to fulfill promises made eight years ago at the 1992 Earth Summit to stabilize—let alone reduce substantially—emissions of heat-trapping gases.[4] The development of carbon-saving technologies over time (e.g., improved techniques for using natural gas in power generation, hybrid cars, etc.) offers the hope of meeting emissions controls in the future with less burden imposed on industry and consumers. Similarly, the development of improved auto exhaust filters for nitrogen oxide emissions could substantially reduce smog in urban areas such as Los Angeles, thereby obviating the need for draconian restrictions on vehicle manufacture in order to meet federal air quality standards. Thus, economists have suggested that the welfare gains from technological innovation might be "large" and that the impact of environmental policies on innovation should be the most important consideration in policy design.[5]

Very little is known from previous literature about the potential welfare gains arising from the impact of environmental policies on technological innovation.[6] In this paper we attempt to provide a general treatment of this issue, using a dynamic social planning model in which the control variables in each period are the amount of pollution abatement and the amount of R&D

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[4] At the 1997 Kyoto conference, the developed countries again pledged to reduce emissions. But the timetable for implementing emission targets was pushed back to 2008-2012—almost 20 years after governments first pledged to control emissions. Moreover, there is widespread skepticism that the agreement will be adopted in anything like its current form (e.g, Portney, 1999).

[5] For example, Kneese and Schultz (1978): " Over the long haul, perhaps the single most important criterion on which to judge environmental policies is the extent to which they spur new technology towards the efficient conservation of environmental quality." Orr (1976): "Technological adaptation rather than resource allocation [is] the key to an effective solution of [environmental problems]."

[6] There are a couple of studies that use numerical simulation models to estimate how endogenous technological change affects the optimal level of carbon taxes (e.g., Nordhaus (1998) and Goulder and Matthai (2000)). We relate our results to these studies below. Parry (1998) and Fischer *et al*. (1999) estimate what fraction of the first-best

investment. R&D enhances a knowledge stock, which reduces the future costs of abatement. We define the discounted Pigouvian welfare gain (PV^P) as the present value of welfare gains from the socially optimal amount of pollution abatement in each period (relative to no abatement) when the state of technology is exogenous. We then solve for the discounted welfare gains from reaching the first-best level of abatement and R&D in each period (relative to no abatement and no R&D), when the state of technology is endogenous. The difference between these welfare two measures is the discounted welfare gain from innovation (PV^I).

The basic finding is that the conditions for PV^I to exceed PV^P are actually quite stringent, and in fact PV^I could easily be small relative to PV^P. For example, even under conservative assumptions, we find that when the initial Pigouvian abatement level is 40% then innovation (and diffusion) must reduce abatement costs by 50% within 10 years, and by a much greater amount over the longer term, for PV^I to be as large as PV^P. It is practically inconceivable that this condition could be met, for example, in the context of carbon abatement, given our current dependency on fossil fuels. The condition becomes even more stringent, if not impossible, to satisfy when the Pigouvian amount of abatement is initially in excess of 60%. Our results apply for flow and stock pollutants, for linear and convex environmental damage functions, and when the welfare gains from innovation and abatement are compared over shorter periods within of time.

The limited welfare gains from innovation initially surprised us, but the result makes intuitive sense. We can bound the maximum possible benefit from innovation in a particular period—when abatement costs have been completely eliminated—by a simple trapezoid under the marginal abatement cost and marginal environmental benefit curves (see below). It is easy to show that the ratio of this trapezoid to the Pigouvian welfare gain triangle is 9, 3, and 1 when the initial Pigouvian level of abatement is 20%, 50%, and 100%, respectively. This reflects the fact that when a pollution externality is severe enough to warrant significant reductions based on current control costs, the Pigouvian social benefit from optimal pollution reduction will be large relative to the potential cost savings from innovation. However, this ratio greatly overstates

welfare gains from innovation are obtained under alternative environmental policies, but they do not estimate the size of these gains relative to the Pigouvian welfare gains.

PV^I/PV^P for two reasons. First, on the optimal path it will take decades (if not longer) to completely eliminate abatement costs; hence, for a whole range of future periods the benefit from innovation relative to the Pigouvian welfare gain is much smaller than these ratios suggest. Second, we need to subtract the costs of R&D from the benefits in order to obtain the net welfare gain.

The bottom line is that, at least in terms of social welfare, promoting technological innovation appears to be *less* important than just controlling pollution, contrary to what some economists previously have speculated. Accordingly, it seems that the primary objective of environmental policy should be the traditional one of achieving the optimal amount of pollution control over time—and promoting innovation should be a secondary concern. This conclusion is preliminary however, because, as discussed later, there are some notable caveats to our analysis. In particular, our analysis does not capture possible spillover benefits to other industries from induced innovation. We do not take into account sources of pre-existing distortion in the economy that may importantly influence the overall welfare effects of environmental policies.

These caveats aside, our results appear to have implications for a broad range of other (non-pollution-related) policy issues. The results suggest that the welfare gains from improving technologies for fish farming are likely to be smaller than the welfare gains from limiting access to natural fish stocks. Similarly, the welfare gains from developing safer consumer products are likely to be smaller than those from enforcing safety standards based on existing technologies. Again, the reason is that innovation is costly and it takes time for innovation to secure a substantial reduction in the costs of fish farming or product safety. More generally, the results suggest that the welfare gains from innovation that reduce the cost of supplying almost any public good (defense, crime prevention, infrastructure, etc.) are likely to be smaller than those from providing the optimal amount of the public good over time.

The rest of the paper is organized as follows. Section 2 lays out our analytical framework and develops our main qualitative and quantitative results. Section 3 relaxes some of the simplifying assumptions in Section 2 and conducts further sensitivity analyses. Section 4 concludes and discusses limitations to the analysis.

2. Basic Results

A. Model Assumptions

Consider an industry where a by-product of production is waste emissions that are detrimental to environmental quality. These emissions may represent air or water pollutants, hazardous or other forms of solid waste, radioactive materials, and so on. In the absence of any abatement measures, economy-wide emissions per period ("baseline" emissions) would be an exogenous amount $\overline{E}$. The cost of reducing emissions by an amount A_t below $\overline{E}$ at time *t*, or emissions abatement, is $C(A_t, K_t)$. K_t denotes the stock of knowledge about possibilities for reducing emissions. A higher value of K_t may represent, for example, improved techniques for replacing coal with natural gas in electricity generation, or a more efficient end-of-pipe technology for treating pollution. We assume that marginal abatement costs are upward sloping and pass through the origin for a given knowledge stock, and that more knowledge rotates the marginal abatement cost curve downwards about the origin but at a diminishing rate.[7] In short $C_{AA} > 0$, $C_A(0, K_t) = 0$, $C_{AK} < 0$, $C_{AKK} > 0$.

Knowledge accumulates as follows:

(1) $$K_{t+1} = K_t + I_t$$

where K_0 is given and I_t is investment in environmentally orientated R&D activities.[8] The cost of R&D is $f(I_t)$ where $f(.)$ is weakly convex. To keep the model parsimonious, and the results conservative, diffusion is subsumed in $f(.)$.[9]

Emissions accumulate in the environment over time as follows:

(2) $$S_t = \overline{E} - A_t + (1-\delta)S_{t-1}$$

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[7] The assumption that the marginal cost schedule passes through the origin is an important assumption and is consistent with the shadow value of pollution equaling zero. This would not be the case in the presence of pre-exisiting distortions, such as energy subsidies.

[8] There is no knowledge depreciation; that is, knowledge cannot be disinvented.

[9] Implicitly then, when we say that innovation has reduced abatement costs by x%, we mean the technologies have been invented and fully diffused. Explicitly incorporating a diffusion lag would have essentially the same effect as increasing the adjustment cost associated with R&D (i.e., assuming a larger f''), and we consider a wide range of scenarios for adjustment costs in our simulations.

where S_t denotes the stock of pollution in the environment at time t and the inherited stock S_0 is given. δ is the decay rate of the stock: $\delta = 1$ for a flow pollutant which decomposes before the start of the next period (this is roughly applicable to sulfur dioxide, nitrous oxides, and particulates). For stock pollutants that accumulate in the environment over time, we have $0 \leq \delta < 1$ (e.g., nuclear waste and carbon dioxide).

Environmental damages at a point in time are given by $\phi(S_t)$ where $\phi' > 0$, $\phi'' \geq 0$. Finally, a social discount rate of r is applied to future benefits and costs, and the planning period extends over an infinite horizon.

B. Analytic Results

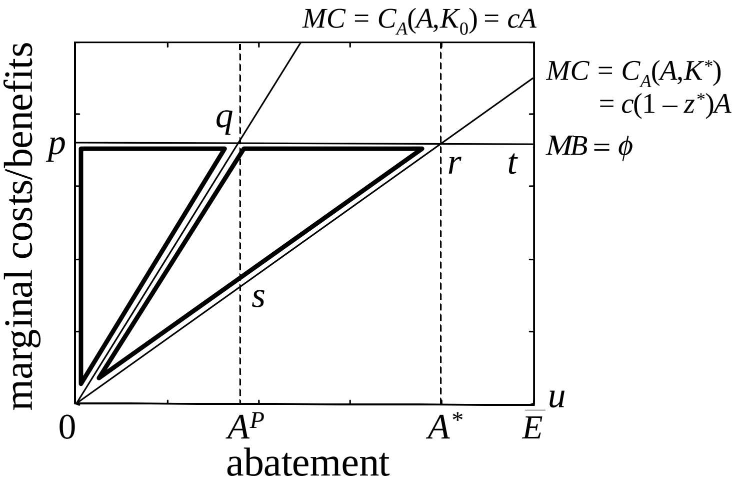
For the purposes of this section, we make some simplifying assumptions to establish our main results in a transparent manner—most of these assumptions are relaxed later. We focus on a flow pollutant ($\delta = 1$) with constant marginal environmental damages from emissions/constant marginal benefits from abatement equal to $\phi > 0$. R&D costs are assumed to be linear ($f'' = 0$). In addition, we use a quadratic abatement cost function:

$$C(A,K) = (1 - z(K - K_0))cA^2 / 2 \tag{3}$$

where $z(.)$ is the proportionate reduction in abatement costs brought about by innovation ($0 \leq z \leq 1$, $z' > 0$, $z'' < 0$ and $z(0) = 0$). For accounting convenience, we also assume that abatement occurs from $t = 1\ldots\infty$, while innovation can occur in period zero.

For the moment, suppose the state of technology is exogenous, as in the traditional Pigouvian model, and knowledge is fixed at K_0 for the planning horizon. The optimal Pigouvian abatement level is the point where marginal abatement costs equal marginal environmental benefits. Using (3), this gives $A^P = \phi / c$ for $t = 1\ldots\infty$ and the resulting Pigouvian welfare gain per period, W^P, is triangle $0pq$ in Figure 1.

Figure 1: Welfare Gains with and without Innovation



We define PV^P as the present discounted value (as of t = 0) of the Pigouvian welfare gains summed from t = 1 to ∞:

(4) $$PV^P = \frac{W^P}{1+r} + \frac{W^P}{(1+r)^2} + \frac{W^P}{(1+r)^3} + \ldots = \frac{W^P}{r}$$

When we allow for innovation, the social planning problem becomes:

(5) $$\underset{A_t, I_t}{\text{Min}} \qquad f(I_0) + \sum_{t=1}^{\infty} \frac{\phi(\overline{E} - A_t) + C(A_t, K_t) + f(I_t)}{(1+r)^t}$$

$$\text{subject to } K_{t+1} = K_t + I_t$$

That is, the planner chooses abatement and innovation in order to minimize the discounted sum of environmental damages, abatement costs, and innovation costs. Using (3) the first order conditions yield:

(6) $$A_t^* = \text{Min}\left(\frac{\phi}{(1 - z(K_t^* - K_0))c}, \overline{E} \right)$$

(7) $$f'(I_t^*) = \frac{-C_K(A_{t+1}^*, K_{t+1}^*) + f'(I_{t+1}^*)}{1+r}$$

From (6), $A_t^* > A^P$: optimal abatement is now greater than in the Pigouvian case because innovation shifts down the marginal abatement cost curve. Note that if $(1-z^*)c\overline{E} < \phi$, we have a corner solution with $A^* = \overline{E}$ and emissions abatement equal to 100% (in Figure 1, $A^* < \overline{E}$).

Equation (7) is an Euler equation specifying that the marginal cost of R&D in period t equals the (discounted) reduction in abatement costs in period t+1 from an increase in the knowledge stock, plus the marginal cost of R&D in period t+1. With our assumption of linear R&D costs, $-C_K(A_t^*, K_t^*) = rf'$. Along with (6) we have two static equations providing implicit solutions for K^* and A^*. Thus, abatement and the knowledge stock are constant over $t = 1\ldots\infty$ and R&D must occur only in period 0 (this is unrealistic, but simplifies our discussion and makes our initial results conservative—see below).

In any given period, the benefit from having a knowledge stock equal to K^* rather than K_0 is denoted W^K, and is indicated by triangle 0*qr* in Figure 1. This consists of the reduction in abatement costs at the Pigouvian amount of abatement (triangle 0*qs*) plus the gain from increasing abatement from A^P to A^* (triangle *qrs*). Using some simple geometry:

$$W^K = \begin{cases} \dfrac{z^*}{1-z^*}W^P & \text{if} \quad \phi = c(1-z^*)A^* \\ \dfrac{z^*}{1-z^*}W^P - \Delta & \text{if} \quad \phi > c(1-z^*)\overline{E} \end{cases} \tag{8}$$

where $\Delta = \left(\phi - (1-z^*)c\overline{E}\right)^2 \big/ \left(2(1-z^*)c\right) > 0$. Δ is positive only in the corner solution where abatement equals 100%, and abatement cannot increase up to the point where marginal abatement costs equal ϕ.

We define the welfare gain to innovation, PV^I, as the discounted sum of benefits from additional knowledge ($K^* - K_0$) in each period, less the cost of R&D which occurs in period zero. Thus:

$$PV^I = \frac{W^K}{1+r} + \frac{W^K}{(1+r)^2} + \frac{W^K}{(1+r)^3} + \ldots - f(I_0^*) = \frac{W^K}{r} - f(I_0^*) \tag{9}$$

Using (4) the welfare gain from innovation relative to the discounted Pigouvian welfare gain is:

$$\text{(10)} \qquad \frac{PV^I}{PV^P} = \frac{W^K/r - f(I_0^*)}{W^P/r} = \frac{W^K - rf(I_0^*)}{W^P}$$

Thus the (discounted) welfare gain from innovation is greater (less) than the (discounted) welfare gain from correcting the pollution externality, when PV^I/PV^P is greater (less) than unity.

We now establish two analytic results that bound the magnitude of PV^I/PV^P:

(i) If $A^P / \overline{E} \leq 1$ *is the optimal (i.e. Pigouvian) proportionate emissions reduction with no innovation, then* $2(A^P / \overline{E})^{-1} - 1$ *is the absolute maximum value of* PV^I/PV^P.

Proof: Suppose that innovation completely and costlessly eliminates abatement costs in the initial period. In this case PV^I/PV^P is simply W^K/W^P, or area 0*qtu* in Figure 1 divided by triangle 0*pq*. Since area 0*pq* equals $\phi A^P / 2$ and area 0*qtu* equals $\phi A^P / 2 + \phi(\overline{E} - A^P)$, then PV^I/PV^P equals $2(A^P / \overline{E})^{-1} - 1$.

(ii) If R&D reduces abatement costs by a factor z, then PV^I/PV^P cannot exceed $z/(1-z)$.

Proof: Using (8) and (10),

$$\frac{PV^I}{PV^P} = \frac{W^K - rf(I_0^*)}{W^P} = \frac{\frac{z}{1-z}W^P - \Delta - rf(I_0^*)}{W^P} \leq \frac{z}{1-z}$$

since Δ and $f(.) \geq 0$ •

Result (i) puts an upper bound on PV^I/PV^P for the case when knowledge accumulation completely eliminates abatement costs at zero cost. According to this formula, when the initial Pigouvian abatement level is 10%, 40%, 60%, or 100%, then the maximum value of PV^I/PV^P is 19, 4, 2.3, or 1 respectively. Straight away, we see that only in cases when the Pigouvian abatement level is fairly modest is there potential for the welfare gains from innovation to be "large" relative to the Pigouvian welfare gains. Intuitively, if a pollution problem is severe enough to warrant a high level of abatement without R&D, then the additional gain to innovation will be relatively small.[10] Conversely, if abatement is initially too costly to justify major emission reductions, the gain to innovation could be more substantial.

Result (ii) puts an upper bound on PV^I/PV^P for the case when innovation does not completely eliminate abatement costs. Here we see that PV^I/PV^P cannot exceed unity if innovation reduces abatement costs by 50% or less. In short then, these simple results demonstrate that there are two necessary conditions for the welfare gains from innovation to be large relative to the Pigouvian welfare gains: innovation must have the potential to substantially reduce abatement costs *and* the initial Pigouvian abatement level must be fairly modest.[11]

It is worth noting that these bounds are easier to establish—and more conservative—when one ignores benefits and only considers cost-effectiveness. Cost-effectiveness focuses on the cost of alternative policies designed to achieve the same emission or abatement target, taking that target as given (Newell and Stavins, 2000; Hahn and Stavins, 1992). This approach is appealing because it both avoids contentious discussion of benefits and disentangles the abatement goal (often a political issue) from the choice of policy design (frequently an administrative concern). Yet, the underlying assumption behind the target choice, if it reveals social preferences, must be that marginal benefits equal or exceed marginal costs at the chosen target. With linear marginal abatement costs and flat marginal benefits, this indicates that the upper bound (with costless and complete elimination of abatement costs) for PV^I/PV^P is, at most, one when the target remains fixed.

C. Numerical Simulations

While the previous results establish unambiguous bounds on the gain to innovation, they overstate the actual value of PV^I/PV^P for two reasons. First, we need to subtract the direct costs of R&D in order to obtain the net welfare gain from innovation. Second, in general it will be

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[10] Thus, without doing any estimation we can say that PV^I is unlikely to exceed PV^P for pollutants for which the Pigouvian pollution reduction is close to or equal to 100%. This appears to be the case for lead emissions from gasoline, which cause adverse human health effects, and CFC emissions, which deplete the ozone layer (see Nichols, 1997, and Hammitt, 1997, respectively).

[11] Note that the maximum value of PV^I/PV^P is given by the smaller of the values from the two formulas. Thus, when z = .8 and A^P = .8, the maximum value of PV^I/PV^P is 1.5, while if A^P = .2 and z = .4, the maximum value is .67.

optimal to smooth out knowledge accumulation over time rather than doing it all in period zero (i.e. f'' is typically positive). Hence, for a whole range of future periods, the benefit from knowledge accumulation will be smaller than the benefits in the steady state when knowledge accumulation is complete.

Therefore, we now generalize the model to allow for convex R&D costs. Smoothing out R&D over time involves striking a balance between the gains of immediate increases in the knowledge stock and the cost savings from gradual adjustment. This is captured by the Euler equation (7) which matches the marginal R&D cost difference in adjacent periods to the one-period return to R&D. The solution to the problem with adjustment costs cannot be completed analytically and therefore we turn to numerical simulations.

For this section we now specify a convex research cost function:

$$f(I_t) = f_1 I_t + f_2 I_t^2 \tag{11}$$

with f_1, $f_2 > 0$. The parameter f_1 determines knowledge capital in the steady state: the lower the value of f_1 the more likely that it will be optimal to (eventually) accumulate enough knowledge to reduce abatement costs by 100%. f_2 determines the speed of adjustment to the steady state: the smaller f_2 is, the shorter the period of transition to the steady state will be. The justification for $f_2 > 0$ is that it is increasingly costly to increase the knowledge stock all at once—at any point in time, there is a limited pool of expert engineers/scientists as well as specialized capital equipment such as research labs. [12]

We then specify the proportionate shift in the abatement cost function due to knowledge:

$$z(K) = 2K - K^2 = 1 - (1 - K)^2 \tag{12}$$

which satisfies $z(0) = 0$, $z' > 0$ for $K < 1$, and $\max(z) = z(1) = 1$. Note that the choice of K_0 is arbitrary since only the distance $K - K_0$ matters. We therefore choose $K_0 = 0$ and, from (12), $K_t = 1$ achieves a 100% reduction in abatement costs.

To start with, we choose $f_1 = 0$ which guarantees in the steady state that the knowledge stock will completely eliminate abatement costs since marginal R&D is now costless. Since our

[12] Similarly, doubling the number of people (with comparable skills) working on this paper will reduce the production time by less than 50%.

aim is to identify an upper bound for PV^I/PV^P in different situations, this assumption also makes our results conservative relative to $f_1 > 0$ (from (10), higher values of f' imply lower relative welfare gains to innovation). Emissions and environmental damages are normalized to imply $\overline{E} = 1$ and $\phi = 1$. We assume the discount rate r equals 5% (alternative values are discussed later).

The remaining parameters, c and f_2, are varied. We choose c to imply that the Pigouvian amount of abatement ($A^P = \phi / c$) either is 10%, 40%, or 60%. Finally, we select different values of f_2 in order to imply a wide range of scenarios for the time it takes for knowledge accumulation to produce a 50% reduction in abatement costs (i.e., half the eventual reduction in abatement costs). The results of our benchmark simulations are summarized in Table 1.

Table 1: Calculations of PV^I / PV^P

Pigouvian abatement level	Time lag until abatement costs halve			
	0	10 years	20 years	40 years
10%	19.00	2.98	0.88	0.16
40%	4.00	1.07	0.46	0.16
60%	2.33	0.79	0.41	0.17

In the first column, we set $f_2 = 0$; consequently, innovation completely and immediately eliminates abatement costs at zero cost. These entries confirm our earlier calculations about the absolute maximum value of PV^I/PV^P.

The next three columns show the effect of incorporating positive and increasingly higher adjustment costs. Suppose the initial Pigouvian abatement level is 40%. In this case, the welfare gain from innovation, defined in Equation (5), is 107%, 46%, and 16% of the Pigouvian welfare gains, defined in Equation (6), when innovation reduces abatement costs by 50% over 10, 20, and 40 years, respectively, along the optimal dynamic path. As predicted earlier, these ratios are higher (lower) if the initial Pigouvian abatement level is smaller (larger). But regardless of the initial Pigouvian abatement levels in this table, PV^I is less than PV^P if it takes 20 years or more for innovation to secure a 50% reduction in abatement costs. Indeed, if the Pigouvian abatement level is initially 60% or more, then PV^I is still less than PV^P if a 50% reduction in abatement costs is secured in only 10 years.

These simulations demonstrate our basic point: the conditions for PV^I to be large relative to PV^P seem to be rather stringent. Innovation must rapidly reduce abatement costs by more than 50% *and* the initial Pigouvian level of abatement must be modest. If high levels of abatement are initially justified regardless of cost, if cost-savings from innovation are small, or if these cost-savings occur with a substantial time lag, then PV^I is unlikely to be as large as PV^P.[13]

How long, then, might it take for technological innovation to substantially reduce abatement costs? The sulfur-trading program—which ultimately will reduce emissions by about 50%—is often heralded as a major success because control costs are now much lower than initially projected. According to Burtraw (1996), abatement costs roughly halved over 10 years. This suggests that PV^I could be roughly the same size as PV^P in this case. However, not all of this cost reduction was due to induced innovation; a substantial portion appears to have resulted from the reduction in costs of transporting low sulfur coal brought about by deregulation of the trucking industry—a change unrelated to the sulfur reduction program. In the context of climate change, the United States is currently pledged to reduce carbon emissions to 93% of 1990 levels by 2008-2012 under the Kyoto Protocol. This will imply an emissions reduction of about 30% below baseline levels (EIA, 1999, p. 89). In this case, the prospects for innovation to substantially cut abatement costs are less promising since there currently are no end-of-pipe treatment technologies nor cost-effective, carbon-free alternatives to fossil fuels on the horizon. It seems unlikely to us that U.S. dependency on coal and petroleum could be cut by 50% in 10-15 years through innovation.[14]

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[13] Another way to interpret these results is that incorporating the cost of R&D can dramatically reduce the potential welfare gains from innovation. For example, when the Pigouvian abatement level is 10% we see that without any costs to R&D the welfare gain from innovation is 19 times the Pigouvian welfare gain. But with R&D costs, the welfare gain from innovation falls to 80% of the Pigouvian welfare gains when it takes 20 years for knowledge accumulation to reduce abatement costs by 50%.

[14] Consistent with these observations, Nordhaus (1998) and Goulder and Mathai (2000) find that allowing for endogenous technological innovation does not substantially change the overall welfare gains from a carbon tax.

Based on our assessment of the likely rate of induced innovation, the discounted welfare gains from innovation are probably going to be smaller—and perhaps much smaller—than the discounted welfare gains from correcting the pollution externality.[15] However, this result is based on a model that is simplified in a number of respects. We now consider how robust this finding is to a variety of generalizations and sensitivity analyses.

3. Alternative Assumptions and Sensitivity Analysis

In this section we discuss the implications of alternative discount rates, research cost functions, nonlinear environmental damages, stock pollutants, planning horizons, and abatement/innovation timing.

A. Discount Rate

In the previous section we assumed a discount rate of 5%. However, there is considerable dispute over the appropriate discount rate to use: the Office of Management and Budget recommends a rate of 7%, while some economists argue for a much lower rate in the context of long-range environmental problems.[16]

Qualitatively, the main point is that a higher (lower) discount rate reduces (increases) the relative welfare gains from innovation. This is because the benefits from innovation occur across a range of future periods while the costs are up-front. Therefore, higher discount rates lower the annualized net benefits of innovation. In contrast (at least for the flow pollutant) benefits and costs from pollution abatement occur simultaneously and the discount rate has no effect on

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[15] Of course this result does not necessarily imply that innovation is unimportant in absolute terms, only that it is probably less important than directly addressing uncorrected pollution externalities. Furthermore, there is nothing incorrect with the argument that new technologies offer the hope of ameliorating unpalatable tradeoffs in the short run between environmental concerns and economic activity. However, the above results remind us that when comparing the welfare gains from pollution abatement in the short run versus the welfare gains from knowledge accumulation over the long haul, discounting can greatly reduce the relative size of the latter effect.

[16] See Portney and Weyant (1999) for a recent discussion of different viewpoints on discount rates.

annualized net benefits.[17] The net effect of varying the discount rate between 2% and 8% on PV^I/PV^P is shown in Table 2.[18]

The first three columns confirm the analytic results in (10) in the case with no R&D costs. In this case the benefits from innovation and the Pigouvian welfare gain are the same in every period so the discount rate has no effect on their ratio. Hence the upper bound values for PV^I/PV^P are unaffected by changing *r*.

Table 2: Effect of Alternate Discount Rates (*r*) on PV^I / PV^P

Pigouvian abatement level	Time lag until abatement costs halve											
	0			10 years			20 years			40 years		
	=2%	=5%	=8%	=2%	=5%	=8%	=2%	=5%	=8%	=2%	=5%	=8%
10%	9.0	9.0	9.0	.00	.98	.36	.05	.88	.28	.39	.16	.08
40%	.00	.00	.00	.13	.07	.63	.32	.46	.22	.63	.16	.07
60%	.33	.33	.33	.37	.79	.52	.92	.41	.23	.52	.17	.09

In the remaining columns, varying the discount rate significantly affects the size of PV^I/PV^P. For a particular time lag until abatement costs are halved, we see from Table 2 that using a discount rate of 8% rather than 5% roughly halves the value of PV^I/PV^P, while using 2% rather than 5% can easily increase PV^I/PV^P by a factor of two or three. Thus, for example, when the Pigouvian abatement level is 40% and innovation reduces abatement costs by 50% in 10 years, varying the discount rate between 2% and 8% produces values of PV^I/PV^P between 2.13 and 0.63.

[17] This result is easy to see for the simplified case of no adjustment costs in the last term in (10).

[18] We also adjust the research cost parameter f_2 to keep constant the time lag until abatement costs halve.

The possibility of a low discount rate raises the potential importance of innovation and increases the range of outcomes under which the welfare gains from innovation dominate the Pigouvian welfare gains. In particular, the gain to innovation with an arbitrarily low discount rate is limited only by the Pigouvian abatement level and the long-run cost reduction, as shown in Section 2B. Our conclusions, however, continue to focus on the assumption that 5% represents the most plausible case (e.g., discussions in Nordhaus, 1994).

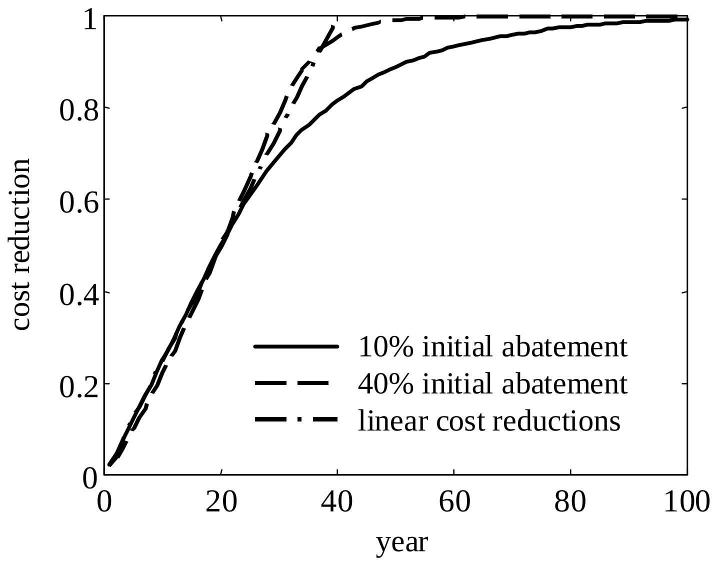
B. Research Costs

We now consider the assumptions concerning research costs *f*(.) and the impact of increased innovation *z*(.). The specification of these functions determines the relative gain to innovation within the theoretical bounds established in the earlier section. That is, *f*(.) and *z*(.) determine the amount of innovation, the implied cost reductions, and the timing of those reductions—but this must be between zero and the maximal gain when abatement costs are immediately and costlessly reduced to zero. Our original choice of $f(I_t) = f_1 I_t + f_2 I_t^2$ with $f_1 = 0$ and $z(K) = 1 - (1-K)^2$ creates a smooth R&D path that asymptotically drives abatement costs to zero (since marginal R&D is costless).

Holding this path of cost reductions fixed, higher research costs unambiguously lower the relative welfare gain from innovation since the Pigouvian welfare gain is unaffected and the gain to innovation net of research costs is lowered. Since it is easy to conjecture that R&D costs could be large and might even exceed the benefits to innovation, we instead focus on the consequences of lowering the cost of innovation. This allows us to bound the maximal gain to innovation conditional on a particular path of cost reductions.

Let us specify a particular path for cost reductions—a reduced form, in some sense, for *f*(.) and *z*(.)—and then compute the relative gain to innovation ignoring any R&D costs. This separates the issue of R&D costs from the issue of innovation lag, allowing us to disentangle their relative importance. For simplicity, we consider a linear path of abatement cost reductions, removing the ambiguity of how research costs are determined by *f*(.) and how a non-linear path of cost reductions might be determined by *f*(.) and *z*(.). For reference, Figure 2 shows the endogenous, optimal path of cost reductions, $z(K_t)$, associated with our earlier “20 year lag until abatement costs halve” specification for both the 10% and 40% Pigouvian abatement levels, alongside this linear alternative. Note that our original quadratic specifications for *f*(.) and *z*(.) generates roughly linear cost reductions up to 50%, and moves asymptotically toward 100% at different rates depending on the initial abatement level. Intuitively, this occurs because once the abatement level itself reaches 100%, the marginal gain to innovation begins to diminish since, looking back to Figure 1, the additional gain *qrs* no longer exists.

Figure 2: Cost Reduction Schedules Under Different Alternatives



Implementing the linear reduction schedule as exogenous and costless innovation over time, we re-compute the relative gain to this innovation in Table 3. With R&D costs removed, this reflects the pure effect of a time lag in innovation, assuming linear cost reductions. The main story from Table 3 is that at ten years, half the maximal gain to innovation is lost entirely due to delay. When innovation requires forty years to halve abatement costs—an annual decline in abatement costs of 1.25% per year—the gain to innovation is equal to or smaller than the Pigouvian gain in all cases.

Table 3. PVI/PVP under Alternative Models of Research Costs and Innovation Effects

Pigouvian abatement level (%)	Innovation Model	Time lag until abatement costs halve			
		0	10 years	20 years	40 years
10	original quadratic *z* & *f*	19.00	2.98	0.88	0.16
	costless linear reductions	19.00	8.61	3.95	1.01
40	original quadratic *z* & *f*	4.00	1.07	0.46	0.16
	costless linear reductions	4.00	2.25	1.31	0.55
60	original quadratic *z* & *f*	2.33	0.79	0.41	0.17
	costless linear reductions	2.33	1.42	0.90	0.44

The relative gain to innovation with costless linear reductions in abatement costs is remarkably similar to the effect of using a 2% discount rate in Table 2. Like the discount rate, alternate assumptions about research costs raise the gain to innovation, limited first by the theoretical bounds established in Section 2B, and now further limited by the time lag until costs are halved. However, it seems reasonable to believe that any time lag in innovation arises because of an endogenous decision about R&D. For that reason we continue to focus on our quadratic model of *f*(.) and *z*(.). With marginal R&D costs starting at zero, we believe this already represents a conservative model of R&D costs.

C. Convex Damages

Linear environmental damages seem to be a reasonable approximation in many cases. In particular, adverse human health impacts are the major source of damages from air pollutants and these seem to increase roughly in proportion with atmospheric pollution concentrations (e.g., Burtraw *et al*., 1997). However convex damages can occur, for example, when there are thresholds beyond which the environment is unable to further assimilate pollution.

For a given Pigouvian abatement level, allowing for convex environmental damages actually *reduces* the size of PV^I/PV^P. This is easy to see from Figure 1. Suppose we rotate the marginal environmental benefit curve clockwise, holding constant the abatement level at which it intersects the marginal abatement cost curve. This increases the Pigouvian welfare gain W^P since there is a larger benefit from infra-marginal abatement. But it reduces the benefits from increasing abatement above A^P, and therefore reduces W^K. Hence PV^I/PV^P must be smaller.

To illustrate the extent of the reduction in PV^I/PV^P, we assume the marginal environmental benefit function is $\phi_1 - \phi_2 A$. We continue to normalize both emissions $\overline{E}$ and the marginal benefits at the Pigouvian abatement level to be one, and consider values of ϕ_2 equal to 0.25, 0.50, and 1.00. In other words, we rotate the marginal benefit schedule about the Pigouvian abatement level, with the slope such that increasing abatement by $\overline{E}$ above the Pigouvian abatement level reduces marginal benefits by 25%, 50% or 100%. We report the results in Table 4 for the case when innovation leads to a halving of abatement costs in 10 years. The first column simply repeats the results from Table 1. The remaining columns show that steeper marginal environmental benefits can lead to considerable reductions in the value of PV^I/PV^P. The effect is similar under different assumptions about the initial Pigouvian abatement level. With a marginal environmental benefits slope of 0.25, 0.50 and 1.00, PV^I/PV^P falls by about 15%, 30% or 50% respectively, relative to the case of constant marginal environmental benefits.[19] In short, allowing for convex rather than linear environmental damages can significantly reduce PV^I/PV^P.

[19] In fact, in the extreme case when the marginal environmental benefit curve is vertical at the Pigouvian level of abatement, then it is easy to infer from Figure 1 that PV^I/PV^P falls to zero.

Table 4. PV^I/PV^P for Flow Pollutant with Convex Environmental Damages

Pigouvian abatement level	Marginal Benefit Slope			
	0	0.25	0.50	1.00
10%	2.98	2.61	2.25	1.64
40%	1.07	0.91	0.78	0.58
60%	0.79	0.65	0.55	0.41

D. Stock Pollutant

The case of a stock pollutant with linear environmental damages produces equivalent results to those of a flow pollutant. Suppose that pollution emissions accumulate in the environment according to equation (2) with $0<\delta\leq 1$, and that the damage from accumulated pollution at time t is ϕS_t. The present value at time t from environmental damages over the rest of the planning period (Φ_t) is therefore:

$$\Phi_t = \phi \sum_{j=1}^{\infty} \frac{S_{t+j}}{(1+r)^j}$$

Using (2) we can obtain:

$$-\frac{\partial \Phi_t}{\partial A_t} = \frac{\phi}{r+\delta}$$

This is the marginal benefit from abatement at time t. It equals the present value of avoided damages from incrementally reduced pollution stocks over all subsequent periods. But this marginal benefit is the same at the start of every period. Thus, the social planning problem for a stock pollutant with linear damages is equivalent to that for a flow pollutant with the same abatement costs, innovation costs, and marginal environmental damages equal to $\phi/(r+\delta)$. Thus, we would obtain exactly the same values for PV^I/PV^P as before for particular Pigouvian abatement levels.

E. Innovation and Abatement over Shorter Planning Periods

It might be argued that, by using an infinite planning horizon, we have understated the value of PV^I/PV^P; that is, PV^I/PV^P might be larger when innovation is compared to abatement over a shorter period of time. Imagine, for example, a policymaker comparing a short-term R&D program to reduce the costs of abatement versus a program to immediately restrict emissions for the next few years. By augmenting a knowledge stock, R&D in one period can yield benefits in all future periods, whereas reducing emissions of a (flow) pollutant for several years yields only limited short-term benefits.

If the choice is between doing R&D now or never, then this argument may have some validity. But this comparison is not really fair: if innovation is not conducted for the first, say, 0 to n periods of the planning horizon, innovation can still begin in period n+1. In our example, the R&D program could be implemented *after* the immediate restriction on emissions. Therefore, the welfare gain from innovation during periods 0 to n is really the welfare gain from starting the optimal innovation path in period 0 rather than delaying its start to period n+1. Using this definition of the gain to innovation and the model of Section 2, it is straightforward to show that the ratio PV^I/PV^P is unaffected when innovation is compared to abatement over an n-period horizon.

Proof: Using equation (9) the welfare gain from beginning the optimal innovation path in period zero rather than period n+1 is:

$$PV_n^I = \{1-(1+r)^{-n}\}PV^I = \{1-(1+r)^{-n}\}\left\{\frac{W^K}{r} - f^*\right\}$$

Using (4) the discounted welfare gain from the Pigouvian amount of abatement from period 1 to period n with no innovation is:

$$PV_n^P = (1+r)^{-1}\left\{\frac{1-(1+r)^{-n}}{1-(1+r)^{-1}}\right\}W^P$$

Dividing PV_n^I by PV_n^P gives exactly the same ratio as in equation (10).

F. Delayed Abatement

Sometimes environmental regulations are proposed long before they actually become binding and therefore they may encourage innovation well before any emissions reduction actually occurs. For example, under the December 1997 Kyoto Protocol the United States does not have to control carbon emissions until 2008-2012. In this final subsection we consider the case when innovation can begin immediately, but abatement is delayed by 10 years.[20] Allowing knowledge to be accumulated over a 10-year period before any abatement occurs raises the value of PV^I/PV^P, since the cost of innovation can be spread over a longer period of time, reducing convex R&D costs.

Table 5 shows the effect of this lead-time on PV^I/PV^P when the Pigouvian abatement level is 40% and for our usual assumptions about how quickly innovation halves abatement costs. In the extreme case with no R&D costs (first column), there is no change in PV^I/PV^P. Here, innovation simply occurs in the one period just prior to abatement. But when the marginal cost of research is upward sloping, it pays to begin knowledge accumulation early rather than waiting 10 years until abatement first occurs. In this case, the value of PV^I/PV^P increases by around 40%. Therefore, allowing for a 10-year lead-time does have a modest impact on lowering the hurdle for PV^I to exceed PV^P, but our qualitative points remain true. Innovation must still produce a major reduction in abatement costs quickly. If, for example, it takes 20 years to reach the 50% reduction in abatement costs, PV^I is still well below PV^P when the initial Pigouvian abatement level is 40%. [21]

[20] That is, in the Pigouvian case there is no R&D and abatement begins in 10 years while in the innovation case, abatement still begins after 10 years but R&D can begin immediately.

[21] In practice, an announcement that pollution control will begin 10 years from now may lack some credibility and hence undermine innovation incentives. For example, the policy may be weakened if the government changes color in the interim period. Moreover, an international agreement to control emissions, such as the Kyoto Protocol, may soon unravel if one major country reneges on its emissions pledge.

Table 5: PV^I/PV^P when Abatement Begins after Ten Years (40% abatement)

	Time lag until abatement costs halve			
	0	10 years	20 years	40 years
Abate Now	4.00	1.07	0.46	0.16
Abate in 10 years	4.00	1.53	0.67	0.22

An important caveat to these results is that the abatement delay must be exogenous and not delayed in order to give innovation a head start. If one imagines a policymaker deciding between an early focus on innovation incentives rather than *immediate* reductions, s/he would compare the scenario with early innovation to one with immediate abatement and no innovation. The relative gain to innovation of 1.53 in the above table, however, is measured relative to Pigouvian gains when abatement begins after ten years. This Pigouvian scenario generates only 60% of the welfare gains associated with an immediate abatement plan (based on ten years of discounting). Thus the gain of early innovation relative to immediate abatement is only 0.92 = 1.53 x 0.60. Therefore, these results do not in any way suggest that abatement should be delayed in order to *permit* innovation.

4. Conclusion

This paper uses a dynamic social planning model to estimate the discounted welfare gains from innovation that reduces the future costs of pollution abatement. These welfare gains are expressed relative to the discounted "Pigouvian" welfare gains from correcting the pollution externality when the state of technology is held fixed over time. In general, we find that the discounted welfare gains from innovation are unlikely to be as large as the discounted Pigouvian welfare gains, and they could easily be a lot smaller. The reason is the benefits from innovation are bounded by the potential reduction in abatement costs and, since R&D is costly, it takes time to accumulate enough knowledge to secure a substantial reduction in abatement costs. We find that the (discounted) welfare gains from innovation could only exceed the (discounted) Pigouvian welfare gains if innovation substantially reduces abatement costs in a short period of time *and* the initial Pigouvian abatement level is fairly modest. Our results apply for both flow and stock pollutants, for linear and convex environmental damage functions, and for comparing innovation and abatement over short and long planning horizons. Very low discount rates and costless R&D can, however, overturn this conclusion. In sum, our analysis casts some doubt on the assertion that technological innovation—rather than pollution control—should be the overriding factor in the design of environmental policies.

At first glance these results may seem surprising because economists and policymakers alike have tended to lean on innovation as an important cornerstone of modern environmental policy, especially with regard to climate change. Why does innovation and "technology policy" attract such attention? One possibility is that stringent emissions reductions may be politically difficult when the costs are concentrated in one industry while the benefits are widely diffused. Incentives for innovation may be more palatable. Also, economists often focus on the cost-effectiveness of different policies associated with a particular emission target. In a cost-effectiveness setting, technological innovation offers the seductive possibility that abatement costs could be eliminated but ignores the magnitude of those costs relative to benefits. In any case, our results in no way rule out the possibility that the *absolute* welfare gains from innovation might be substantial, only that they are probably smaller than the welfare gains from pollution control over time.

There are some limitations to our analysis that might be useful to relax in future work and hence our results should be viewed with some caution. For example, we have compared the welfare gains from the socially optimal amount of innovation to the welfare gains from the socially optimum amount of pollution control. In practice, environmental policies may not be set optimally, due to "government failure" or because of extreme uncertainty over the (marginal) benefits and costs of pollution abatement. It might be fruitful to explore the welfare gains from innovation in a setting when pollution control is sub-optimal.

We also focus only on the first-best welfare gains from pollution control and innovation, while in practice policy is conducted in a second-best setting. In particular, recent research has shown that the welfare gains from certain pollution control policies can be greatly reduced by their impact on raising product prices, reducing real factor returns, and consequently compounding distortions from pre-existing taxes in factor markets (e.g., Goulder *et al*. (1999)). The impact of innovation-promoting policies on pre-existing tax distortions has not yet been estimated in the literature. In fact, it is possible that such policies may reduce the efficiency costs of pre-existing taxes to the extent that investment in R&D comes at the expense of consumption rather than investment in other activities. This is because, due to taxes on the income from investment, investment is "too low" relative to consumption. Consequently, in a second-best setting the (general equilibrium) welfare gains from increasing innovation may be more favorable relative to the welfare impacts of pollution control.

On the other hand, due to other second-best considerations, the supply curve of R&D may understate true opportunity costs. This occurs if environmentally focused R&D crowds out other (commercial) R&D, and the social rate of return on this R&D exceeds the private rate of return due to spillovers from knowledge (e.g., Nordhaus, 1998). In this regard then, our results may *overstate* the welfare gains from innovation.

Another limitation is that we ignore possible spillover benefits of new abatement technologies to other industries. If these spillover benefits are environmental—for example a new technique for reducing carbon emissions by using more natural gas can also reduce sulfur emissions—they can raise the overall social benefits from innovation. If the spillover benefits are economic however, for example the private cost savings from reduced fuel requirements, they may already be internalized to some extent, prior to the introduction of an environmental policy.

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