How Large Are the Welfare Gains from Technological Innovation Induced by Environmental Policies?

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Abstract

This paper examines whether the welfare gains from technological innovation that reduces future abatement costs are larger or smaller than the "Pigouvian" welfare gains from optimal pollution control. The relative welfare gains from innovation depend on three key factors¾the initially optimal level of abatement, the speed at which innovation reduces future abatement costs, and the discount rate. We calculate the welfare gains from innovation under a variety of different scenarios. Mostly they are less than the Pigouvian welfare gains. To be greater, innovation must reduce abatement costs substantially and quickly and the initially optimal abatement level must be fairly modest.

Key Words: innovation, welfare, regulation, endogenous, technological, change, R&D

JEL Classification Numbers: Q16, Q28, O32, O33

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1. Introduction

Some economists have speculated that technological advance is likely to be the most important factor in achieving environmental quality goals. 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"; and Orr (1976): "Technological adaptation rather than resource allocation [is] the key to an effective solution of [environmental problems]."[1] Clearly, over a period of decades innovation may go a long way in alleviating unpalatable short-run trade-offs between economic activity and the environment. But when evaluating environmental policies on the basis of costs and benefits what matters is the welfare gain from induced innovation. This paper examines whether the welfare gains from abatement cost-reducing innovation are in fact large or not relative to the "Pigouvian" welfare gain from achieving optimal pollution control.

There is a fairly well developed literature on technological innovation and the environment. This literature has explored the implications of induced innovation for the choice among different types of emissions control instruments and the optimal stringency of emissions

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[1] Others have made the more controversial claim that costs of environmental regulations might even be negative owing to induced innovation (see Porter and van der Linde 1995 and Palmer et al. 1995 for different perspectives on this).

controls.[2] Much of the recent research has focused on the implications of technological innovation for the costs and optimal level of carbon control policies over time.[3] However, one issue that has not received much attention is the magnitude of the welfare gains from induced innovation.

Knowing the size of the welfare gains from innovation would be useful for a number of reasons. First, it would indicate to what extent previous, exogenous-technology models may have understated the net benefits to society from environmental regulations. Indeed, if the welfare gains from innovation are larger than the welfare gains from pollution control, previous cost–benefit studies may have omitted the most important source of welfare gain![4] Second, it may shed some light on the quantitative importance of previous theoretical analyses demonstrating that different emissions control instruments provide different incentives for technological innovation—the larger the welfare gains from innovation the stronger the case for preferring instruments that are more effective in promoting innovation.[5] Third, if the potential welfare gains from induced innovation are large, this may provide a strong efficiency argument for buttressing environmental policies with other instruments, such as research subsidies, tax credits, and technology prizes, to promote innovation.

[2] See, for example, Downing and White (1986), Milliman and Prince (1989), Jaffe and Stavins (1995), Jung et al. (1996), Kemp (1997), Parry (1995, 1998), Petrakis et al. (2000) and Fischer et al. (2002). For a good review see Jaffe et al. (2000).

[3] See, for example, Peck and Teisberg (1994), Kolstad (1996), Wigley et al. (1996), Nordhaus (1998), Goulder and Schneider (1999) and Goulder and Mathai (2000).

[4] See, for example, Cropper and Oates (1990), Morgenstern (1997), and Portney and Stavins (2000) for cost–benefit discussions of environmental regulations that do not consider the magnitude of the efficiency gains from innovation.

[5] Previous literature has shown that (equivalently scaled) market-based instruments usually provide stronger incentives for innovation than technology mandates and performance standards, and that emissions taxes can provide more incentives than freely allocated emission permits (e.g., Milliman and Prince 1989, Jung et al. 1996, Parry 1998, Fischer et al. 2002, Keohane 1999).

This paper provides a preliminary assessment of the relative magnitude of the welfare gains from induced innovation. We use a dynamic social planning model in which the control variables are annual pollution abatement and R&D expenditures, where R&D investment enhances a knowledge stock that reduces future abatement costs. We define the Pigouvian welfare gains as the present value of welfare gains from optimal emissions abatement in each period with exogenous technology. We then solve for the discounted welfare gains from the first-best level of abatement and R&D in each period with endogenous technology. The difference between these two welfare measures is the welfare gain from innovation.

The welfare gain from innovation, expressed relative to the Pigouvian welfare gain, boils down to three key factors. First, the optimum abatement level in the first period. If the optimum abatement level is initially small, the Pigouvian welfare gain will be small and the potential to further increase welfare by reducing abatement costs is large.[6] Second, the speed with which innovation reduces future pollution control costs on the optimal innovation path, which depends on the costs of developing improved abatement technologies: faster cost reductions imply greater gains to innovation. Third, the social discount rate: a lower rate increases the relative welfare gain from innovation because the benefits from innovation occur in the future while costs are up-front.

Our analysis illustrates the welfare gain from innovation over a broad range of different scenarios for these three effects. In most cases the welfare gain is smaller than the Pigouvian welfare gain—for it to be larger requires that innovation substantially reduce abatement costs quickly (by roughly 50% within 10 years) *and* that the optimal amount of abatement is initially fairly modest. The 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 of time.

[6] The *cost savings* from innovation is larger when there is more abatement over which to reduce costs. However, our focus is on the mark-up in the *welfare gain* from optimal emissions control, when account is taken of induced innovation.

We are aware of two other studies that calculate the welfare gain from induced innovation, both in the context of moderate carbon taxes—Nordhaus (1998) and Goulder and Mathai (2000). In both cases induced innovation has relatively minor effects on welfare (at least in the central case estimates).[7] Our analysis differs by providing a taxonomy that applies for pollutants in general and by illustrating results over a broad range of scenarios for the amount of abatement, the optimal speed of innovation, discount rates, the shape of the environmental damage function, and the length of the planning horizon.

There are a number of important qualifications to the results. For example, we evaluate innovation only in terms of social welfare: innovation may still be of primary concern to policymakers because of the long-run effect on ameliorating environmental and economic conflicts, even if reductions in pollution control costs, when discounted back to the present, are relatively modest. Moreover, in many of our simulations the welfare gains from innovation are a sizeable fraction of the welfare gains from pollution control. Thus, they can still be very important, even though they might be less than the gains from pollution control. Furthermore, the results are sensitive to the discount rate, over which there is much dispute for long-range problems. For our benchmark case we use a discount rate of 5%; using a lower value significantly increases the range of outcomes for which the welfare gains from innovation dominate those from optimal pollution control. Additional limitations are discussed below.

The rest of the paper is organized as follows. Section 2 describes the model and presents our benchmark results. Section 3 relaxes a number of simplifying assumptions and provides an extensive sensitivity analysis. Section 4 concludes and discusses caveats.

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7 According to Nordhaus (1998) this is because firms already have an incentive to develop energy-saving technologies to reduce private production costs, and a moderate carbon tax would do little to augment this incentive. In addition, more R&D into carbon-reducing technologies may crowd out R&D elsewhere in the economy, producing a welfare loss if the social rate of return exceeds the private rate of return on the forgone R&D. Goulder and Mathai (2000) emphasize that their findings are sensitive to the curvature of the marginal abatement cost function: for example, induced innovation has more effect on welfare and optimal abatement when the marginal cost function is concave rather than convex.

2. Benchmark Results

2.1. Model Assumptions

Consider an industry where a by-product of production is waste emissions that are detrimental to environmental quality (e.g., air or water pollutants, hazardous waste). In the absence of emissions abatement, "baseline" emissions in period t would be an exogenous amount $\overline{E}$. The cost of reducing emissions by A_t below $\overline{E}$, or emissions abatement, is $C(A_t, K_t)$. K_t denotes the stock of knowledge about possibilities for reducing emissions. A higher 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. In addition, more knowledge rotates the marginal abatement cost curve downwards about the origin but at a diminishing rate. Thus $C_{AA} > 0$, $C_A(0, K_t) = 0$, $C_{AK} < 0$, $C_{AKK} > 0$.

Knowledge accumulates as follows:

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

where K_0 is given and I_t is investment in environmentally oriented R&D activities. The cost of R&D (i.e., the cost of scientists, engineers, research equipment, etc.) is $f(I_t)$ where $f(.)$ is weakly convex. To keep the model parsimonious, and the results conservative, diffusion is subsumed in $f(.)$. There is no knowledge depreciation (knowledge cannot be disinvented); thus, $K_t \geq K_{t-1}$.

Emissions accumulate in the environment over time as follows:

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

where S_t denotes the stock of pollution at time t and the initial stock S_0 is given. δ is the decay rate of the stock: $\delta = 1$ for a flow pollutant (e.g., sulfur dioxide, nitrous oxides, and particulates) and $0 \leq \delta < 1$ for stock pollutants (e.g., nuclear waste, carbon dioxide, toxics).

Environmental damages at time t are $\phi(S_t)$ where $\phi' > 0$, $\phi'' \geq 0$. A social discount rate of r is applied to future benefits and costs, and the planning period extends over an infinite horizon.

2.2. Analytic Results

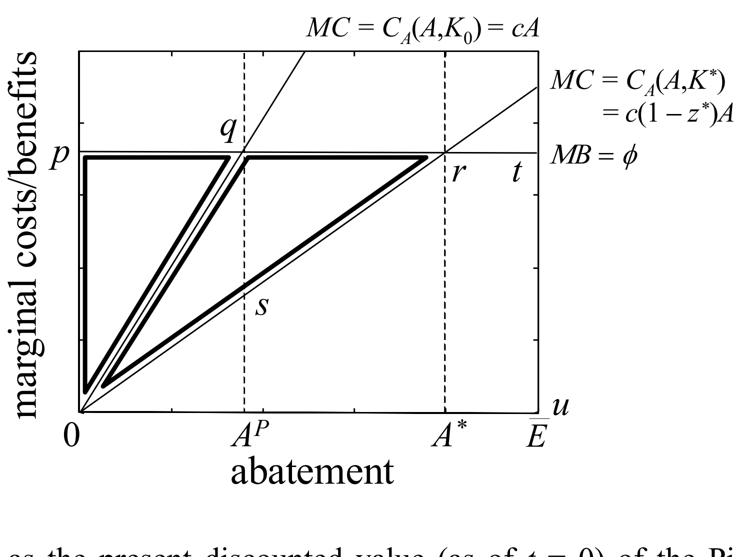
We now make some simplifying assumptions to establish some benchmark results in a transparent manner; most of these assumptions are relaxed later. We focus on a flow pollutant with constant marginal environmental damages; that is, $\delta = 1$ and $\phi' = \phi > 0$. The marginal cost of research is constant ($f'' = 0$). In addition, we use a quadratic abatement cost function:

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

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

To begin with, suppose the state of technology is exogenous as in the traditional Pigouvian model: knowledge is fixed at K_0 for the entire planning horizon. Optimal abatement (A^P) is where marginal abatement cost equals marginal environmental benefit (or marginal damage from emissions). Using (3) this gives $A^P = \phi / c$ for $t = 1\ldots\infty$ and the Pigouvian welfare gain per period, denoted W^P, is triangle 0*pq* 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 ∞:

$$(4) \qquad PV^P = \sum_{t=1}^{\infty} \frac{W^P}{(1+r)^t} = \frac{W^P}{r}$$

Allowing for innovation, the social planning problem becomes:

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

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

That is, choose abatement and innovation 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), $A_t^* > A^P$ (since $1-z^* < 1$): optimal abatement is greater than in the Pigouvian case because innovation lowers the marginal abatement cost curve. If $(1-z^*)c\overline{E} < \phi$, we have a corner solution with emissions abatement equal to 100% and $A^* = \overline{E}$.

Equation (7) is an Euler equation specifying that the marginal cost of innovation 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 innovation in period $t + 1$. With our assumption that f' is constant, $-C_K(A_t^*, K_t^*) = rf'$. 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 innovation occurs only in period 0 (this is unrealistic but simplifies our discussion and, as discussed below, makes our benchmark results conservative).

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 $0qr$ 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:

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

where $\Delta = \left\{\phi - (1-z^*)c\overline{E}\right\}^2 / \left\{2(1-z^*)c\right\} > 0$. Δ is positive only in the corner solution with 100% abatement.

We define the welfare gain from innovation, PV^I, as the discounted sum of benefits from additional knowledge ($K^* - K_0$) over all periods, less the cost of innovation in period zero. Thus:

$$(9)\, PV^I = \sum_{t=1}^{\infty} \frac{W^K}{(1+r)^2} - f(I_0^*) = \frac{W^K}{r} - f(I_0^*)$$

Using (4):

$$(10)\, \frac{PV^I}{PV^P} = \frac{W^K - rf(I_0^*)}{W^P}$$

The (discounted) welfare gain from innovation is greater (less) than the (discounted) Pigouvian welfare gain 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 $A^P / \overline{E} \le 1$ is the Pigouvian abatement level relative to baseline emissions then the maximum value of PV^I/PV^P is $2(A^P / \overline{E})^{-1} - 1$.

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 innovation reduces abatement costs by a factor z then the maximum value of PV^I/PV^P is z/(1–z).

Proof: Using (8) and (10),

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

Since Δ and $f(.) \geq 0$, $PV^I / PV^P \leq z/(1-z)$.

Result (i) puts an upper bound on PV^I/PV^P for the case when innovation completely eliminates abatement costs with no cost to innovation. 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. Therefore, only in cases when the Pigouvian abatement level is relatively modest (less than 40%) is there potential for the welfare gains from innovation to be several times as large as the Pigouvian welfare gains. Intuitively, if a pollution problem is severe enough to warrant a high level of abatement without innovation, then the additional welfare gain to innovation will be relatively small. Conversely, if abatement is initially too costly to justify major emission reductions, the potential welfare gains from innovation can be relatively large.[8]

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 ($z \leq 0.5$).

These results demonstrate that, in the highly simplified analysis so far, 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 not be too large.

[8] According to this result PV^I is unlikely to exceed PV^P for pollutants for which the Pigouvian pollution reduction is around 100%. This appears to be the case for lead emissions from gasoline and ozone-depleting CFC emissions (see Nichols 1997 and Hammitt 1997, respectively).

2.3. Numerical Simulations

The previous results may seriously overstate the actual value of PV^I/PV^P for two reasons. First, research costs are positive and we need to subtract them in order to obtain the net welfare gain from innovation. Second, in general it will be optimal to smooth out knowledge accumulation over time rather than doing it all in period zero; that is, f'' is typically positive.[9] 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 has been completed.

We now generalize the model to allow for convex research costs. Smoothing out innovation 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 equates the difference in marginal innovation costs in adjacent periods with the one-period return to innovation. The model with adjustment costs cannot be solved analytically, and therefore we use numerical simulations.

We adopt the following innovation cost function:

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

where f_1 and f_2 are positive parameters. f_1 determines knowledge in the steady state: the smaller f_1 is, the more likely that it will be optimal to 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 transition period to the steady state.

We also specify the following functional form:

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

The choice of K_0 is arbitrary because only the difference $K - K_0$ 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 implies that the steady state knowledge stock will completely eliminate abatement costs because the first unit of research in a period always has zero cost. As discussed in the next section, this leads us to overstate PV^I/PV^P relative to the more

[9] It is increasingly costly to enhance 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.

realistic case of $f_1 > 0$. 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).

We choose c to imply that the Pigouvian amount of abatement ($A^P = \phi / c$) is 10%, 40%, or 60%. Finally, we select different values of f_2 to imply a wide range of scenarios for the time it takes for knowledge accumulation to reduce abatement costs by 50% on the optimal innovation path.

Table 1 summarizes the benchmark simulations. In the second column, we set $f_2 = 0$; consequently, innovation completely and immediately eliminates abatement costs at zero cost. These entries confirm our earlier calculations of the maximum value of PV^I/PV^P.

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

Initial 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

The next three columns show the effect of incorporating positive and increasingly higher adjustment costs for research. Suppose the initial Pigouvian abatement level is 40%. In this case, the welfare gain from innovation is 107%, 46%, and 16% of the Pigouvian welfare gain when innovation reduces abatement costs by 50% over 10, 20, and 40 years, respectively (and by 100% in the steady state). In addition, and as predicted earlier, the ratios in Table 1 diminish as the Pigouvian abatement level rises. But regardless of the initially optimum abatement level, PV^I is less than PV^P if it takes 20 years or more for innovation to reduce abatement costs by 50% on the optimal dynamic path. Indeed, if the Pigouvian abatement level is initially 60% or more, PV^I is less than PV^P even if abatement costs are reduced by 50% in 10 years.

These simulations demonstrate that the conditions for PV^I to be large relative to PV^P are rather stringent in our model. Innovation must rapidly reduce abatement costs by more than 50% *and* the initial Pigouvian level of abatement must be fairly modest. If the initial Pigouvian abatement level is large, if cost savings from innovation are small, or if these cost savings occur with a substantial time lag, then PV^I is smaller than PV^P.[10]

In practice how long might it take for technological innovation to substantially reduce abatement costs? Under the tradable permit program for sulfur, which has roughly halved emissions, abatement costs were about 50% lower 10 years into the program than initial projections (e.g., Carlson et al. 2000). For illustrative purposes let us assume that the program is optimal from a Pigouvian standpoint.[11] According to our analysis, this would suggest that PV^I is about the same size as PV^P. However, not all of the reduction in sulfur control costs was due to induced innovation; a substantial portion resulted from the deregulation of the railroad industry, which reduced transport costs for low-sulfur coal. Taking this onto account would lower PV^I below PV^P in this illustrative example.

In the context of climate change, if the United States had stuck with the Kyoto Protocol, it would have had to reduce carbon emissions by around 30% below baseline levels by 2008–2012 (Energy Information Administration, 1999, pp. 89). Again, for illustrative purposes suppose that this represents the optimal Pigouvian amount of abatement. According to our analysis, for PV^I to exceed PV^P innovation would have to cut abatement costs by 50% in less than 15 years. Given the current dependency of the U.S. economy on fossil fuels and that, unlike in the case of other air pollutants, there is currently little prospect of developing economically viable end-of-pipe treatment technologies, it seems highly unlikely that innovation could halve carbon abatement costs within such a short time frame.

Of course, the above discussion is based on a highly simplified model with specific assumptions about functional forms (e.g., for environmental damages, research costs) and parameter values (e.g., the discount rate). In the next section we consider how robust the results

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[10] Another way to interpret these results is that incorporating research costs can dramatically reduce the potential welfare gains from innovation. For example, when the Pigouvian abatement level is 40% without any research costs the welfare gain from innovation is 4 times the Pigouvian welfare gain. But with research costs, the welfare gain from innovation falls to only 46% of the Pigouvian welfare gain when it takes 20 years for innovation to reduce abatement costs by 50%.

[11] In practice, marginal environmental benefits appear to be higher than marginal abatement costs, implying that the program is not stringent enough (Burtraw et al., 1998).

are to a variety of generalizations and sensitivity analyses. Other limitations that are beyond the scope of the paper are discussed in Section 4.

3. Generalizations and Sensitivity Analysis

In this section we discuss discount rates, research cost functions, environmental damage functions, stock pollutants, shorter planning horizons, and shorter abatement/innovation timing.

3.1. Discount Rate

The benchmark simulations assume a discount rate of 5%, which is a typical value used by economists (e.g., Nordhaus 1994). However, there is considerable dispute over the appropriate rate. The Office of Management and Budget recommends a rate of 7%, while on the other hand a theoretical case can be made for using a lower discount rate when investments have very long-range benefits.[12]

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, whereas the costs are up-front. Therefore, higher discount rates lower the annualized welfare gains from innovation. In contrast (at least for flow pollutants) benefits and costs from pollution abatement occur simultaneously, and the discount rate has no effect on annualized welfare gains.[13]

The effect of varying the discount rate between 2% and 8% on PV^I/PV^P is shown in Table 2.[14] In first three columns under the "Time lag" heading there are no research costs. Here the

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[12] See for example Newell and Pizer (2000). The discount factor is a convex function of the discount rate. Therefore, using a discount factor calculated simply from the average discount rate will understate the expected value for the discount factor given a probability distribution for the discount rate. This understatement starts to become significant when benefits occur several decades or more into the future. See Portney and Weyant (1999) for a broader discussion of viewpoints on the appropriate discount rate.

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

[14] For these simulations, we adjust the research cost parameter f_2 to keep constant the time lag until abatement costs halve.

benefits from innovation and the Pigouvian welfare gain are the same in every period, so the discount rate has no effect on their ratio [see equation (10) when $f(.) = 0$].

Table 2. PV^I / PV^P Calculations under Alternate Discount Rates

Pigouvian abatement level (%)	Time lag until abatement costs halve											
	0			10 Years			20 Years			40 Years		
	r=2%	r=5%	r=8%	r=2%	r=5%	r=8%	r=2%	r=5%	r=8%	r=2%	r=5%	R=8%
10	19.0	19.0	19.0	8.00	2.98	1.36	4.05	0.88	0.28	1.39	0.16	0.08
40	4.00	4.00	4.00	2.13	1.07	0.63	1.32	0.46	0.22	0.63	0.16	0.07
60	2.33	2.33	2.33	1.37	0.79	0.52	0.92	0.41	0.23	0.52	0.17	0.09

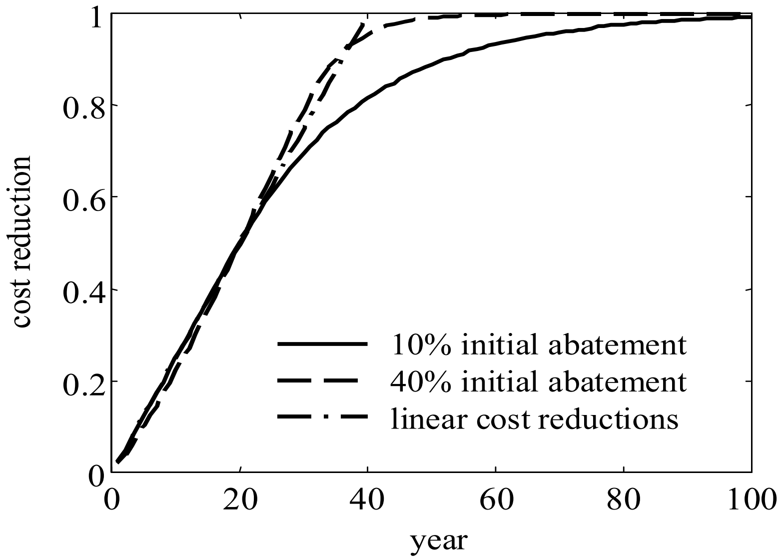
In the remaining columns, varying the discount rate significantly affects the size of PV^I/PV^P. For a particular time lag until abatement costs are halved, we see from Table 2 that using a discount rate of 8% rather than 5% roughly halves the value of PV^I/PV^P, while using 2% rather than 5% can easily increase PV^I/PV^P by a factor of two or three. 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.

Another way to view these results is that using a lower discount rate increases the range of outcomes under which the welfare gains from innovation exceed the Pigouvian welfare gains. From the last three columns in Table 2, PV^I exceeds PV^P in 2 out of 9 cases when the discount rate is 5%, but in 6 out of 9 cases when the discount rate is 2%.

3.2. Research Costs

Introducing research costs into the model lowers PV^I/PV^P, relative to its value when innovation is costless and all innovation occurs in the first period, for two reasons. First, the direct costs of innovation, and second, the lagged adjustment of the knowledge stock and hence abatement costs. In this subsection we separate out these two effects in order to assess the maximum value of PV^I/PV^P under different functional form/parameterizations for $f(.)$ and $z(.)$, for a given path of abatement cost reductions.

Figure 2. Abatement Cost Reduction Schedules Under Different Alternatives



For simplicity, we consider a linear path of abatement cost reductions over time, removing the ambiguity of how a nonlinear path might be determined by $f(.)$ and $z(.)$. For reference, Figure 2 shows the endogenous, optimal path of abatement cost reductions, $z(K_t)$, associated with our earlier "20-year lag until abatement costs halve" specification for the cases when the initial Pigouvian abatement is 10% and 40%, alongside the linear alternative. The benchmark quadratic specifications for $f(.)$ and $z(.)$ generate roughly linear cost reductions up to 50%, and thereafter move asymptotically toward 100% at different rates depending on the initial abatement level.[15]

Implementing the linear reduction schedule as exogenous, and ignoring innovation costs, we re-compute PV^I/PV^P. The results are reported in Table 3. Comparing the left column with the costless linear reductions shows the reduction in the maximum value of PV^I/PV^P due to the pure effect of the innovation lag, for a given abatement level and time to halving abatement costs. Then comparing the costless linear reduction case with the quadratic case shows the further

[15] Intuitively, this occurs because once the abatement level itself reaches 100%, the marginal gain to innovation begins to diminish since in Figure 1 the additional gain *qrs* no longer exists.

reduction in PV^I/PV^P because of the direct costs of innovation. These results indicate that the lagged effect of innovation has more effect on reducing PV^I/PV^P than subtracting out research costs, though both effects are substantial. For example, when the initial Pigouvian abatement level is 40% and abatement costs halve in 10 years, the lagged effect of innovation reduces PV^I/PV^P from 4.0 to 2.25, and subtracting innovation costs reduces it further to 1.07.

Table 3. PV^I/PV^P 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

We can imagine alternative functional forms/parameterizations for $f(.)$ and $z(.)$ that might yield lower innovation costs than in our benchmark, for a given schedule of abatement cost reductions.[16] The upper bound value for PV^I/PV^P in these cases is indicated by the entries for the costless linear reductions in Table 3. Here we see that the maximum value for PV^I/PV^P exceeds one in many cases; however only when the initial Pigouvian abatement is 10% and abatement costs halve in less than 20 years is it conceivable that the welfare gains from innovation could be several times the Pigouvian welfare gains.

[16] However, with marginal R&D costs starting at zero, we believe our benchmark already represents a conservative model of R&D costs.

3.3. Convex Damages

The assumption of constant marginal environmental damages from emissions appears to be a reasonable approximation for certain problems.[17] However, convex damages can occur, for example, when there are thresholds and discontinuities in ecological effects (e.g., Muradian 2001).

For a given Pigouvian abatement level, allowing for convex environmental damages *reduces* the size of PV^I/PV^P. This is easy to see from Figure 1. Suppose that we rotate the marginal environmental benefit curve clockwise about point *q*. This increases the Pigouvian welfare gain W^P (triangle 0*pq*) because there is a larger benefit from inframarginal abatement. But it reduces the benefits from innovation W^K because it reduces the gain from increasing abatement above A^P (i.e. it reduces triangle *qrs*). 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 environmental benefit 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 1% above the Pigouvian abatement level reduces marginal benefits by 0.25%, 0.5%, or 1%.

Table 4 shows the results for the case when innovation leads to a halving of abatement costs in 10 years. The first column under the "marginal benefit slope" heading simply repeats the results from Table 1. The remaining columns show that steeper marginal environmental benefits can lead to considerable reductions in 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.[18]

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[17] For example, human fatalities are the major environmental damage component for major air pollutants like sulfur, particulates, and nitrogen oxides, and the number of fatalities appears to be roughly linear in the atmospheric concentration of these pollutants (e.g. Burtraw et al., 1998).

[18] 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 because the Pigouvian welfare gain become infinite.

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

3.4. Stock Pollutant

For our purposes, the case of a stock pollutant with constant marginal environmental damage is operationally equivalent to that of a flow pollutant with constant marginal damage. 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:

$$(13)\ \Phi_t = \phi \sum_{j=1}^{\infty} \frac{S_{t+j}}{(1+r)^j}$$

Using (2) and (13) we can obtain:

$$(14) - \frac{\partial \Phi_t}{\partial A_t} = \frac{\phi}{r+\delta}$$

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 constant marginal damage from the stock is equivalent to that for a flow pollutant with the same abatement costs, innovation costs, and marginal environmental damage in emissions equal to $\phi/(r+\delta)$. Thus, we would obtain the same values for PV^I/PV^P as before for given Pigouvian abatement levels.

3.5. 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 with abatement over a shorter period. Imagine, for example, a policymaker comparing a short-term R&D program to reduce the future costs of abatement with a program to simply reduce 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 questionable: 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 program to simply reduce emissions for the next few years. Therefore, the welfare gain from innovation in this "short horizon" experiment 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 welfare gain to innovation (PV^I) and the model of Section 2, it is straightforward to show that PV^I/PV^P is unaffected when innovation is compared with the Pigouvian gain (PV^P) measured over a shorter n-period horizon, rather than an infinite horizon.

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

$$(15)\ PV_n^I = \{1-(1+r)^{-n}\}PV^I = \{1-(1+r)^{-n}\}\left\{\frac{W^K}{r} - f^*\right\}$$

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

$$(6)\, PV_n^P = (1+r)^{-1}\left\{\frac{1-(1+r)^{-n}}{1-(1+r)^{-1}}\right\}W^P$$

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

3.6. 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 Kyoto Protocol countries do 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.[19] 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 benchmark 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 notable impact on lowering the hurdle for PV^I to exceed PV^P. However, our qualitative results are still valid. 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%.[20]

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

[20] 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 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 10 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

4. Conclusion

This paper assesses the magnitude of the welfare gain from abatement cost-reducing innovation, relative to the welfare gain from optimal pollution control over time. The relative welfare gain depends on three factors—the initially optimal abatement level, the speed with which innovation reduces future abatement costs (on the optimal innovation path), and the social discount rate. Under most parameter scenarios, the welfare gain from innovation is smaller than that from pollution control—for the welfare gain to be larger requires that innovation quickly reduce abatement costs by a substantial amount (by roughly 50% within 10 years) *and* that the optimal amount of abatement initially be fairly modest.

These findings appear to contradict earlier assertions by some economists that technological advance might be more important than achieving optimal pollution control in the design of environmental policies. They may also reinforce concerns about the efficiency of the Bush administration's plan for reducing the growth of carbon emissions primarily through technology subsidies rather than by direct emissions controls.[21]

[21] Technology subsidies, however, may be far more attractive politically than emissions reductions that impose a substantial cost burden on energy producers and consumers.

However, for a number of reasons the results should not be taken to imply that technological innovation is unimportant. First, there are other criteria besides social welfare on which to evaluate environmental policies (and economists probably had these other criteria in mind when asserting the importance of technological advance). For example, innovation is obviously very important if policymakers are concerned about ameliorating economic/ environmental conflicts for future generations. Alternatively, the policy objective might be to minimize the costs of achieving a specific environmental goal. This is relevant when environmental benefits point to an unambiguous goal, when uncertainty about environmental benefits focuses attention on a particular goal, or when the political process separates goal setting and implementation. Based on the considerable uncertainty surrounding the benefits of climate change mitigation, for example, Dowlatabadi (1998) chose a fixed stabilization target and found that allowing for technical change reduces the costs of achieving that target by 50%, suggesting that technical change is very important.[22]

None of this is inconsistent with our result that the welfare gains from innovation tend to be less than those from optimal pollution control. The underlying assumption behind an unambiguous environmental goal, if it reveals social preferences, must be that benefits exceed the costs of achieving the goal—whatever the costs. That is, what we call the Pigouvian gain is large relative to any potential cost savings from innovation. Once an environmental goal is decided, however, the Pigouvian gain becomes irrelevant and the potential importance of innovation is unlimited—hence its frequent appearance in the literature.

Second, even though the welfare gain from innovation may be smaller than that from optimal pollution control, it is still a sizeable fraction of the Pigouvian welfare gain in many cases, implying that prior studies that ignore induced innovation may have seriously underestimated the net benefits from environmental regulations. Moreover, even if the welfare gains from innovation are not that large *relative* to those from pollution control, they may still be large in *absolute* terms.

[22] This calculation does not account for the costs of R&D, however. See also Carraro and Hourcade (1998).

Third, our analysis uses a social planning model in which innovation and abatement in each period are both socially optimal. In practice, environmental policies may not be set optimally for political or other reasons; indeed until recently policymakers in the United States relied on "command and control" policies to reduce pollution rather than more efficient market-based approaches. In future work it would be useful to compare the welfare gains from innovation and pollution control in the (more realistic) case when the stringency of environmental regulation, and perhaps the choice of instrument, are inefficient.

Fourth, our model is highly simplified and omits a variety of complicating factors that might affect the welfare comparison. These include possible spillover benefits of environmental technologies to other industries or other countries, strategic behavior in product and research markets, efficiency effects from crowding out R&D in other sectors of the economy, and interactions between environmental policies and distortions in the economy created by the tax system. It is also possible, as Porter and van der Linde (1995) have argued, that innovative efforts to reduce pollution can have the added benefit of reducing other production costs. Although most economists have been skeptical of such benefits (Palmer et al. 1995), it remains a potent argument among supporters of increased environmental regulation—especially those regulations that encourage or force technology changes.

Finally, even in our simplified model the results should be treated with caution. They are sensitive to the discount rate, and a low rate substantially raises the importance of innovation. Moreover, the costs of developing future abatement technologies are not known ex ante; consequently, we can only illustrate plausible ranges of outcomes for the welfare effects of innovation, rather than provide accurate estimates.

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