Does Technological Innovation Really Reduce Marginal Abatement Costs? Some Theory, Algebraic Evidence, and Policy Implications*

Yoram Bauman, Whitman College
Myunghun Lee, Inha University
Karl Seeley, Hartwick College**

Abstract

The existing literature models innovation in pollution control as a reduction in marginal abatement costs. We show that this assumption is inappropriate for production process innovations such as fuel switching. Algebraically, we examine the effects of different innovation types on marginal abatement cost curves, showing that some desirable innovations *increase* marginal abatement costs. Empirically, we estimate marginal abatement costs for sulfur dioxide by measuring the output distance function for electric power in Korea. Regression results confirm that production process innovations did raise marginal abatement costs in this case. One policy implication: economic instruments do not always provide stronger innovation incentives than command-and-control policies.

Keywords: Marginal Abatement Costs, Production Process Innovations, Technological Change

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** Corresponding author: Department of Economics, Hartwick College, Oneonta, NY, 13820, USA; seeleyk@hartwick.edu; (607) 431-4628.

I. Introduction

The possibility that innovation in pollution control can help alleviate the tradeoff between environmental protection and industrial production has been of significant interest to economists since at least the mid-1970s, when Kneese and Schultze (1975) wrote that "over the long haul, perhaps the most important single criterion on which to judge environmental policies is the extent to which they spur new technology toward the efficient conservation of environmental quality."[1] Such new technologies can be *end-of-pipe measures,* such as installing scrubbers on smokestacks, or *production process measures,* such as developing more fuel-efficient boilers or burning coal with lower sulfur content (Hanley et al., 1997).

Following Kneese and Schultz is an extensive theoretical literature (e.g., Downing and White, 1986; Mendelsohn, 1984; Milliman and Prince, 1989; and Montero , 2002) that examines the incentive structures created by Pigovian taxes, tradeable permits, command-and-control regulations, and other environmental policies. A survey by Jaffe et al. (2003) summarizes these findings as indicating that "market-based instruments for environmental protection provide better incentives than command-and-control approaches for the cost-effective diffusion of desirable, environmentally-friendly technologies."

The dominant framework for this literature is the graphical approach shown in Figure 1. Papers in this tradition include Downing and White (1986), Milliman and Prince (1989), Palmer et al. (1995), Jung et al. (1996), Montero (2002), Parry et al. (2003), Biglaiser and Horowitz (1995), Parry (1998), and Jaffe et al. (2003). We will call this dominant framework the "marginal" approach because of two of its principal components. First, innovation is modeled as a reduction in marginal abatement costs, e.g., from MAC_1 to MAC_2 in Figure 1. Second, the gains from innovation for a firm facing a Pigovian tax of τ is asserted to be the area bounded by *OFCB*.

In this paper, we identify some limitations in the marginal approach, especially in the context of production process innovations. The first limitation comes from the tendency in much of the literature using the marginal approach to focus on minimizing abatement costs while output is either implicitly or explicitly held fixed. Firms have a broader goal – profit maximization – and failure to attend to this broader goal can lead the marginal approach astray. Intuitively, such difficulties will not arise in the case of innovations in end-of-pipe abatement technology: here profit maximization and abatement cost minimization are effectively the same problem, and the graphical analysis described above correctly quantifies the gain from innovation. With production process innovations, however, cost minimization with output held constant cannot substitute for profit maximization. In these cases, the marginal approach incorrectly measures the gain from innovation.[2]

This paper focuses on a second problem with the marginal approach: it inappropriately limits the definition of innovation to include only reductions in marginal abatement costs at all margins. The intuitive appeal of this definition is obvious, but other researchers (e.g., Downing and White (1986), quoted below in Section II) have acknowledged that the connection between innovation and everywhere-lower marginal abatement costs is tenuous, even for end-of-pipe abatement technology. Our main assertion is that this connection is in fact nonexistent in the case of production process innovations. Such innovations are likely to increase marginal abatement costs at some margins, and in important cases will increase marginal abatement costs at *all* margins.

Section II of this paper provides context: our point is not that innovations that increase marginal abatement costs have never been discussed, but rather that such innovations are vastly more important than the literature suggests. Section III uses a simple algebraic model to show how archetypal pollution control innovations can increase marginal abatement costs. As a result, while end-of-pipe innovations are unambiguously pollution-reducing, the effect of other innovations depends on preferences for environmental quality and sometimes on the elasticity of demand for output. Section IV provides empirical support: we estimate the marginal abatement cost of SO_2 and rate of production process innovation by measuring the Shephard (1970) output distance function for the Korean electric power industry.[3] Section V discusses policy implications, e.g., by questioning the superiority of economic incentive policies in promoting innovation. Section VI contains concluding remarks.

II. Context

Three strands of literature relate to the topic at hand. The first is the marginal approach, which goes back at least as far as Zerbe (1970) and Wenders (1975). As noted above, this literature downplays (but does not completely ignore) the importance of innovations that increase marginal abatement costs. For example, Downing and White (1986) point out that innovations might reasonably raise marginal abatement costs at some margins while lowering them at others, but then dismiss this possibility by noting that the "more commonly discussed" innovations are those which lower abatement costs at all margins. More recently, the survey article by Nelissen and Requate (2004) argues that innovations "do not necessarily lead to declining marginal abatement costs" but also notes that declining marginal abatement costs are assumed "in most of the literature."

A second strand of literature (an early example is Magat, 1978) uses frameworks other than the marginal approach to study incentives for innovation. In particular, Requate (1998) and Requate and Unold (2003) criticize the "partial-partial" nature of the dominant approach and instead use models that allow for consideration of entry/exit and other general equilibrium effects. Valuable though these contributions are, they fail to highlight what we see as a fundamental shortcoming in the marginal approach: the association of innovation with lower marginal abatement costs. Indeed, one paper that avoids the marginal approach (Requate, 1995) is so focused on output effects that it claims that it *does* follow the marginal approach.[4]

A third strand of literature considers innovation in the context of other issues such as macroeconomic growth (Gradus and Smulders, 1996; Smulders, 1999) or international trade (Ulph and Ulph, 1996; di Maria and Smulders, 2004). The macro models incorporate some form of "resources" or "pollution" as an input to production. In different ways, these models have investigated whether innovations are "pollution-using" or "pollution-saving," analogous to the established classification of technological change as labor-using or labor-saving (see, e.g., Burmeister and Dobell, 1970). In general, this literature tends to find that innovation increases the marginal benefit of pollution and thus in many situations will lead to an increase in the optimal level of pollution. Our paper emphasizes the possibility and importance of similar situations in the microeconomic context typically used for the theory of environmental policy. The extensive literature on instrument choice in environmental policy is dominated by microeconomic models, so those models need to accurately reflect the effects on costs of different types of innovations.

As a final piece of context, it is worth noting an ambiguity about the phrase "innovation in pollution control." Some authors (e.g., Wenders, 1975) clearly limit their analyses to innovations in end-of-pipe abatement technologies. Others are not so clear: for example, Zerbe (1970) focuses on end-of-pipe abatement but also brings up fuel switching, thereby extending the scope of his analysis to include innovations in production processes.

The resulting ambiguity arguably exists to this day. Many papers (e.g., Milliman and Prince, 1989) discuss "innovation in pollution control" without clarifying the intended scope of this phrase. In some papers, brief comments hint at generality; examples include Zerbe's mention of fuel switching and Parry's (1998) footnote referring to "the substitution of natural gas for coal." In other papers, it is not clear whether the authors are interested only in innovations in end-of-pipe abatement technologies or also in production process innovations.

What is clear is that the results of these analyses have been widely applied to both types of innovation. For example, Hahn and Stavins (1991) cite Milliman and Prince (1989) in asserting that "incentive-based policies have been shown to be more effective in inducing technological innovation and diffusion…than conventional command-and-control approaches." The survey article by Jaffe et al. (2003) explicitly mentions "process innovation" and considers a "hybrid motor vehicle engine" as a potential innovation. An even clearer example is the reliance on the marginal approach in Palmer et al. (1995). Their paper is a rebuttal of Porter and van der Linde's (1995; see also Porter, 1991) defense of the Porter Hypothesis, a defense that emphasizes the importance of production process innovations.

Our work emphasizes the importance of clarifying the scope of the phrase "innovation in pollution control." To the extent that research is focused exclusively on end-of-pipe abatement technologies, the marginal approach may not be inappropriate. But most research and policy work appears to encompass production process innovations as well as end-of-pipe measures, and in this case—as we show in the next two sections—the marginal approach has significant shortcomings.

III. Algebraic Demonstration

We construct our model along the same lines as Nelissen and Requate (2004), using a function $C(e)$ to represent the "cost" of emissions. This cost is the difference between the maximum profit in an unregulated situation, where firms will choose $e_{\max}$, and profit when emissions are constrained to some level $e < e_{\max}$.[5]

Output is determined by the production function $q = f(x, \delta)$, where x is the input and δ is a productivity parameter. The production function has conventional properties with respect to the input ($f_x > 0$, $f_{xx} < 0$). Increases in δ, which can be thought of as "productivity innovations," increase both the output and the marginal product of the input ($f_\delta > 0, f_{x\delta} > 0$).

A cleanliness parameter ω governs the relationship between the amount of input used and the amount of gross emissions s (that is, emissions before end-of-pipe abatement efforts):[6]

$$s = \frac{1}{\omega} x .$$

Increases in ω, which can be thought of as "cleaner-production innovations," reduce the level of gross emissions per unit of input.

End-of-pipe abatement is the difference between gross emissions, s, and final emissions, e, and the cost of that abatement is given by $\frac{1}{\alpha} A(s - e)$. The term α is our final innovation parameter; increases in α, which can be thought of as "clean-up innovations," reduce the cost of cleaning up gross emissions. We assume that end-of-pipe costs increase at an increasing rate, and that cleaning up nothing costs nothing:

$$A' > 0,\ A'' > 0,\ A(0) = 0.$$

Denoting the price of inputs by z, the full profit function becomes

$$\pi = pf(x,\delta) - zx - \frac{1}{\alpha} A\left(\frac{1}{\omega} x - e\right). \tag{1}$$

The firm's choice of x when e is unrestricted yields values of $x_{\max}$, $e_{\max}$, and $\pi_{\max}$. Under these circumstances it cannot make sense to spend money on end-of-pipe abatement, so $e \equiv s$, $A(0) = 0$, and $x_{\max}$ is found by differentiating

$$\pi = pf(x,\delta) - zx \tag{2}$$

with respect to x. $e_{\max}$ is then $1/\omega\, x_{\max}$, and $\pi_{\max} = pf(x_{\max}, \delta) - zx_{\max}$.

To find the restricted profit function $\pi(e)$, we first define the choice of input x as a response to an exogenous e. Differentiating equation (1) with respect to x and setting the result equal to zero gives us

$$pf_x(x,\delta) - z = \frac{1}{\alpha}\frac{1}{\omega}A'\left(\frac{1}{\omega}x - e\right), \tag{3}$$

and we can solve this equation to get $x(e)$, the optimal quantity of input for any limited amount of e. An examination of (3) establishes the intuitively appealing proposition that $x'(e) > 0$ (as more emissions are allowed, input – and output – go up).

Arriving finally at $C(e) = \pi_{\max} - \pi(e)$, the specific component functions assumed here lead to

$$C(e) = p\left[f(x_{\max},\delta) - f\left(x(e),\delta\right)\right] - z\left[x_{\max} - x(e)\right] + \frac{1}{\alpha}A\left(\frac{1}{\omega}x(e) - e\right). \tag{4}$$

As with $x(e)$, the parts of $C(e)$ display some intuitively appealing traits. As e goes down, you give up more output (because $x(e)$ goes down), save a little on input (for the same reason) and spend more on end-of-pipe abatement. This last follows from the assumptions of $f_{xx} < 0$ and $A'' > 0$, which mean that there's a balance between the increasing marginal foregone revenues from less production and the increasing marginal cost of end-of-pipe abatement. These assumptions also mean that $C'(e) < 0$ and $C''(e) > 0$ (because further reductions in e can only be achieved by ever-more costly sacrifice of output, or ever-more costly end-of-pipe abatement). $C(e)$ has its maximum at $e = 0$ and declines continuously to $C(e_{\max}) = 0$.

The analysis now proceeds by examining changes in $e_{\max}$ and $\pi_{\max}$ and $C(0)$ in response to different kinds of innovations. For end-of-pipe and cleaner-production innovations, the quantity of the good produced in the unregulated case is unaffected by the innovation, so we simplify the analysis by assuming a fixed output price. We relax that assumption when examining productivity innovations.

End-of-pipe improvements

We start with an α-innovation. In the absence of regulation, no end-of-pipe abatement will be done, regardless of how cheap it is, so α-innovations do not change $e_{\max}$ or $\pi_{\max}$. Denoting the original cost as $C_1(e)$ and the post-innovation cost as $C_2(e)$, this tells us that the horizontal intercepts of $C_1(e)$ and $C_2(e)$ are the same. At the other end of the cost function, $C_2(0) < C_1(0)$; if nothing else, the firm could choose the same $x(0)$ as before and clean up the resulting s at lower cost, but with continuous functions for $f(\cdot)$ and $A(\cdot)$, it will in fact choose a slightly higher $x(0)$ and cheaply clean up the greater gross emissions that result. In any case, the innovation leaves unregulated profit unchanged while increasing the profit from zero emissions, thus reducing the cost of zero emissions. Translating these cost functions to marginal cost functions, the innovation leaves the horizontal intercept of the marginal abatement cost curve unchanged while dropping all other values for marginal abatement cost. It is the classic "reduced marginal abatement cost" assumed in most of the microeconomic literature, illustrated in Figure 1. For clarity and intuitive appeal, we prefer to look at the problem in terms of "marginal emissions benefits" (MEB), as in Figure 2; zero abatement in Figure 1 corresponds to maximum emissions in Figure 2, and maximum abatement in Figure 1 corresponds to zero emissions in Figure 2.

Cleaner-production

Increases in ω have no effect on $x_{\max}$ (or, in turn, on $\pi_{\max}$) because ω, like α, is missing from equation (2). But since $e_{\max} = s(x_{\max}) = \frac{1}{\omega}x_{\max}$, $e_{\max}$ is reduced. This tells us that the horizontal intercepts of both the abatement cost curve and the marginal abatement cost curve are shifted leftward by ω-innovation.

The other end of the curves is trickier. Start by considering a case in which there is no end-of-pipe technology, so zero emissions means zero profits, regardless of any increases in ω. Since π_{max} is the same before and after innovation, and $C(0)$ is also unchanged by the new technology, $C_1(e)$ and $C_2(e)$ both start from the same vertical intercept. $C_2(e)$ then falls more quickly to reach its horizontal intercept. Translating this to marginal abatement cost curves, the post-innovation curve must be steeper than the original curve. Furthermore, the area under both marginal curves must be equal, since that area is the value of $C(0)$, which is also the unchanged π_{max}. This implies that the vertical intercept of the post-innovation marginal curve must be higher than on the original marginal curve. We refer to this as "front-loading" the marginal benefits of emissions: the marginal benefits of the first units are raised by the innovation, but they fall at a faster rate so as to reach zero at a lower level of emissions than pre-innovation. This is shown in Figure 3.

What if end-of-pipe abatement is possible? This complicates the left end of the cost curve because end-of-pipe abatement acts as a backstop to curtailing production. If abatement costs are low enough, it can be profitable to produce a positive amount of output and then clean up all the gross emissions that result. In other words, it is possible to have $C_1(0) < \pi_{max}$ if $\pi_1(0) > 0$. But we also know that $\pi_2(0) > \pi_1(0)$, because even if $x(0)$ were unchanged there would be fewer gross emissions to clean up and therefore smaller end-of-pipe abatement costs after the innovation; in fact, with continuous functions there's some increment of x that is warranted by the ω-innovation, trading off some of the reduced clean-up for increased production, making the increase in profits even larger than the comparison with an unchanged $x(0)$.

If production is profitable at zero emissions in the post-innovation scenario, then part of the argument used to explain Figure 3 falls away. In this case we know that $C_2(0) < C_1(0)$, so the area under the marginal abatement cost curve post-innovation is smaller than it is pre-innovation and the vertical intercept of the post-innovation curve does not necessarily lie above that of the pre-innovation curve. In general, high end-of-pipe abatement costs will push $\pi(0)$ toward zero, preserving the "front-loading" situation, while lower end-of-pipe abatement costs bring $C_2(0)$ down below $C_1(0)$, and the bigger that difference is, the more likely it is that the post-innovation marginal cost curve does not cross the pre-innovation curve, as illustrated in Figure 4.

Productivity innovations

As explained above, the two types of innovations explained so far have no impact on output decisions in the absence of regulation, so we simplified the analysis by assuming a fixed output price.[7] With δ-innovations, however, changes in the unregulated output quantity are almost guaranteed, so a fixed-output-price assumption is too big a simplification.

Making the output price flexible, equation (2) becomes

$$\pi = p[f(x,\delta)]f(x,\delta) - zx$$

and x_{max} is now determined by

$$p'(\cdot)f_x(\cdot)f(\cdot) + p(\cdot)f_x(\cdot) = z. \tag{5}$$

By the assumptions about the form of $f(\cdot)$, we know that increases in δ increase both f and f_x; we can also assume that the inverse demand function is negatively sloped. So the second term on the LHS says we should increase x_{max} in response to an increase in δ, while the first term says we should decrease it. If demand is highly elastic then the magnitude of p' is small and the second term dominates, leading to an increased $x_{\max}$; the more inelastic the demand, the more likely it is that the first term dominates. This gives us two cases: in Case A, demand is relatively elastic and $x_{\max}$ (and $e_{\max}$) move to the right as δ increases, while in Case B, demand is relatively inelastic, so $x_{\max}$ and $e_{\max}$ move to the left. In either case, $\pi_{\max}$ increases with a δ-innovation.[8]

The behavior of $e_{\max}$ determines the lower end of the new marginal emissions benefit curve. At the other end of the curve, an increase in productivity has an ambiguous effect. The "cost" of having zero emissions is $C(0) = \pi_{\max} - \pi_0$. We know that $\pi_{\max}$ increases as δ grows, but increased productivity also has a non-decreasing effect on $\pi(0)$, so the net effect on $C(0)$ is not clear. As before, we denote the original cost as C_1 and the post-innovation cost as C_2. It is at least plausible that $C_2(0) > C_1(0)$ (zero emissions represent greater foregone profits after innovation than before), and this is true regardless of whether $e_{\max}$ increases or decreases following an increase in δ. Now consider an instance of Case A where output demand is just sufficiently elastic to move $e_{\max}$ slightly to the right, while at the same time $C_2(0)$ is significantly greater than $C_1(0)$. This means that the area under *MEB** must be significantly greater than the area under *MEB*, since these areas are $C_2(0)$ and $C_1(0)$, respectively. That in turn implies that the vertical intercept of *MEB** is higher than the vertical intercept of *MEB*, while the increase in $e_{\max}$ moves the horizontal intercept to the right. Figure 5 illustrates this instance of Case A.

However, with a smaller difference between $C_2(0)$ and $C_1(0)$, including all instances in which $C_2(0) < C_1(0)$, the vertical intercept of *MEB** will lie *below* the vertical intercept of *MEB*, though with the horizontal intercept moved to the right by the increase in $e_{\max}$. This is illustrated in Figure 6, and can be thought of as "back-loading" the marginal benefits of emissions: the marginal benefit falls on the earlier units while rising on the later ones.

Turning to Case B, the marginal abatement curve has its horizontal intercept moved to the left by increases in productivity. As before, the relative size of $C_2(0)$ and $C_1(0)$ determines the shift in the vertical intercept. In all cases where $C_2(0)$ is bigger, and also where $C_2(0)$ is smaller but not by too much, the vertical intercept of *MEB** will be higher, and the situation is qualitatively identical to the "front-loading" scenario described for cleaner-production innovations and illustrated in Figure 3. Where $C_2(0)$ is sufficiently small, the vertical intercept moves down, and we again have the situation illustrated in Figure 4.

In sum, the marginal approach, depicted graphically as in Figure 1 or Figure 2, is only applicable to end-of-pipe innovations, where the unregulated outcome ($A = 0$ in Figure 1, or $e_{\max}$ in Figure 2) is unaffected by adoption of the new technology. In all other cases (except by coincidence), these points will shift in one direction or another, so analyses based on pivoting the *MAC* or *MEB* curve around a fixed horizontal intercept may lead to incorrect conclusions. Instead, the appropriate curve from among Figures 3 through 6 will be a better guide.

Implications for the optimum

With this more diverse set of marginal abatement cost curves, more interesting possibilities arise. With α-innovations we see unambiguously that the new social optimum is cleaner than the old one (the optimal level of e goes down). The same is true for cleaner-production innovations and productivity-enhancing innovations that shift *MEB* inward, as illustrated in Figure 4. In some other δ-innovations, however, it is most likely that the optimal level of pollution goes *up*, as marginal abatement costs are everywhere or almost everywhere higher than before. And with both the "front-loading" examples (some instances of Case B of δ-innovation and most instances of ω-innovation), and the "back-loading" examples (the remaining instances of Case B of δ-innovation) the result depends on where the marginal abatement benefit curve (or equivalently, the marginal emissions damages curve) falls. The steeper the damages curve, the more likely we are in the upper region of the marginal abatement cost curve. With "front-loaded" marginal emissions benefits, this is where innovation raises marginal costs, thus leading to a more polluted social optimum; with "back-loaded" marginal emissions benefits, this upper region is where innovation reduces marginal costs, leading to a less polluted social optimum.

Two things are important to point out here. The first is somewhat counterintuitive: when dealing with "front-loaded" curves, the more serious the environmental problem (i.e., the steeper the marginal emissions damage curve), the more likely the social planner is to respond to an innovation by choosing more pollution. To the extent that this makes sense, it's that the social optimum in the face of a serious problem is highly restrictive of consumption, so it is reasonable to take the opportunity the new technology affords to increase consumption considerably with only moderate increases in pollution, rather than accepting a small increment to our miserly consumption and improving the environment further.[9]

The second point to make concerns the connection between preferences and whether a technology is pollution-increasing or pollution-saving. The steepness of the emissions damage curve is partly a function of the physical damage caused, but also partly a function of the value put on that damage by people – a function of our preferences. And the distinction between Cases A and B of δ-innovation rests on the elasticity of demand for the output, which is another way that preferences play a role. This means that α-innovations are unambiguously pollution-reducing whereas most other innovations, whether δ or ω, are not in themselves either pollution-reducing or pollution-increasing but interact with our preferences to have one effect or the other.

In all of this we simplify by modeling an industry that is monolithic in its adoption decision and by letting industry profit be implicitly synonymous with the gross social benefit from pollution, which is then balanced against the social cost of pollution captured in the marginal emissions damage curve. There is fertile ground in relaxing this simplification, but we leave that for future explorations.

IV. Empirical Evidence

Conducting an empirical test of the validity of the algebraic demonstration requires the estimation of marginal abatement costs and rates of production process innovation. For these purposes we use Shephard's (1970) output distance function. We investigate the Korean electric power industry, which was totally dependent on fuel switching – i.e., the use of lower sulfur fuel or natural gas – until 1998; this fact enables us to eliminate the possibility of innovations in end-of-pipe abatement technology, thus simplifying the analysis.[10]

IV.1 Measurement of the Output Distance Function

Consider a production technology of producing a vector of outputs, $y \in \Re_{+}^{M}$ with a vector of inputs, $x \in \Re_{+}^{N}$. The vector of outputs not only includes desirable ones, $y_1 \in \Re_{+}^{H}$, but undesirable ones, $y_2 \in \Re_{+}^{M-H}$, which are generated as by-products, so that $y = [y_1, y_2]$. The output set, $B(x)$, is the set of all output vectors that are technically feasible with x. Following Färe et al. (1993) and Coggins and Swinton (1996), we assume that the technology satisfies weak disposability; that is, if $y \in B(x)$, then $\theta y \in B(x)$ for every $\theta \in [0,1]$, implying that y_2 cannot be reduced without a sacrifice of reduction in y_1.

For the purpose of analyzing rigorously, we employ the output distance function introduced by Shephard (1970). Allowing for technological change, this function is defined as

$$O(x, y, t) = \inf\{\mu : (y/\mu) \in B(x)\}, \tag{6}$$

where t is the time index and $y \in B(x)$ if and only if $O(x, y, t) \leq 1$. The distance function is monotonically non-increasing in x, non-decreasing in y_1, and non-increasing in y_2. It is also homogenous of degree one in *y*. The value of the output distance function measures the maximal proportional inflation of the output vector required to attain the frontier of the technology given the input vector. Note that technically efficient production is achieved as $O(x, y, t) = 1$.

The rate of technological change, defined as the rate at which outputs can be proportionally expanded over time with inputs held constant, is calculated as

$$RT = -\frac{\partial O(x,y,t)}{\partial t} \tag{7}$$

Since regaining technically efficient production demands more outputs, the value of the derivative itself would be negative.

The revenue function is defined as the maximized revenue subject to the value of the output distance function

$$R(x,p,t) = \max_y \{py : O(x,y,t) \leq 1\}, \tag{8}$$

where $p \in \Re^M$ is a vector of output prices. Following Färe et al. (1993), we derive the vector of output prices by applying the envelope theorem on the first order conditions for the Lagrangian problem for equation (5):

$$p = R(x,p,t) \cdot \nabla_y O(x,y,t). \tag{9}$$

The use of a dual output distance function, defined as $O(x, y, t) = \sup_p \{py: R(x, p, t) \leq 1\}$, and Shephard's lemma yields

$$\nabla_y O(x,y,t) = p^*(x,y,t), \tag{10}$$

where $p^*(x, y, t)$ is a vector of revenue maximizing output prices or normalized output shadow prices. Substituting (10) into (9) we obtain

$$p = R(x,p,t) \cdot p^*(x,y,t). \tag{11}$$

Let p_1 and p_2 denote the vectors of undeflated shadow prices for desirable and undesirable outputs, respectively. Assuming that the observed price of one desirable output, y_{11}, equals its shadow price, p_{11}, we can calculate the shadow price of each undesirable output, y_{2i}, for $i = M\text{-}H,\ldots, M$ as

$$p_{2j} = p_{11} \cdot \frac{\partial O(x,y,t)/\partial y_{2i}}{\partial O(x,y,t)/\partial y_{11}} \geq 0 \tag{12}$$

This shadow price can be interpreted as the opportunity cost of reducing an additional unit of undesirable output in terms of forgone desirable output, which is equivalent to the marginal cost of pollution abatement to the producer (Coggins and Swinton, 1996; Hailu and Veeman, 2000).

To compute p_{2j} in equation (12), a parameterization for $O(x, y, t)$ is needed. Suppose that the output distance function takes a translog functional form

$$\begin{aligned} \ln O(x,y,t) = {} & \alpha_0 + \sum_{i=1}^{N} \alpha_i \ln x_i + \sum_{j=1}^{M} \beta_j \ln y_j + \frac{1}{2}\sum_{i=1}^{N} \sum_{i'=1}^{N} \alpha_{ii'} \ln x_i \ln x_{i'} + \frac{1}{2}\sum_{j=1}^{M} \sum_{j'=1}^{M} \beta_{jj'} \ln y_j \ln y_{j'} \\ & + \sum_{i=1}^{N} \sum_{j=1}^{M} \gamma_{ij} \ln x_i \ln y_j + \alpha_t t + \frac{1}{2}\alpha_{tt} t^2 + \sum_{i=1}^{N} \alpha_{it} t \ln x_i + \sum_{j=1}^{M} \beta_{jt} t \ln y_j , \end{aligned} \tag{13}$$

where i, i' indexes inputs and j, j' indexes desirable and undesirable outputs.

Following Aigner and Chu (1968), a linear programming technique can be used for the computation of the parameters in equation (13). The objective function, $\sum_{t=1}^{T} \ln O(x, y, t)$ is maximized under a number of constraints, where $t = 1, \ldots, T$ indicates the observations. Specifically, (i) $\ln O(x, y, t) \leq 0$, since $O(x, y, t) \leq 1$. For the monotonicity condition, (ii) $\partial \ln O(x, y, t) / \partial \ln x \leq 0$, $\partial \ln O(x, y, t) / \partial \ln y_1 \geq 0$, and $\partial \ln O(x, y, t) / \partial \ln y_2 \leq 0$. For the imposition of linear homogeneity in outputs, (iii) $\sum_{j=1}^{M} \beta_j = 1$, $\sum_{j'=1}^{M} \beta_{jj'} = \sum_{j=1}^{M} \gamma_{ij} = \sum_{j=1}^{M} \beta_{jt} = 0$. Finally, (iv) $\alpha_{ii'} = \alpha_{i'i}$ and $\beta_{jj'} = \beta_{j'j}$ for symmetry.

IV.2 Data and Empirical Results

We use annual time-series data for the Korean fossil-fueled electric power industry over the period 1970-98. The model consists of one desirable output (electricity), one undesirable output (sulfur dioxide), and three inputs (capital, labor, and fuel). The electricity output (Q) is measured in 10^3 GWh. The capital input (K) is the value (in trillion wons, Korean currency) of total assets, deflated by the consumer price index (1995 =100). The fuel (F) and labor (L) inputs are measured in trillion Kcal and annual average number of employees, respectively. The price of electricity (p_Q) is an average annual sale price (in wons) for 1 kWh power, deflated by the consumer price index. All these data are reported in *Business Statistics* (published by the Korea Electric Power Corporation). The emissions of SO_2 (S) in 10^6 tons are reported in the *Environmental Statistics Yearbook* (published by the Ministry of Environment). Table 1 contains summary statistics for the data, which are available upon request.

Imposing constraints such as monotonicity, homogeneity, and symmetry, we derive the parameters by measuring equation (13). Regarding the curvature conditions of the output distance function, all observations satisfy convexity in outputs and quasi-concavity in inputs.[11] The parameter estimates are presented in Table 2. These estimates are used to calculate the value of the output distance function for each year; these are shown in the second column of Table 3. The average value of distance is 0.9924, indicating that electricity production, on average, could be increased by 0.7 % if plants operated on the boundary of the production technology.

The use of equation (12) enables us to derive annual estimates of marginal abatement cost for 1 Kg of SO_2 (MAC_t); these appear in the third column of Table 3. The values of MAC_t vary from a low of 0 in 1987 and 1998 to a high of 0.399 dollars per kg in 1984.[12] Zero marginal abatement cost indicates that plants operate on the horizontal segment of the production technology where the quantity of undesirable output is measured on the horizontal axis; in those years, SO_2 was freely disposed probably due to less effective monitoring and enforcement. The value of MAC_t continuously increased up to 1985; it also showed a tendency to increase from 1987 (when it had a value of zero) through 1997. The average value of MAC_t is 0.184 dollars per kg over the sample period.[13] This average is about 40% lower than the three-year (1990-92) average values for Wisconsin coal-burning electric plants obtained by Coggins and Swinton (1996).

The estimated yearly rate of technological change, obtained by calculating equation (7), is presented in the fourth column of Table 3. The annual values of RT_t are mostly positive over the sample period. The value of RT_t steadily increased from -0.36 percent in 1970 to 2.47 percent in 1978, trended downward during the period 1978-90, and then trended upward until 1997. The average rate of technological change is 1.12 percent over the period 1970-98.

The average annual SO_2 emission rates (ER_t) in grams of SO_2 per 10^3 Kcal of fuel input are reported in the fifth column of Table 3. Throughout the 1970s, the annual emission rate was steady at about 7 grams SO_2 per 10^3 Kcal. Thereafter it fell consistently due to more stringent sulfur regulations. Until 1998, the plants were required to use low-sulfur fuels to comply with tightened concentration limits on SO_2 emissions.

In order to analyze the factors that might affect the annual marginal cost of SO_2 abatement, we make a simple OLS regression of MAC_t on RT_t and ER_t.[14] But, error terms are found to have second order autocorrelation and, as a result, the second order autoregressive model is employed:[15]

$$MAC_t = \underset{(0.136)}{-0.116} + \underset{(0.029)}{0.152RT_t} + \underset{(0.024)}{0.027ER_t} + \varepsilon_t \tag{14}$$

where the value of R^2 is 0.74 and the numbers in the parentheses are standard errors.[16] The results indicate that technological innovation increased marginal abatement cost of SO_2 during the 1970-98 period, which is statistically significant. An increase in the emission rates also raised marginal abatement cost, but its coefficient is not statistically significant.[17]

The Malmquist index can be decomposed into technical efficiency and technical change components; the technical change component represents the average of RT for periods t–1 and t. The result of an OLS regression of MAC_t on the average of RT is

$$MAC_t = \underset{(0.084)}{-0.007} + \underset{(0.046)}{0.187\overline{RT}_{t-1,t}} - \underset{(0.015)}{0.005ER_t} + \varepsilon_t,$$

where the value of R^2 is 0.66. In comparison with equation (14), the parameter estimate for RT measure remains little changed in its magnitude, sign, and significance.

V. Policy Implications

Our theoretical and empirical results show that the marginal approach is inappropriate for studying many types of innovation, especially production process innovations. For one important policy implication, consider Parry et al. (2003), which questions the importance of technological innovation in pollution control. Using a theoretical argument based on the marginal approach, they conclude that "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."

We would argue for a different interpretation. Because Parry et al. base their work on the marginal approach, their conclusion only applies to innovations that reduce marginal abatement costs. End-of-pipe measures may fit into this frame, but production process innovations are unlikely to. Our interpretation, then, is that promoting *end-of-pipe* innovation may be less important than just controlling pollution. But there is no limit on the potential gain from production process innovations, which suggests that it is these innovations that policymakers (and researchers) should focus on.

For a second policy implication, consider the oft-cited advantage that economic instruments have over command-and-control policies in providing incentives for innovation. The common argument in favor of economic instruments is that they are "more flexible": while direct controls constrain firm behavior, e.g., by mandating emission limits or specifying abatement technologies, economic instruments give firms the freedom to take maximum advantage of innovations. More formally, the argument is that the set of options S_D available to a firm facing direct controls is a proper subset of the set of options S_E available to a firm facing economic instruments: $S_D \subset S_E$. If, for example, direct controls mandate the use of a certain type of scrubber, the options available to a firm facing economic instruments include *but are not limited to* the use of that scrubber; the firm therefore has the flexibility to take advantage of innovations in scrubber technology (or alternative strategies such as input substitution, e.g., the use of low-sulfur coal).[18]

Consider a firm with technology T^0 that is considering an R&D investment that will yield technology T^1. What is the firm's gain from this innovation under, say, Pigovian taxes, as compared to its gain under various types of direct controls (abbreviated C & C)?[19]

Assume that firm behavior under the two policy regimes is identical prior to innovation. Profits under the two policies will therefore differ only by the Pigovian tax payment:

$$\pi^0_{\max}(\mathrm{C\,\&\,C}) = \pi^0_{\max}(\mathrm{tax}) + \tau \cdot e^0, \tag{15}$$

where τ is the Pigovian tax rate, e^0 is the pre-innovation firm's emissions level (under both policies), and $\pi^i_{\max}(z)$ is the maximum profit for a firm using technology T^i and facing regulatory policy z. The firm's gain from innovation (i.e., from the switch from technology T^0 to T^1) under policy z can be expressed as $\Delta\pi(z) = \pi^1_{\max}(z) - \pi^0_{\max}(z)$. One can now determine the conditions under which economic instruments unambiguously provide (weakly) superior incentives for innovation than direct controls, i.e., $\Delta\pi(\mathrm{C\,\&\,C}) \le \Delta\pi(\mathrm{tax})$.

The key issue turns out to be the post-innovation firm's behavior under direct controls, and in particular its choice of emissions, e^1. If the firm facing direct controls lowers its emissions ($e^1 \le e^0$), the firm facing the Pigovian tax has the option of mimicry: it could choose to behave in an identical manner and emit e^1 units of emissions. Calling the resulting profits $\pi^1_S(\mathrm{tax})$ yields

$$\pi^1_{\max}(\mathrm{C\,\&\,C}) = \pi^1_S(\mathrm{tax}) + \tau \cdot e^1. \tag{16}$$

Subtracting equation (15) from equation (16) produces

$$\begin{aligned} \pi^1_{\max}(\mathrm{C\,\&\,C}) - \pi^0_{\max}(\mathrm{C\,\&\,C}) &= \pi^1_S(\mathrm{tax}) - \pi^0_{\max}(\mathrm{tax}) + \tau(e^1 - e^0) \\ &\le \pi^1_S(\mathrm{tax}) - \pi^0_{\max}(\mathrm{tax}) \\ &\le \pi^1_{\max}(\mathrm{tax}) - \pi^0_{\max}(\mathrm{tax}), \end{aligned} \tag{17}$$

i.e., $\Delta\pi(\mathrm{C\,\&\,C}) \le \Delta\pi(\mathrm{tax})$.

Of the two crucial inequalities in this proof, the first arises from our assumption that $e^1 \le e^0$. The second inequality is essentially tautological: $\pi^1_{\max}(\mathrm{tax})$ is by definition the maximum profit under a Pigovian tax, so it must be at least as large as any of the firm's other options. It is this second inequality that encompasses the vaunted flexibility of economic instruments. As long as $e^1 \le e^0$, Pigovian taxes provide (weakly) superior incentives for innovation than absolute limits on emissions, limits on emissions per unit output, technology-based standards, and any other form of direct control.

The proof above also identifies the problem that arises when $e^1 > e^0$: mimicry becomes problematic because economic instruments impose an additional burden on the firm (namely, the cost of additional emissions) that does not exist under direct controls. The set of *profit options* available to the firm under direct controls is no longer a proper subset of the set of profit options available to the firm under economic instruments.[20] For $e^1 > e^0$, the inequality used in (17) no longer holds.

To sum up, if the innovation *does* increase emissions under direct controls, no general conclusion can be made: economic instruments such as Pigovian taxes may or may not provide stronger incentives for innovation than direct controls. As we explore in Sections III and IV, production process innovations are likely to increase the marginal benefits of emissions, and therefore lead individual firms to increase emissions in a wide variety of circumstances. As a result, the assertion that economic instruments provide stronger incentives for production process innovation remains unproven. (This conclusion has also been reached by Bruneau, 2004.)

There is only slightly more clarity when it comes to analyzing different types of direct controls. One result is this: since individual firms *cannot* increase emissions under absolute emissions limits, economic instruments *will* provide stronger incentives for innovation in this case. But this policy does not dominate the policy landscape. More prevalent are limits on emissions per unit output, or direct specifications of technology.[21] *Despite claims to the contrary, these policies are not universally inferior to economic instruments when it comes to providing strong incentives for innovation.*

This is a particularly interesting result for technology-based standards, which have frequently been singled out for criticism, e.g., by Bohm and Russell (1985), Jaffe et al. (2003), and Magat (1978). For example, the statement by Bohm and Russell, cited in footnote 18, is partially true, in that it applies to that part of the firm's operations that are covered by the design standard. But a firm required to use a particular scrubber can still pursue production-process innovations such as more-efficient generators, and in some cases will have a stronger incentive to pursue those innovations than it would under a Pigovian tax.

There are two important caveats that must be added to this discussion. First, as pointed out in Requate and Unold (2003), our analysis takes place in a "partial-partial" world that fails to consider entry/exit or other general equilibrium effects. Second, our analysis focuses on positive questions about the strength of various policy tools, not on normative questions about the optimality of those tools. Although papers from Kneese and Schultze (1975) to Jaffe et al. (2003) contain explicit or implicit suggestions that "more is better" when it comes to innovation, it is of course possible to have too much of a good thing: at some point more is not better. Identifying the location of that point is beyond the scope of this paper, but the issue of optimal—rather than maximal—incentives for innovation is an important one that deserves further study.

VI. Concluding Remarks

This paper has identified significant limitations in the existing approach to innovation in pollution control, especially as it relates to production process innovations. Because the marginal approach inappropriately limits the definition of innovation to include only reductions in marginal abatement costs at all margins, it applies only to some innovations in end-of-pipe abatement technologies. Since production process innovations are likely to be crucial in addressing key issues such as agricultural pollution and global warming, the economics perspective on these topics is incomplete and possibly misleading.

Our findings have at least one important policy implication. For production process innovations that increase marginal abatement costs and therefore lead individual firms to increase their emissions, the superiority of economic incentive policies in promoting innovation over command-and-control regulations is refutable. Direct controls such as limits on emissions per unit output or technology-based standards are not universally inferior to economic instruments in providing strong incentives for innovation.

Beyond that, our work poses a puzzle. In the environmental sciences there is a general concern that we are not protecting the environment enough. Indeed, while some places have seen improvement in local indicators such as water quality and air quality, a broader picture incorporating factors such as climate change, habitat destruction, and species loss suggests that stronger measures would be desirable, if they could be made "affordable." Many innovations, both end-of-pipe and process, do just that, in the sense that we could have more consumption *and* a healthier environment. What the macroeconomic literature suggests, reinforced now by our microeconomic model, is that innovations can easily lead to a higher optimum level of pollution. That is, given the option of polluting less and consuming more, it could be rational for us to instead pollute more and consume a lot more.[22]

There are only two ways of resolving this contradiction. One is the possibility that the natural scientists are wrong and our environmental problems aren't that bad. The other is that the comparison of optima is misleading: yes, optimal pollution post-innovation exceeds optimal pollution pre-innovation, but we're currently polluting so much more than the optimal amount that the post-innovation optimum is less than current emissions.

Lastly, our work suggests that whether a new technology is pollution-reducing or pollution-increasing depends not only on the physical attributes of the technology itself, but also on our preferences, as captured in the marginal emissions damage curve and the elasticity of demand. Awareness of this could avoid nasty surprises following the implementation of policy.

What may be called for as future research is an approach that integrates the analysis of innovation in pollution control into analyses of innovation more generally. Such an approach would encompass both production process and end-of-pipe innovations. It would also effectively obviate the distinction between "environmental" and "non-environmental" innovations.[23] Eliminating this distinction could benefit social welfare analyses, which presumably are interested in both types of innovation. And it would be a fitting result for environmental economics, many of whose practitioners advocate the use of economic instruments such as Pigovian taxes to eliminate the distinction between "environmental" and "non-environmental" goods.

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Table I

Descriptive Statistics

Variable	Unit	Mean	S.D.	Min.	Max.
Q	10^3 GWh	48.28	37.75	7.94	141.96
S	10^6 tons	0.342	0.135	0.129	0.609
K*	10^{12} wons	8.628	8.008	0.369	30.685
L	10^3 workers	13.254	2.625	9.266	18.355
F	10^{12} Kcal	111.22	81.94	22.00	315.99
p_Q*	wons/kWh	45.826	23.722	6.340	72.080

* Constant 1995 wons

Table II

Parameter Estimates for Output Distance Function

Parameter	Estimate	Parameter	Estimate
α_0	0.3226	β_{SS}	-0.0459
α_K	-0.2349	γ_{KQ}	0.0279
α_L	1.2574	γ_{KS}	-0.0279
α_F	-1.8996	γ_{LQ}	-0.0537
β_Q	1.1941	γ_{LS}	0.0537
β_S	-0.1941	γ_{FQ}	0.0576
α_{KK}	0.0320	γ_{FS}	-0.0576
α_{KL}	0.0134	α_t	0.0818
α_{KF}	0.0314	α_{tt}	0.0023
α_{LL}	-0.0359	α_{Kt}	-0.0093
α_{LF}	-0.3130	α_{Lt}	0.0235
α_{FF}	0.4622	α_{Ft}	-0.0402
β_{QQ}	-0.0459	β_{Qt}	-0.0061
β_{QS}	0.0459	β_{St}	0.0061

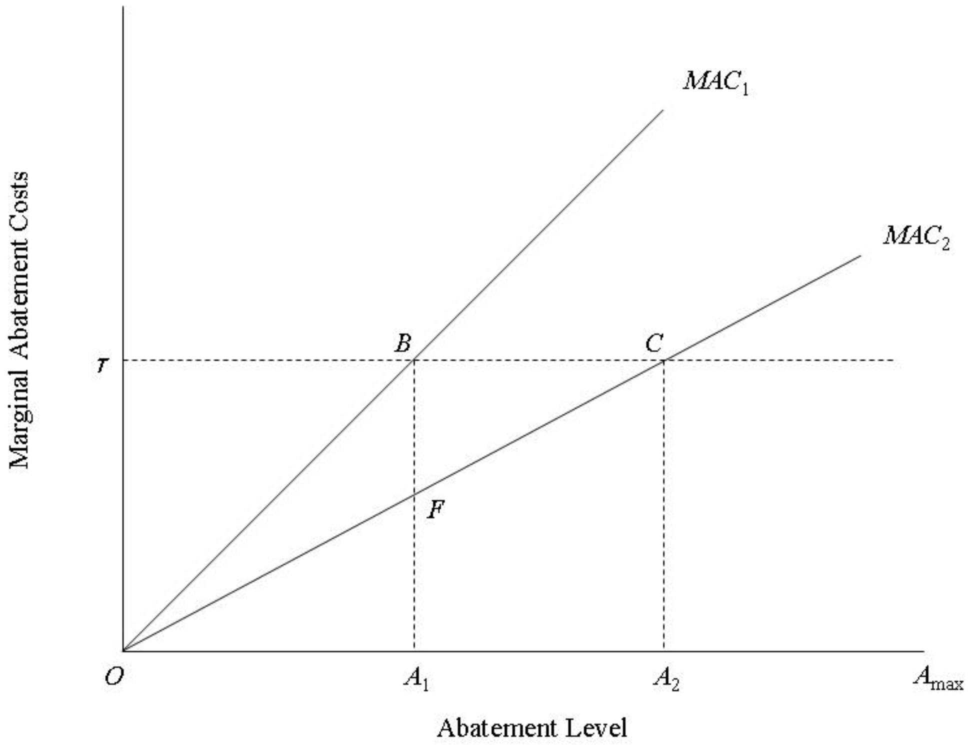
Table III

Annual Marginal Abatement Cost and Rate of Technological Change

Year	Value of Distance	Marginal Abatement Cost (dollars / SO_2 kg)*	Rate of Technological Change (%)	Emission Rate (SO_2 g /10^3 Kcal)
1970	0.9401	0.012	-0.36	6.848
1971	0.9809	0.016	-0.05	7.233
1972	1.0000	0.024	0.32	7.263
1973	0.9893	0.032	1.07	7.166
1974	0.9847	0.050	1.14	7.395
1975	0.9862	0.086	1.36	7.433
1976	1.0000	0.108	1.66	7.341
1977	0.9903	0.135	2.03	7.225
1978	1.0000	0.157	2.47	7.026
1979	0.9895	0.214	2.23	7.221
1980	0.9845	0.333	2.11	7.139
1981	0.9943	0.337	1.95	7.040
1982	1.0000	0.353	2.10	6.966
1983	0.9935	0.360	1.75	6.242
1984	1.0000	0.399	1.64	4.775
1985	1.0000	0.398	1.23	3.983
1986	0.9978	0.296	0.30	3.263
1987	1.0000	0.000	-0.24	1.868
1988	1.0000	0.145	0.67	1.810
1989	1.0000	0.117	0.28	1.925
1990	0.9960	0.120	0.25	1.953
1991	0.9958	0.209	0.43	2.230
1992	0.9872	0.185	0.68	1.905
1993	0.9791	0.173	0.64	1.861
1994	1.0000	0.179	1.31	1.444
1995	1.0000	0.203	1.44	1.339
1996	1.0000	0.336	1.72	1.304
1997	0.9921	0.351	1.90	1.121
1998	1.0000	0.000	0.49	1.252
Average	0.9924	0.184	1.12	4.537

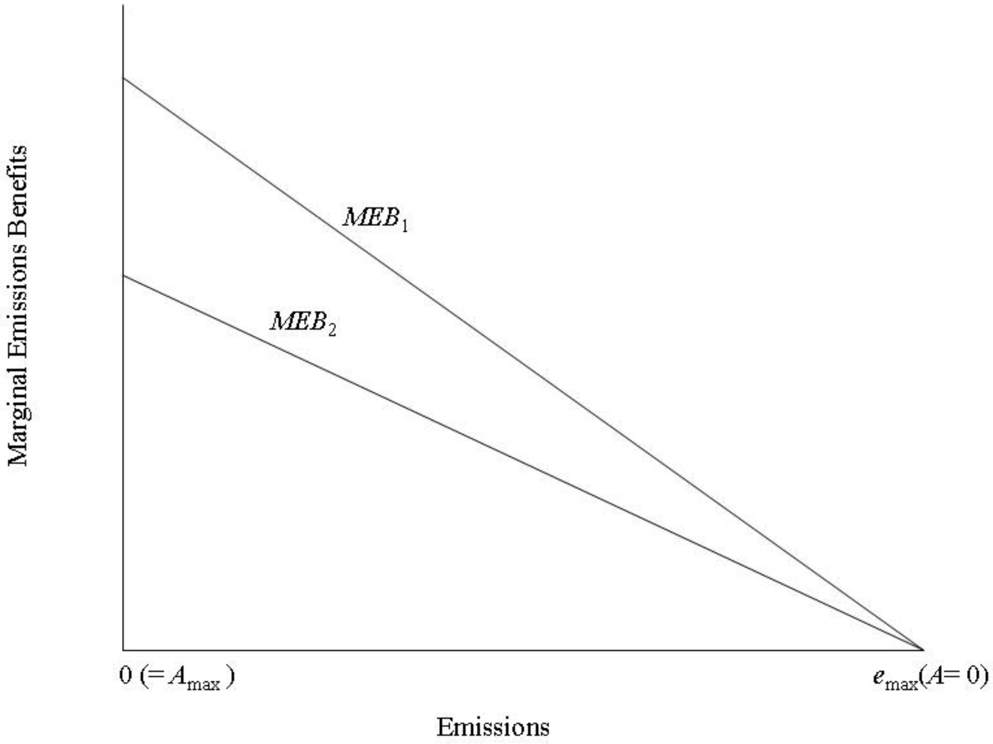
* Wons (Korean currency) are converted into U.S. dollars at the recent exchange rate of 1,200 wons to the dollar.

Figure 1



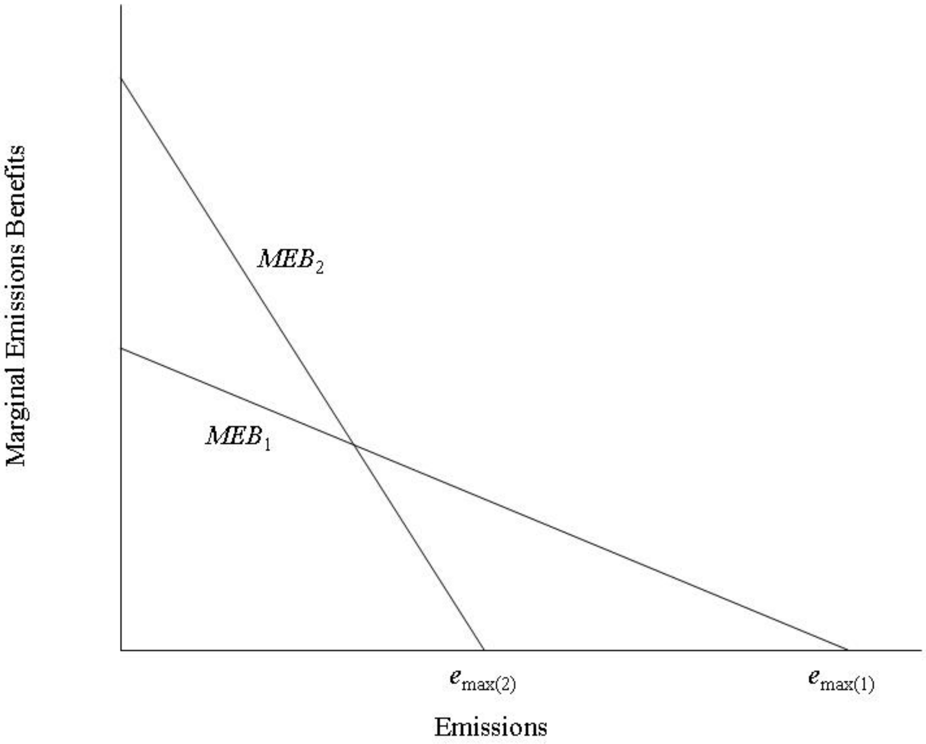
The Marginal Approach, With Area *OFCB* Representing the Gain From Innovations Under a Pigovain Tax of τ

Figure 2



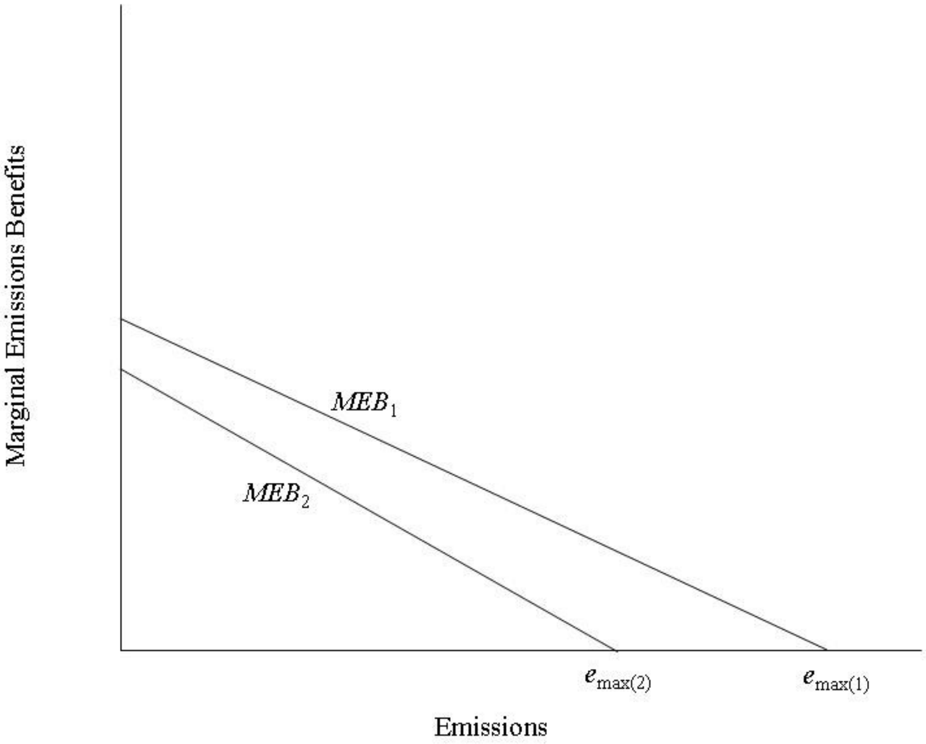
The Marginal Emissions Benefit Curves Corresponding to the Marginal Abatement Cost Curves in Figure 1

Figure 3



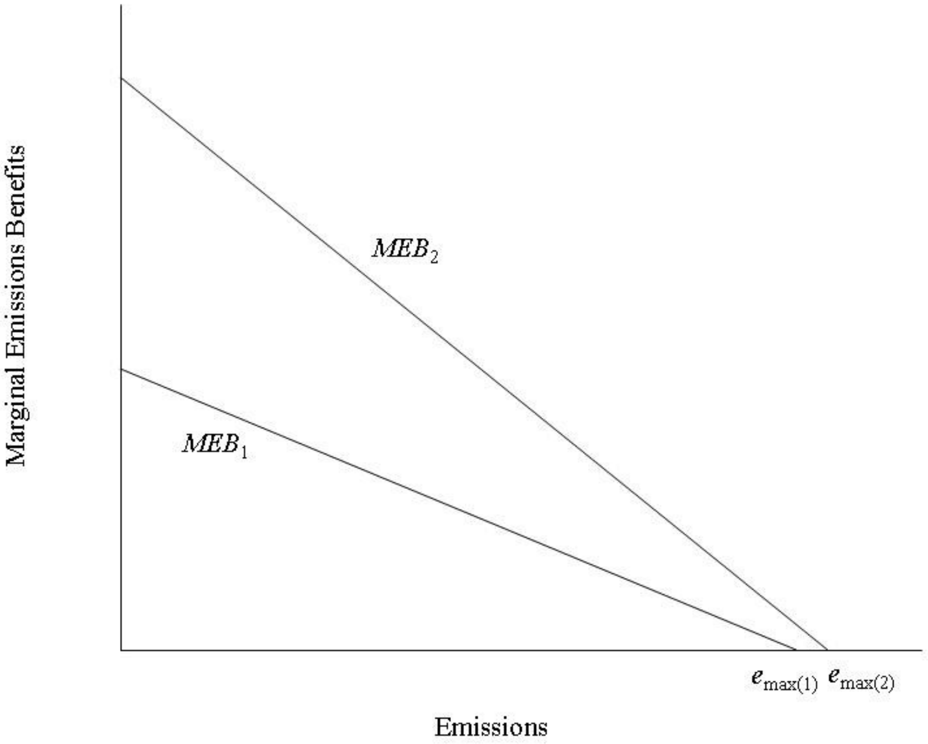
An Innovation That “Front-Loads” Demand for Pollution

Figure 4



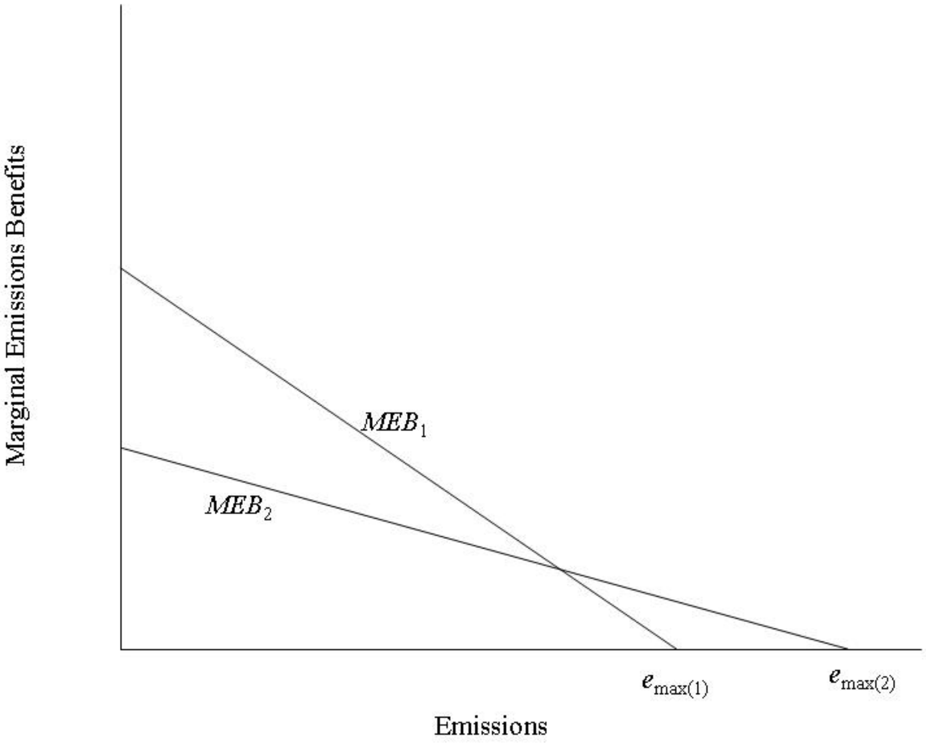
Cleaner-production Innovation With Low End-of-Pipe Costs

Figure 5



A Resource-Enhancing Innovation That Increases the Marginal Benefits of Emissions At All Margins

Figure 6



A Resource-Enhancing Innovation That “Back-Loads” Demand for Pollution

[1] For a contrary opinion, see Parry et al. (2003). We return to this paper in Section V.

[2] See Bauman (2003) for a simple algebraic demonstration. Note that the marginal approach *does* correctly identify the optimal amount of abatement, even for production process innovations.

[3] Färe et al. (1993), Coggins and Swinton (1996), and Hailu and Veeman (2000) employed a distance function to estimate the shadow prices or marginal abatement costs of undesirable pollutants. Färe et al. obtained 1,043.40 dollars per ton of BOD, one of four pollutants emitted by U.S. (Michigan and Wisconsin) paper and pulp mills. Coggins and Swinton found that the average shadow price of SO_2 equals about 292.70 dollars per ton in U.S. (Wisconsin) coal-fired electric plants. Hailu and Veeman attained 123 (286) dollars per metric tonne of BOD (TSS) in the Candian pulp and paper industry.

[4] The introduction to the paper claims to study "two possible technologies, a conventional one that causes high marginal abatement costs and an innovative one that leads to low marginal abatement costs but that incurs an additional fixed cost." But the model itself identifies "an innovative technology with relatively low pollution." As we argue in Section III, this means that the innovative technology will have *higher* marginal abatement costs at some and possible all margins.

[5] The profit in this second case is *before* payment of any emissions taxes or the purchase or foregone sale of any emissions permits that may be required.

[6] In mentioning the possibility of increasing marginal abatement costs, Nelissen and Requate (2004) describe a model in which gross emissions are proportional to *output*. A case can be made for either version; we find proportionality to input more intuitive.

[7] Price effects could influence $C(0)$ in the case of ω as well, but wouldn't qualitatively change the range of possible outcomes, unlike the case here.

[8] If the fixed-price assumption is restored, the first term on the left-hand-side of equation (5) drops out, since $p' = 0$. This in turn implies that $x_{\max}$ and $e_{\max}$ both unambiguously increase, making this merely an instance of Case A described in this paragraph.

[9] This same point is made in Requate (1995), p. 302: "Note, however, that … emissions may go up through innovation… The intuition is that if the damage function is sufficiently steep, output must be close to zero—that is, marginal utility of consumption is close to its maximum. If the new technology is much cleaner … one can produce much more output with one unit of pollution … [so] a raise of output after innovation may more than outweigh a small increase of pollution."

[10] According to the History of Korean Electricity, provided by Korea Electric Power Corporation, scrubbers were first introduced in 1998.

[11] In calculating the principal minors of the Hessian matrix, we round off the figures to the fifth decimal.

[12] Wons are converted into U.S. dollars at the recent exchange rate of 1,200 wons to the dollar.

[13] A referee suggests a directional output distance function (Färe et al.; 2005) to obtain another annual sequence of MAC_t. The average value of MAC_t over the sample period increases by 50%, which is expected. If we allow for a simultaneous expansion of desirable outputs and contraction of undesirable outputs, the production technology permits an investment in improving boiler fuel-efficiency or a shift to a production process that is effective in removing sulfur dioxide, given restrictions on sulfur dioxide emissions. It is obvious that these long-run responses cost more than fuel switching to lower sulfur.

[14] A referee raises a problem of endogeneity because both MAC_t and RT_t are given by the same technology. But, as allowing for the technological change in the distance function, equation (3), we implicitly assume that it is occurring constantly and exogenously. So, the rate of technical change defined on the distance function could be considered to be exogenous.

[15] Without imposing the second order autoregressive restriction, we have

$$\begin{aligned} MAC_t = {} & 0.132 + 0.115\ RT_t - 0.017\ ER_t \\ & (0.041)\ (0.025) \quad (-0.007) \end{aligned}$$

where the value of R^2 is 0.46.

[16] Since variables MAC_t and RT_t are themselves estimates, standard errors for equation (11) are required to be adjusted. Unfortunately, they have no estimated standard errors, because distance function is measured with linear programming (i.e., nonstochastic technique). Kolstad and Turnovsky (1998) point out "One problem is that the (distance) function itself is unobservable, involving how close to the production frontier the firm is operating; thus errors are undefined…" Nevertheless, the distance function has been recognized as a useful tool for estimation of marginal abatement for undesirable outputs.

[17] It might be explained by the fact that SO_2 emissions are regulated by the PPM unit, which does not necessarily coincide with the measure unit of actual emission rate (SO_2 g /10^3 Kcal) used in this study.

[18] For example, Bohm and Russell (1985) note that "incentives to develop new options diminish the smaller the scope of adjustment allowed by the policy, *ceteris paribus*. Thus, with effluent charges, a maximum number of compliance alternatives are acceptable and hence, technological R&D may be pursued in any direction. At the other extreme, a design standard leaves no room for innovation."

[19] The discussion that follows applies equally to other types of economic instruments, and to a wide variety of direct controls; all we assume about direct controls is that this type of regulatory policy acts by imposing constraints on firm behavior rather than by changing the firm's objective function (Baumol and Oates, 1988).

[20] To formalize this idea, normalize profits to zero under the original technology and assume that the firm facing direct controls makes a gain of *G* from the innovation. The mimicry argument suggests that the firm facing economic instruments can make a gain of at least *G* by behaving in the same manner. This is not true if mimicry necessitates an increase in emissions.

[21] Helfand (1991) and Bohm and Russell (1985) indicate that technology standards and limits on emissions per unit input or output are common forms of regulation, suggesting that the theoretical dominance of absolute emissions limits is not warranted by their practical importance.

[22] Again, Requate (1995) makes a very similar point (see note 9).

[23] It is difficult to differentiate "environmental" innovations from "non-environmental" ones. Some innovations– such as efforts to improve the fuel efficiency of power plants or motor vehicles–may be pursued for environmental reasons (e.g., to reduce a Pigovian tax payment), or non-environmental reasons, or both. And it is likely that all innovations, even those nominally undertaken for non-environmental reasons, will have environmental impacts because of output or price effects.