Limitations in the Standard Approach to Innovation in Pollution Control

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Abstract

The literature on technological innovation in pollution control (e.g., Milliman and Prince [6]) is dominated by a "marginal" approach that equates innovations with reductions in marginal abatement costs. This paper shows that this approach is appropriate only for innovations in end-of-pipe waste treatment efforts, and not for production process innovations such as the use of low-sulphur coal. After providing examples and proofs to support this claim, we discuss its implications and describe a profit-based approach that can be applied more generally.

Keywords: Conservation and Pollution; Technological Change and Innovation

1 Introduction

In the extensive literature on technological innovation and environmental protection, the concept of innovation is tightly bound to the idea of lower marginal abatement costs. This is most clearly evident in the dominant (graphical) approach in the literature, as shown in figure 1 (on page 4).[1] Here innovation lowers marginal abatement costs from MAC to MAC^*, producing a "gain from innovation" equal to the area $OFCB$. If the firm faces a Pigovian tax of p_B, Palmer et al. [7] provide the following description of this "marginal" approach:

> [Figure 1] also depicts the gains to the polluting firm from [the innovation], which can be divided into two parts. The source of the first part is that the earlier level of abatement activity becomes cheaper; the amount of gain here is given by triangle OFB. The second part comes from the new technology. The company will choose to abate a greater amount of pollution and thus avoid paying the pollution charge on that additional pollution; the gain here is the triangle BCF... The total gains to the polluting firm from innovation would thus be the area bounded by $OFCB$.

According to the marginal approach, a profit-maximizing firm would compare this "gain from innovation" with the (fixed) costs R of researching, developing, and implementing the innovation, and would pursue the innovation if and only if the benefit (the area $OFCB$) exceeded the cost (R).

[1] Papers in this tradition include [2], [6], [5], and [7]. Algebraic approaches including [1] and [8] also identify innovation with lower marginal abatement costs.

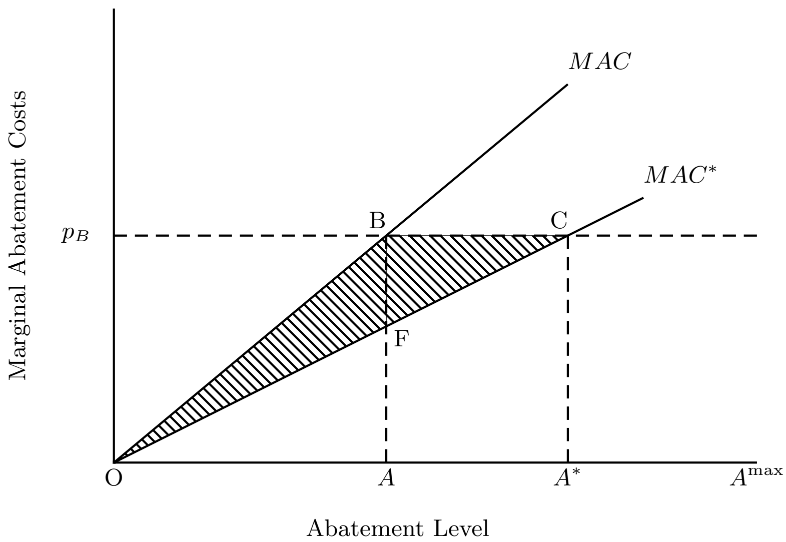

Figure 1: The marginal approach, with shaded area $OFCB$ representing the gain from innovation.

This analysis is purported to be quite general, and its conclusions have become a standard reference on the incentive effects of different environmental policies. For example, Hahn and Stavins [3] cite Milliman and Prince in writing, "Incentive-based policies have been shown to be more effective in inducing technological innovation and diffusion. . . than conventional command-and-control approaches." Palmer et al. [7] rely on the marginal approach in their vigorous dismissal of the claim (advanced in Porter and van der Linde [10]) that economists have adopted a "static mindset" that ignores production process innovations.

This paper will show that the marginal approach is in fact quite limited. In section 2 we present examples of innovations that do not fit into the marginal framework. Section 3 provides a profit-based perspective and shows that the marginal approach is only valid for innovations in end-of-pipe abatement technologies. In the conclusion we discuss the implications of our work and present opportunities for further research.

2 The Fallacy of the Margin

This section will demonstrate that the previously assumed relationship between the desirability of an innovation and its impact on marginal abatement costs does not exist. This point will be made clear via three examples: the first and third describe potentially desirable innovations that increase marginal abatement costs; the second describes an "innovation" that reduces marginal abatement costs but is obviously undesirable.

All three examples feature a power station operating in a competitive market. The firm has one input, coal, and two outputs, electricity and sulphur dioxide (SO_2). The abatement options available to a polluting firm are categorized in Hanley, Shogren, and White's [4, page 108] textbook description of abatement cost functions:

> For a firm, an abatement cost function describes the cost of reducing the output of an emission. In general, firms have a number of options open to them to reduce emissions. First, they may reduce output of their product. So, if a coal-fired power station wishes to cut its output of waste gases, such as SO_2, it can reduce the number of hours that its furnaces run. Electricity output falls, but so does the output of SO_2. Second, a firm may change its production process. Thus, the power station could switch to a combustion process that produces less waste gases per kwh of electricity, or else substitute low-sulphur coal for its existing coal input. Finally, the power station can install a filter on the end of its chimney to remove SO_2 from the waste gas stream (a process known as flue gas desulphurisation). This 'end of pipe' technology is available for many production processes...

Of these three abatement options—curtailing production, changing production processes, and engaging in end-of-pipe clean-up—the concept of innovation applies to the final two.

For expositional purposes, we will assume that end-of-pipe abatement is not possible for the firm in our examples. In other words, given a certain technology or production process (e.g., the use of high-sulphur coal), the firm can reduce emissions only by reducing the amount of coal it burns. As a result, the firm's marginal cost of abatement under a given technology is the profit it foregoes by curtailing production by one unit of coal. Equivalently, its marginal benefit of emissions is the added profit it gets from being allowed to process one more unit of coal. (The equivalence between marginal abatement costs and marginal emissions benefits holds more generally, and will yield valuable insights throughout this paper.)

A mathematical treatment is not essential in understanding what follows, but we provide it here as an option. Let F, G, and B represent the firm's input (coal, with market price p_F), its good output (electricity, with market price p_G), and its bad output (sulphur dioxide), respectively. The firm's production functions are given by $G(F) = \alpha F^{\frac{1}{2}}$ and $B(F) = \omega F$, where $\alpha > 0$ and $\omega > 0$ are some positive constants. It will be helpful to rewrite these as $F = \frac{B}{\omega}$ and $G = \alpha \left(\frac{B}{\omega} \right)^{\frac{1}{2}}$. Marginal abatement costs (or, equivalently, marginal emissions benefits) are therefore determined by the impact of B on G and F: additional emissions allow for additional output but require additional inputs, so that

$$MAC = p_G \cdot \frac{\mathrm{d}G}{\mathrm{d}B} - p_F \cdot \frac{\mathrm{d}F}{\mathrm{d}B} = p_G \cdot \frac{\alpha}{2\sqrt{\omega B}} - p_F \cdot \frac{1}{\omega}. \tag{1}$$

Facing a Pigovian tax of p_B, a profit-maximizing firm would determine the optimal amount of abatement according to $MAC = p_B$.

The first innovation we will consider is one which allows the firm to generate extra electricity for each unit of coal, e.g., a method of improving the generator's heat factor. Because this innovation allows the firm to squeeze added value from each unit of emissions (or, equivalently, from each unit of coal), curtailing production will be more costly for the firm *after* innovation, meaning that the firm's marginal abatement costs will *increase*. (This result is also clear from equation 1: an increase in α increases MAC.) From the marginal perspective of figure 1, the firm appears to be regressing. Instead of lowering marginal abatement costs from MAC to MAC^*, the innovation raises marginal abatement costs from MAC^* to MAC, thereby producing a "loss from innovation" equal to the area $OFCB$. Here the marginal perspective is clearly at odds with the intuitive appeal of this innovation.

For our second example, imagine that a mysterious scientist offers to sell the firm an innovation (sight unseen) that will reduce marginal abatement costs, e.g., from MAC to MAC^* in figure 1. What is the maximum amount the firm should pay for this innovation? According to the marginal approach, the firm's benefit from the innovation will be the area $OFCB$, and so the firm should be willing to pay up to this amount for the innovation. But the innovation under consideration is obviously worthless: it is to reduce the firm's output price to a fraction of the market price! This "innovation" will reduce the firm's foregone profits from curtailing production, and consequently will reduce the firm's marginal abatement costs. (This result is also clear from equation 1: a reduction in p_G reduces MAC.[2])

[2]If the reader is uncomfortable with the idea of a price change constituting an innovation, consider instead the replacement of modern generators with outdated clunkers, i.e., the reverse of our first example. Equation 1 shows that α and p_G have similar effects on MAC.

Since our first two innovations are not obviously environmentally motivated, for our final example we consider an innovation for which a Pigovian tax or other environmental policy provides the only possible source of motivation—the use of low-sulphur coal in place of less expensive high-sulphur coal. Intuitively, this innovation allows the firm to produce more electricity per unit of sulphur dioxide, and therefore *increases* marginal abatement costs. This intuition is not entirely correct,[3] but the point is clear: environmentally motivated innovations do not reduce marginal abatement costs always and everywhere.

3 The Profit Perspective

The examples in the previous section suggest that marginal considerations are a red herring when it comes to innovation. What profit-maximizing firms care about is not marginal costs and benefits but total costs and benefits—i.e., profits. In this section we develop the profit perspective.

Figure 1 clearly (and correctly) shows that a profit-maximizing firm facing a Pigovian tax of p_B will operate at point A if its technology corresponds to marginal abatement costs of MAC, and will operate at point A^* if its technology corresponds to MAC^*. The associated profit curves π and π^* must therefore peak at A and A^*, respectively. But this tells us nothing about the vertical

[3] The firm is producing more electricity per unit of sulphur dioxide, so decreasing returns to scale eventually reverses the result. This can be seen from equation 1: a decrease in ω increases MAC for small values of B (i.e., for the first few units of production) but reduces MAC for large values of B. (This is true regardless of the magnitude of the change in p_F.) In essence, the innovation allows the firm to "front-load" the benefits of emissions.

placement of these curves: figures 2 and 3 (on pages 11 and 12) both show profit curves π and π^* that are consistent with figure 1's depiction of marginal abatement costs. In figure 2 profits are higher with π, and in figure 3 profits are higher with π^*. The vertical placement of π and π^* is therefore a crucial issue, and figure 1 provides no guidance in this matter.

For a mathematical treatment consistent with the various figures,[4] consider a firm facing a Pigovian tax of $p_B = 6$; each unit of abatement therefore provides the firm with a constant marginal abatement benefit of 6. The firm's technology options correspond to marginal abatement costs of $MAC(a) = \frac{5a}{6}$ and $MAC^*(a) = \frac{a}{2}$. The firm's profit curves must therefore be $\pi(a) = 6a - \frac{5}{12}a^2 + c$ and $\pi^*(a) = 6a - \frac{1}{4}a^2 + c^*$. Marginal considerations cannot determine the constants of integration c and c^*; a comparison of figures 2 and 3 shows that these constants play a key role in the firm's choice of technology.

If we assume for simplicity that there are no R&D costs, figure 2 (on page 11) shows the correct profit perspective for the first two examples in the previous section.[5] Here the vertical placement of the two profit curves is determined by equating profits at $A^{\max}$, the point of full abatement. Since our firm can reduce emissions only by reducing the amount of coal it burns, full abatement means

[4] The functions described in this paragraph match the lines and curves in figures 1–3.

[5] The profit perspective for the third example—low-sulphur coal—is more complicated, but also equates profits at point $A^{\max}$. Note that positive R&D costs of R would shift the π^* curve down by R, and that the pertinent issue in comparing the two technologies is the placement of the two profit curves relative to each other. Their absolute placement is not relevant to our analysis, and in fact cannot be determined from figure 2 since point O does not necessarily coincide with zero profits.

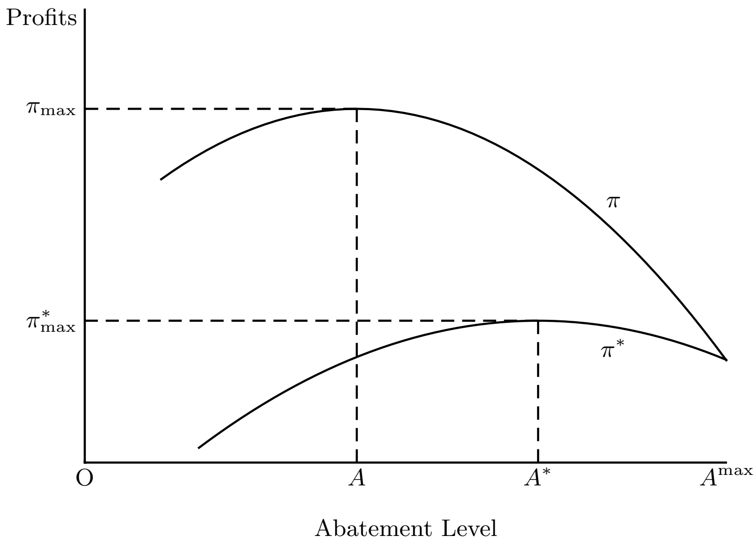

Figure 2: The correct profit perspective, assuming no R&D costs and no production at point $A^{\max}$.

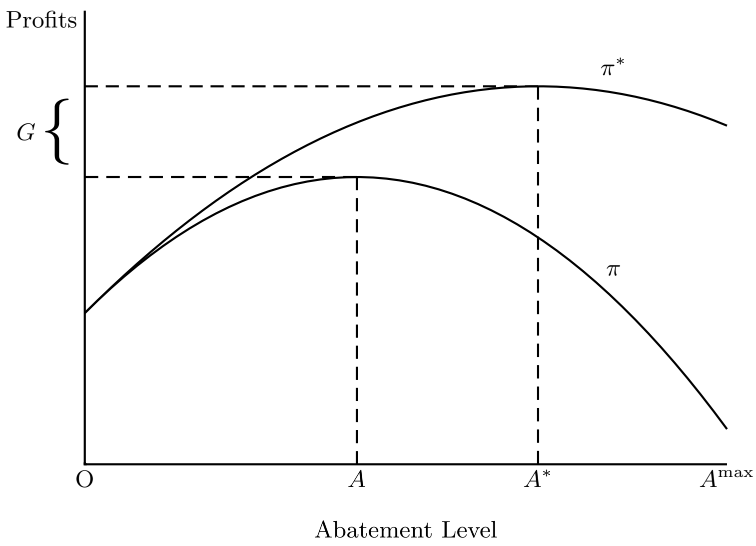

Figure 3: The (misleading) profit perspective according to the marginal approach, assuming no R&D costs and no production at point O. The distance G is equal to the area $OFCB$ in figure 1.

that the firm must shut down. As a result, the pre- and post-innovation firms' profits at point $A^{\max}$ differ only by the fixed costs of R&D, which we assume to be zero.

According to figure 2, the profit curve π is the better choice. Improving the generator's performance may raise marginal abatement costs from MAC^* to MAC, but the profit perspective shows that the firm is progressing, not regressing. Cutting the firm's output price may lower marginal abatement costs from MAC to MAC^*, but it is nonetheless a bad idea.

In contrast, the marginal approach asserts that π^* is the better choice if there are no R&D costs: the firm benefits from setting its output price below the market price and suffers from improving the generator's performance. The (misleading) profit perspective corresponding to this marginal approach is shown in figure 3 (on page 12). Here the vertical placement of the two profit curves is determined by equating profits at O, the point of zero abatement.[6]

That the marginal approach equates pre- and post-innovation profits at point O is intuitively clear from figure 1 and from Palmer et al.'s description of area $OFCB$. Mathematically, we can derive this result using the fundamental theorem of calculus:

[6] The meaning of "zero abatement" is clear from figure 1: point O represents the firm's preferred emissions level in the absence of all regulations. A firm unconstrained by environmental regulations of any sort would operate at point O. This point may change as a result of the innovation (e.g., go down because of the use of low-sulphur coal), but the marginal approach can be adapted to incorporate this possibility.

$$
\begin{aligned}
OFCB &= \int_O^{A^*} [p_B - MAC^*(a)]\,\mathrm{d}a \;-\; \int_O^{A} [p_B - MAC(a)]\,\mathrm{d}a \\
&= \int_O^{A^*} \left[\frac{\mathrm{d}}{\mathrm{d}a}\pi^*(a)\right] \mathrm{d}a \;-\; \int_O^{A} \left[\frac{\mathrm{d}}{\mathrm{d}a}\pi(a)\right] \mathrm{d}a \\
&= [\pi^*(A^*) - \pi^*(O)] - [\pi(A) - \pi(O)] \\
&= [\pi^*(A^*) - \pi(A)] + [\pi(O) - \pi^*(O)]
\end{aligned}
$$

The second-to-last line in this derivation shows that the distance G in figure 3 is equal to the area $OFCB$ in figure 1: both represent the "gain from innovation" according to the marginal approach. The last line in this derivation shows that the marginal approach will correctly quantify the gains from innovation if and only if $\pi(O) = \pi^*(O)$.

A similar result is true more generally: if the innovation involves R&D expenditures of R, the marginal approach will correctly quantify the net gains from innovation if and only if $\pi(O) - \pi^*(O) = R$, i.e., if and only if the pre- and post-innovation firms' profits at point O differ only by fixed R&D costs. Barring a numerical coincidence, this condition will be met only when the pre- and post-innovation firms have identical revenues and variable costs at point O, i.e., only when the firms sell the same quantity of outputs for the same price, and produce those outputs from the same quantities of inputs. In other words, the marginal approach is correct only when the pre- and post- innovation firms' *production processes* are identical.

We can now see how our examples from section 2 run afoul of the marginal approach. A lower output price reduces post-innovation profits at point O ($\pi(O) > \pi^*(O)$, as shown in figure 2), and this loss exceeds the "gain from innovation" shown in figure 1. Improving the generator's performance creates a "loss from innovation" according to figure 1, but this loss is more than compensated for by increased profits at point O. The marginal approach is also inappropriate in the case of low-sulphur coal: profits at point O will change because of the higher factor price p_F and perhaps also because of physical changes in the production process resulting from the input substitution.

We can also see why the marginal approach works for end-of-pipe innovations. Point O is the point of zero abatement, so by definition the firm is not engaging in any end-of-pipe abatement at this point. It follows that the innovation would not change the firm's behavior at point O. The marginal approach is valid because the firm pollutes first and asks abatement questions later.

4 Conclusion

One additional result can be seen from figure 2: an everywhere-lower marginal abatement cost curve is generally not a good thing! This result may become less surprising when one considers the equivalence between marginal abatement costs and marginal emissions benefits. (For an additional comparison, note that lowering marginal emissions benefits is like lowering a consumer's demand curve; in general, this would be expected to lower consumer surplus.) The only case in which a firm might be interested in an innovation which lowered its entire marginal emissions benefit curve would be if the innovation provided a benefit at point $A^{\max}$, i.e., under a 100% abatement requirement.[7]

Of course, the beauty of innovation is its unlimited potential. Innovation might well allow the firm to continue production under a 100% abatement requirement, for example if the innovation is to generate electricity from solar power rather than fossil fuels. A reasonable conclusion is that figure 2, like figures 1 and 3, provides a restricted and incomplete perspective. Figures 1 and 3 implicitly assume that profits at point O differ only by the costs of R&D, so their perspective is appropriate only for innovations in end-of-pipe waste treatment. Figure 2 assumes that profits at point $A^{\max}$ differ only by the costs of R&D, so its perspective is appropriate only when considering innovations that are "non-revolutionary", i.e., only when the pre- and post-innovation firms both shut down under a 100% abatement requirement.

Fortunately, a universally appropriate, unrestricted approach is possible—namely, to determine the gains from innovation via an algebraic comparison of profits before and after innovation: $\Delta\pi = \pi^*_{\max} - \pi_{\max}$. Such an approach would not need to make assumptions about marginal abatement costs or technological possibilities, and could therefore provide a truly general model of innovation in pollution control.

The conclusions of such an analysis would reverse some existing results. For

[7]This possibility provides the only reasonable interpretation of figure 3: the profit curve π^* is the preferred choice because of the profit differential at $A^{\max}$—a profit differential substantial enough to compensate for the post-innovation firm's *lower* marginal abatement costs!

example, the marginal approach leads Milliman and Prince [6] to assert that industry-wide adoption of a new technology would lead each firm to abate more under a Pigovian tax, so that in aggregate there would be a significant reduction in emissions. Assuming that the pollutant in question has a marginal external damage function that increases in emissions (e.g., that the marginal damage of the tenth ton of SO_2 exceeds that of the first ton), an optimizing regulator would respond by reducing the rate of the Pigovian tax. Milliman and Prince note that tax reductions benefit the firms in the industry, and conclude that the firms will support optimal agency response under a Pigovian tax. (A similar analysis shows that they will oppose optimal agency response under standards or tradable permits, since the optimal agency response to innovation in these cases is to tighten standards and issue fewer permits.)

Our analysis shows that innovations might well lead to an increase in aggregate emissions, so that the optimal agency response is to increase the Pigovian tax rate. In this case, the firms will oppose optimal agency response under a Pigovian tax, and support it under standards or tradable permits. This partial reversal of Milliman and Prince's results may have significant implications for regulatory policy in areas where firms have powerful lobbies.

Another implication of our work comes from a reinterpretation of Parry, Pizer and Fischer [9], who use the marginal approach to determine an upper bound for the welfare gains from technological innovation. Specifically, their upper bound comes from considering a 'super-scrubber' innovation that "completely and costlessly eliminates abatement costs" (p. 10). Based on that upper bound, they argue that innovation is less important than previously thought.

Our work provides a twist to this argument. Parry et al.'s analysis is correct in the case of end-of-pipe innovations, suggesting that these innovations (which have been the *de facto* focus of previous analyses) actually are unimportant. But their upper bound does not hold for production process innovations: the potential gains from an innovation that squeezes extra electricity from each ton of coal are not bounded by the total abatement costs for SO_2.[8] So it is production process innovations—such as those discussed in Porter and van der Linde [10]—that have the potential to be truly important. Since these innovations have been almost entirely overlooked, the need for further research in this area is clear.

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