The Effects of Environmental Policy on Technological Change in Pollution Control

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Abstract

The Effects of Environmental Policy on Technological Change in Pollution Control

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An extensive literature (e.g., Downing and White [7], Milliman and Prince [24]) examines the role of environmental policy in encouraging (or discouraging) innovation in pollution control. This dissertation critiques this literature, identifies important shortcomings, and develops alternative approaches that facilitate the analysis of a wider range of policy instruments (such as limitations on emissions per unit output) and potential innovations (such as production process innovations). These alternative approaches are used to (1) show that economic instruments *do not* always provide stronger incentives for innovation than command-and-control policies, and (2) generalize previous analyses by considering innovations in production processes in addition to innovations in end-of-pipe abatement technologies.

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Chapter 1

INTRODUCTION

Environmental policies are often motivated by static considerations, most notably the desire to reduce pollution levels in the immediate future. But such policies have a long-run impact as well: by providing greater or lesser incentives for firms to pursue technological change, environmental regulations can alter the landscape in which firms operate in the years and decades ahead. These dynamic considerations are an important part of environmental policy, and many economists argue that they are a key reason to favor economic instruments such as Pigovian taxes over more-traditional command-and-control regulations.

This dissertation addresses some theoretical aspects relating to technological innovation in pollution control. The remainder of this chapter provides an outline of the dissertation. Note that, whenever possible, the chapters are written so that they make sense not only as a whole but also as independent entities; in some cases this has necessitated a modest amount of repetition.

Chapter 2 reviews the extensive literature on this subject. It also describes how the material in this dissertation fits into and contributes to this literature.

Chapter 3 questions a common assertion in the literature: that economic instruments always provide greater incentives for innovation than command-and-control regulation. This chapter proves that this assertion *does not* hold for one common type of command-and-control regulation (limits on emissions per unit output) and identifies general conditions under which economic instruments *do* always provide stronger incentives for innovation. Chapter 3 also serves as an introduction to the principal mathematical techniques used in this dissertation.

Chapter 4 identifies two fundamental limitations in the existing literature. First, the dominant approach used in the literature is only valid for innovations in end-of-pipe abatement technology (e.g., scrubbers), and not for production process innovations (e.g., fuel switching). Second, the existing literature models innovation as a reduction in marginal abatement costs. This assumption lacks generality even for innovations in end-of-pipe abatement technology, but is particularly inappropriate for production process innovations. This chapter examines the effect of different types of innovation on marginal abatement cost curves, showing that many desirable innovations actually *increase* marginal abatement costs.

Chapter 5 addresses the limitations described in the previous chapter by introducing a more general approach that works for all types of innovation. Following the methodology of Milliman and Prince [24], this chapter evaluates the gain to firms from innovation, diffusion, and agency response under five different policies: absolute emission limits (in the form of absolute emissions limits[1]), Pigovian taxes, Pigovian subsidies, auctioned permits, and grandfathered permits. Milliman and Prince conclude that auctioned permits and Pigovian taxes usually provide the greatest incentive for technological change; the approach used in this chapter identifies the circumstances under which this conclusion generalizes.

Chapter 6 extends this analysis by developing a temporal model and by accounting for the possibility of entry and exit. Despite these extensions, there are a number of potential improvements for the model and the analysis; the concluding chapter (Chapter 7) identifies these as possible areas for future research.

The concluding chapter also cautions against drawing policy implications from this work, and it is worth emphasizing some of those cautionary notes here. A number of unrealistic assumptions underlie the analysis, most notably the *ceteris paribus* assumption that the context for innovation (the market price, the number of firms in the industry, etc.) is the same under different policies. This would certainly *not* be the case in practice: Pigovian taxes, for example, would lead to a higher market price and a smaller number of firms than Pigovian subsidies. By assuming that the context for innovation is identical under these

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[1] The focus of this chapter is on expanding the analysis to include different types of innovation, most notably production process innovation. A possible area for future research is expanding the analysis to include different types of direct control instruments; this would address the concerns raised in Chapter 3.

and other policies, the *ceteris paribus* approach leads to some unlikely conclusions, most notably that taxes and subsidies can have identical effects. These conclusions should be understood as stemming from the model's limitations and assumptions, and should not be used as the basis for making policy recommendations.

Chapter 2

LITERATURE REVIEW

Technological change is a wide-ranging topic with an extensive literature, both in general and in the specific case of innovation in pollution control. In brief, the main thread of this dissertation follows Zerbe [45], Downing and White [7], Milliman and Prince [24], and similar analyses. Section 2.1 provides a detailed review of the literature. Section 2.2 then discusses the contribution of this dissertation in the context of that literature.

2.1 Overview of the Literature

A considerable amount of energy has been devoted to studying various economic arrangements in a static context. Most notably, the First Fundamental Theorem of Welfare Economics describe the conditions under which competitive markets produce Pareto efficient results. It is tempting to conclude that such results lie at the heart of economists' general preference for competitive markets over alternatives such as government mandates regarding prices and output.

An alternative perspective comes from Schumpeter [41, p. 81]:

> [The] process of Creative Destruction is the essential fact about capitalism.... [T]here is no point in appraising the performance of that process *ex visu* of a given point in time; we must judge its performance over time, as it unfolds through decades or centuries. A system—any system, economic or other—that at *every* point of time fully utilizes its possibilities to the best advantage may yet in the long run be inferior to a system that does so at *no* point of time, because the latter's failure to do so may be a condition for the level or speed of long-run performance.

Schumpeter's argument for the pre-eminence of dynamics helped to establish a tension between dynamic and static perspectives that is evident to this day in many branches of economics.

One such branch is environmental economics, and in particular the analysis of pollution control. The original focus (as in Pigou [33]) was on static efficiency: the need for government intervention in the presence of externalities. In comparing and contrasting different types of government intervention—notably, "economic instruments" such as Pigovian taxes vis-à-vis direct controls such as technology standards—the static case rested on the ability of economic instruments to achieve a given level of pollution control at least cost.

The Schumpeterian perspective comes from economists such as Kneese and Schultze [18, p. 82]: "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." Another early contribution came from Orr [27]: "It seems to me that the greatest advantage of effluent charges relative to alternative control mechanisms is in their provision of decentralized incentives for technological change.... The strength of effluent charges lies in their ability to move things in generally desirable directions even when we lack the knowledge to provide price structures that are efficient in either the allocative or innovative sense."

This quote suggests (and the rest of Orr's article confirms) that his case rests on three contentions. The first (not directly evident in the quote) is that economic instruments are superior based on static considerations. The second is that economic instruments are superior based on dynamic considerations. The third is that dynamic considerations are more important than static considerations in the context of pollution control.

In a surprising turn of events, Orr's first contention—that economic instruments are superior based on static considerations—is no longer the unassailable proposition it once was: the debate on the so-called double dividend hypothesis has called into question the static properties of economic instruments in a second-best world.[1] These questions are of such a serious nature that Parry and Oates [31, p. 10] feel the need to assert that they

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[1] See for example the analytic and numerical analysis of Goulder et al. [9], who find that "[p]rior taxes can eliminate the cost-advantage of market-based instruments (emissions taxes and permits) over technology mandates or performance standards, particularly if the former policies fail to generate revenues and use the revenues to finance cuts in the prior distortionary taxes."

"do not see these new findings as grounds for abandoning the economist's case for pricing incentives for environmental protection"—a conclusion they reach entirely on the grounds of dynamic considerations:

> The argument here has been limited to an essentially static framework. And, as economists have long argued, one of the most important properties (in fact, perhaps the most important) of incentive-based instruments for environmental management is the inducement that such instruments provide for the development and adoption of new techniques for pollution control.

Regardless of how the double dividend debate is resolved, it has clearly placed added weight on Orr's second and third contentions: that dynamic considerations favor economic instruments, and that dynamic considerations trump static considerations.

The focus of this dissertation is on dynamic incentives, and as such relates to Orr's second contention: that economic instruments are superior based on dynamic considerations.Before discussing this issue in more detail, however, it is worth noting that this dissertation also pertains to Orr's third contention: that dynamic considerations trump static considerations. Many authors who have made this claim have left it unsubstantiated. An exception is Parry, Pizer, and Fischer [32], who conduct a theoretical analysis and reach the opposite conclusion, namely that "the welfare gains from innovation tend to be *less* than those from optimal pollution control" (emphasis added). Chapter 4 of this dissertation puts an important caveat on this result: while Parry, Pizer, and Fischer's analysis is valid for innovations in end-of-pipe pollution control, it is not valid for production process innovations such as energy efficiency improvements.[2] This is an especially timely contribution to the literature given the double dividend debate and its purported implications for the static properties of economic instruments.

In contrast to the paucity of work on Orr's third contention, a great many studies have addressed Orr's second contention—that economic instruments are superior based on dynamic considerations—by examining the dynamic properties of various environmental

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[2] This caveat also applies to related publications such as Fischer, Parry, and Pizer [8].

policy instruments and comparing them with each other. General overviews can be found in Jaffe, Newell, and Stavins [14] and Kemp [17], so this section focuses on the literature most directly related to this dissertation.

The earliest theoretical analysis of dynamic incentives under different policy instruments is Zerbe [45]. He concludes that economic instruments provide stronger incentives than direct controls, but in doing so he makes two crucial assumptions. The first is that direct controls are synonymous with absolute emissions limits ("Each firm can emit no more than x tons of SO_2"). The second assumption equates innovation with reductions in marginal abatement costs. (Chapter 4 describes this assumption in more detail.)

Later works—commonly cited ones include Wenders [44] and Downing and White [7]—buttress Zerbe's conclusion; they also replicate his assumptions. This dissertation loosens Zerbe's assumptions, and in doing so makes three significant contributions to this line of the literature. First, Chapter 3 shows that Zerbe's conclusions do not always hold under other types of direct controls, e.g., limits on emissions per unit output. Second, Chapter 4 shows that Zerbe's approach limits his analysis to innovations in end-of-pipe abatement technologies. Third, Chapter 5 provides a more general approach that encompasses production process innovations as well as innovations in end-of-pipe abatement technology.

Two other lines in the literature are evident in the pathbreaking analysis in Downing and White [7]. One relates to their interest in *optimal* incentives for innovation. While most of the authors who precede or succeed them focus on the issue of maximal incentives ("Do economic instruments create stronger incentives for innovation than absolute emission limits?"), Downing and White also consider whether economic instruments create the optimal level of incentives for innovation. Their focus here is on whether the private benefits from innovation equal the social benefits from innovation. While this dissertation does not address the subject of optimal incentives for innovation, the distinction between maximal and optimal incentives is important to keep in mind throughout the analysis.

The other line of literature that is evident in the work of Downing and White [7] concerns the process of technological change. Instead of examining the behavior of a single firm in an otherwise unchanging context, Downing and White consider the possibility of a regulatory response to innovation, e.g., a reduction in the Pigovian tax rate or a tightening of absolute emission limits.

This effort is the first attempt to connect the literature on innovation in pollution control with the literature on innovation in general. The latter body of literature brings up a number of issues relevant to innovation in pollution control. For example, Rogers [39] discusses the importance of diffusion, i.e., of technology transfer (either via licensing or via spillover) from the innovating firm to other firms. A related issue concerns the possibility of innovation by an outside firm seeking to sell or license its discovery to firms inside the industry; in this case patents and spillover effects are of particular importance.

The key paper that brings these general results to bear on the issue of innovation in pollution control is Milliman and Prince [24]. Their major contribution is a deeper consideration of the interplay between innovating and non-innovating firms, and between firms and regulators. For example, their model considers the possibility of innovation by an outside firm. (Empirical work by Griliches [10] and Nadiri [26] suggests that spillover effects are neither negligible nor total, meaning that patenting firms stand to gain some but not all of the benefits accruing to other firms from their discovery. In accordance with these findings, Milliman and Prince consider an outside firm that earns some but not all of the benefits accruing to other firms from its innovation.)

Milliman and Prince's methodology is described in detail in Chapter 5. For present purposes it is sufficient to note that they adopt the same assumptions as Zerbe (mentioned above). The major contribution of this dissertation to this line of the literature is to eliminate one of those assumptions: the approach in Chapter 5 encompasses production process innovations as well as innovations in end-of-pipe abatement technology. Another contribution is made in Chapter 6, which extends the model to incorporate temporal issues and account for the possibility of entry and exit.

2.2 Key Issues

This section identifies nine important considerations and uses these considerations to describe the existing literature and the contribution that this dissertation will make.

The first consideration is the **agent of technological change.** Von Hippel [43, p. 3] notes that "[i]t has long been assumed that production innovations are typically developed by product manufacturers." His empirical work demonstrates that "the sources of innovation vary greatly. . . . In some fields, innovation users develop most innovations. In others, suppliers of innovation-related components and materials are the typical sources of innovation. In still other fields, conventional wisdom holds and product manufacturers are indeed the typical innovators." His work suggests that the profit motive is a primary driver for innovation.

In the context of pollution control, the possible sources of innovation range from outside firms (seeking patent royalties or equipment purchases from polluting firms) to the pollution firms themselves (seeking higher profits from their own operations and/or from patent royalties paid by other polluting firms and/or from strategic advantage) to government researchers (e.g., in universities). Because the objective function of this last group is uncertain, this dissertation focuses on the first two groups.

The second consideration is the **motivation for technological change.** Dosi [6] identifies the two main approaches as "technology-push" and "demand-pull." The former approach puts researchers and inventors in the driver's seat; it views technological progress as exogenous to the economic system. The latter approach, which is the focus of most economic analyses, views technological progress as endogenous to the economic system, with economic forces such as price changes playing a major role in determining the quantity and direction of research leading to technological change. This "induced innovation" viewpoint was first advanced by Hicks [13, pp. 124–125], who argued that "a change in the relative prices of the factors of production is itself a spur to invention, and to invention of a particular kind—directed to economizing the use of a factor which has become relatively expensive." This dissertation follows the Hicksian tradition by analyzing the incentives that firms have to pursue technological change.

The third consideration is the **direction of technological change.** Binswanger and Ruttan [4] note that Hicks and other early analysts of "induced innovation" were primarily motivated by questions about workplace automation, particularly its effects on the labor market. A key question was whether technological change was naturally biased *toward* the use of machines and *away from* the use of labor.

The literature on environmental economics does contain some work in this tradition. For example, Smith [42] and McCain [22] introduce unpriced environmental goods into a Hicksian model and find that innovation is biased in favor of the use of those goods.[3] Magat [19, 20] considers investment decisions for a firm that can choose between R&D that will increase output and R&D that will reduce emissions. Finally, Bellas [2, ch. 3] considers firm incentives to pursue inframarginal reductions in abatement costs vis-à-vis marginal reductions.

More commonly, however, the environmental economics literature is less concerned with the *direction* of environmental innovation than with its *existence.* Beginning with Zerbe [45], the dominant approach is a binary choice model: the firm is assumed to choose between its existing technology and the possibility of one single (exogenously given) new technology. The firm's only decision is to whether or not to expend R&D resources to pursue the new technology. This dissertation follows the majority of the literature in adopting this binary choice approach.

The fourth consideration concerns the **process of technological change.** Rogers [39] provides a detailed description of the multi-stage process that is technological change. This dissertation follows Milliman and Prince's [24] modified version, which divides technological change into three stages. The first stage is innovation: a single firm decides whether or not to pursue a new technology; this stage is the focus of much existing work, and of Chapters 3 and 4 of this dissertation.

The second stage is diffusion: the new technology spreads to other firms in the industry. Chapter 5 of this dissertation follows the model in Milliman and Prince in which all firms are identical, diffusion to all firms occurs simultaneously, and—if there are patents—the innovating firm gains a fraction z of the benefits accruing to these other firms. (If $z = 0$

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[3] This result parallels the static result that firms will overuse unpriced environmental goods. One connection between the two results comes from the observation that innovation can be viewed as similar to input substitution; as Rosenberg [40] puts it, "[From a historical perspective, the] analytical distinction between technological change and mere factor substitution becomes extremely difficult to maintain. . . . *Today's* factor substitution possibilities are made possible by *yesterday's* technological innovation" (emphasis in original). Just as the static result shows that firms do not have appropriate incentives to substitute into inputs (such as low-sulphur coal) that benefit the environment, the dynamic result shows that firms do not have appropriate incentives to substitute into knowledge inputs (such as pollution control innovation) that benefit the environment.

patents are worthless and all the benefits of diffusion accrue to the non-innovating firms; if $z = 1$ patents are all-powerful and all the benefits of diffusion accrue to the innovating firm; and if $0 < z < 1$ then patents allow the innovating firm to gain some but not all of the gains from diffusion.) This model is of course not the only approach to diffusion; the survey in Jaffe, Newell, and Stavins [14] ably summarizes the relevant issues, both in general and those particular to environmental policy. These include different approaches to modelling diffusion—for example, epidemic models or probit models—and issues such as spillover. (One alternative to Milliman and Prince's z, for instance, is Fischer, Parry, and Pizer's [8] model in which non-innovating firms can either purchase the right to use the innovation or adopt a freely available but imperfect substitute; the amount of the patent royalty is determined endogenously in accordance with a Nash equilibrium.)

The final stage is agency response: the regulatory body observes the change in the market and reacts accordingly, e.g., by adjusting the rate of a Pigovian tax. Agency response obviously does not exist in unregulated markets, so this final stage is of particular interest in the case of environmental policy. Along with the second stage, this third stage is discussed only in in Chapter 5.

Also of particular interest in the case of environmental policy is the fifth consideration, the **nature of regulation.** Not surprisingly, economists are particularly interested in economic instruments; this dissertation follows Downing and White [7], Milliman and Prince [24], and others in considering a range of economic instruments including Pigovian taxes, Pigovian subsidies, auctioned permits, and grandfathered permits. Less thoroughly examined are different types of command-and-control policies. Despite the existence of many such policies in practice (see Helfand [12] and Bohm and Russell [5, p. 419]), the theoretical literature on innovation in pollution control equates direct regulations with absolute limits on emissions (i.e., each firm cannot emit more than x units of pollution per year). Chapter 3 begins to address this shortcoming by investigating some properties of other types of direct controls.

The sixth consideration is the **nature of pollution control innovation.** Mathematically, the vast majority of the literature equates such innovation with reductions in marginal abatement costs at all margins (see for example Downing and White [7], Milliman and Prince [24], Jung, Krutilla, and Boyd [16], Montero [25], Parry [29], and Biglaiser and Horowitz [3]). Chapter 4 examines the limitations of this approach.

A related issue is the distinction between end-of-pipe abatement activities (such as scrubbers) and production process changes (such as fuel switching or enhanced energy efficiency). Although some early analysts such as Wenders [44] (and perhaps early policy-makers as well) focused on end-of-pipe abatement technologies, most articles in the existing literature claim to address both types of innovation. This dissertation shows that the dominant approach used in the literature is valid only for end-of-pipe abatement technologies; it also provides a more general approach that addresses production process changes as well as end-of-pipe innovations.

The seventh consideration is **market structure.** Schumpeter [41] and others argue that a great deal of innovation happens in oligopolistic situations rather than competitive markets; game theoretical treatments of such situations can be found in Montero [25] and Requate [35, 36, 37, 38]. This is a promising area for future research, but this dissertation—like much of the existing literature—focuses on competitive markets.

The eighth consideration is the **market context.** This dissertation follows Zerbe [45] and others in assuming that the context of the firm's decision does not change under different policy instruments: exogenous variables such the market prices of inputs and outputs are the same under all policies.[4] Although this *ceteris paribus* approach lacks a certain amount of realism—market price, for example, would be higher under Pigovian taxes than under Pigovian subsidies—it does allow analysts to compare the effects of different policy instruments on firms that are in otherwise-identical situations. For the same reason, the different policies are structured so that firm behavior prior to innovation is identical under all the policies; this implies that the market price of tradable permits must be equal to the Pigovian tax rate, and that each firm's emissions under taxes or permits equal its limit under absolute emission limits.[5]

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[4] Although Zerbe does not make this assumption explicit, it follows from his use of MC_1 and MC_2 to represent marginal abatement costs before and after innovation, respectively; if prices changed under different policies, these marginal cost curves would be different.

[5] See Malueg [21] for one possible result when all other things are not assumed to be equal. As discussed in Chapter 5, the *ceteris paribus* approach also necessitates some other unrealistic assumptions, namely

The ninth and final consideration is **mathematical approach.** Much of the literature focuses on abatement cost minimization, often via the graphical approach used by Downing and White [7], Milliman and Prince [24], Palmer, Oates, and Portney [28], Fischer, Parry, and Pizer [8], and others. (Algebraic approaches along the same lines can be found in Montero [25], Biglaiser and Horowitz [3], and Parry [29].) This approach implicitly assumes that production levels of the firm's good output are held constant; otherwise, abatement cost minimization is not equivalent to profit maximization. Since innovation—especially production process innovation—may well influence production levels, this dissertation breaks from the literature by developing an approach based directly on profit maximization.

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that entry and exit are prohibited and that demand is perfectly elastic so that output changes don't affect market price.

Chapter 3

ARE ECONOMIC INSTRUMENTS REALLY BETTER?

Many economists use dynamic considerations to argue for the use of economic instruments such as Pigovian taxes instead of command-and-control regulations. Assertions of the importance of dynamic considerations and the superiority of economic instruments in providing incentives for innovation have changed little over the past thirty years:

> Orr, 1976 [27, p. 442]: “It seems to me that the greatest advantage of effluent charges relative to alternative control mechanisms is in their provision of decentralized incentives for technological change.”
>
> Bohm and Russell, 1985 [5, p. 445]: “[We are] tempted to stress the advantages of economic incentive systems in the long-run context [because of the] extra push [they provide] toward the development of new production and discharge reduction technology. . . ”
>
> Porter and van der Linde, 1995 [34, p. 111]: “Where possible, regulations should include the use of market incentives. . . Such approaches allow considerable flexibility, reinforce resource productivity, and also create incentives for ongoing innovation. Mandating outcomes by setting emission levels, while preferable to choosing a particular technology, still fails to provide incentives for continued and ongoing innovation and will tend to freeze a status quo until new regulations appear. In contrast, market incentives can encourage the introduction of technologies that exceed current standards.”

The superiority of economic instruments in promoting innovation is supported by an extensive theoretical literature, e.g., Wenders [44], Zerbe [45], Downing and White [7], Milliman and Prince [24], and Jung, Krutilla, and Boyd [16]. Most of this literature examines a variety of economic instruments—Pigovian taxes, Pigovian subsidies, auctioned or grandfathered permits—but only one type of command-and-control regulation: absolute emissions limits, i.e., limits on total firm emissions.

This exclusive focus on absolute emissions limits is puzzling. Jaffe and Stavins's [15] useful categorization of non-economic instruments indicates that absolute emissions limits are only one kind of *performance standard*; others are limits on emissions per unit output or per unit input. Direct controls can also involve *technology standards* that mandate specific technologies such as scrubbers or that simply mandate that firms adopt Best Available Control Technology (BACT), Reasonably Available Control Technology (RACT), or Lowest Achievable Emission Rate (LAER). Helfand [12] and Bohm and Russell [5, p. 419] 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.[1]

The purpose of this chapter is to re-examine dynamic considerations using a more-inclusive view of command-and-control policies. Section 3.1 provides background and describes the basic set-up of the problem. Section 3.2 contains a counter-example showing that economic instruments *do not* always provide the strongest incentives for innovation. Section 3.3 discusses general conditions under which economic instruments *do* provide stronger dynamic incentives. The applicability of these general conditions to specific types of innovations and policy instruments is discussed in Section 3.4, which also comments on the distinction between *optimal* incentives for innovation and *maximal* incentives for innovation.

3.1 Background and Set-up

As discussed in Chapter 2, the process of technological change in pollution control can be broken down into three stages: *innovation*, the discovery and adoption of some new thing by an individual agent; *diffusion*, the spread of that new thing across a community, industry, or other social system; and *agency response*, the reaction of regulatory agencies (e.g., via

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[1] The real-world applicability of absolute emissions limits may be hampered by what students of money laundering call "smurfing": breaking down activities into small pieces in order to avoid regulatory scrutiny.

reductions in a Pigovian tax rate) to the changes brought about by innovation and diffusion.

This chapter concerns itself with only the first stage: innovation. An early model in this area is that of Magat [19, 20], who analyzes the decisions of a firm which can invest in both abatement technologies and production technologies. His results are mixed, but he does conclude [20, p. 21] that "technology-based standards provide the weakest incentives for both abatement technology and output technology innovation…"

More recent studies have followed the binary choice model described in Chapter 2: a firm currently using technology T^0 is considering a switch to technology T^1. The benefit of the new technology is lower abatement costs; the cost is the R&D expenditure necessary to develop and implement the new technology. The basic question is this: how do different regulatory policies affect the firm's incentive to adopt the new technology? Other things equal, the more the innovation increases the firm's profits, the greater the firm's incentive to pursue the new technology.[2]

In order to make other things equal, firm behavior (e.g., its choice of inputs and outputs) is assumed to be identical under the various regulatory policies prior to the innovation. Although somewhat contrived, this assumption accomplishes the important task of focusing attention on the effect of the innovation. (Malueg [21] shows that relaxing this assumption can change the incentive structure.)

This chapter's results follow from this binary choice approach, which dominates the literature and to date has unanimously favored the use of economic instruments over direct controls.

3.2 A Counter-example

Consider a simple model of a coal-burning power plant. The plant has one input (coal, K, with market price p_K), one good output (electricity, G, with market price p_G), and one waste output (sulphur dioxide, W). The firm's production functions are $G(K) = K^{\frac{1}{2}}$ and $W(K) = \alpha K$, where α is some positive constant. The innovation to be considered is

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[2] To put it another way, the greater the benefit of the new technology, the more the firm is willing to invest in R&D in order to acquire it.

one which allows for a reduction in α, e.g., an improvement in scrubber technology. The innovation has fixed R&D costs of R and no marginal costs.

The firm's incentive for innovation under a given policy (e.g., Pigovian taxes) is given by the difference in its profits before and after innovation. The larger the profit differential, the higher the research costs R the firm is willing to bear in order to develop the innovation.

The policies to be compared are Pigovian taxes and a limit on emissions per unit output. Note in what follows that the two policies have been normalized so that the firm's behavior before innovation is identical under the two policies.

Under a Pigovian tax of p_W, the firm chooses K to maximize profits,

$$\pi = p_G K^{\frac{1}{2}} - p_W \alpha K - p_K K.$$

For the purposes of the counter-example, set $p_G = 4$, $p_W = 1$, $p_K = .8$, and $\alpha = 1.2$ so that the firm's profit function becomes

$$\pi = 4K^{\frac{1}{2}} - 2K.$$

This yields optimal values of $K = 1$, $G = 1$, $W = 1.2$, and $\pi = 2$.

Next assume that the innovation reduces α to .4 and carries a fixed cost of R so that the firm's profit function if it adopts the innovation becomes

$$\pi = 4K^{\frac{1}{2}} - 1.2K - R.$$

This yields optimal values of $K = \frac{25}{9}$, $G = \frac{5}{3}$, $W = \frac{10}{9}$, and $\pi = \frac{10}{3} - R$. So the firm's gain from the innovation under the Pigovian tax is the profit differential $\left(\frac{10}{3} - R\right) - 2 = \frac{4}{3} - R$.

Now consider an emissions limit of $\frac{W}{G} \leq 1.2$. The firm chooses K to maximize

$$\pi = p_G K^{\frac{1}{2}} - p_K K$$

subject to the constraint on emissions per unit output. Substituting in using the specified prices yields

$$\pi = 4K^{\frac{1}{2}} - .8K.$$

Before innovation (i.e., with $\alpha = 1.2$), the solution to this constrained maximization problem is $K = 1$, $G = 1$, $W = 1.2$, $\frac{W}{G} = 1.2$, and $\pi = 3.2$. The firm's pre-innovation behavior under the standard is therefore identical to its pre-innovation behavior under the Pigovian tax.

After the innovation, profits are

$$\pi = 4K^{\frac{1}{2}} - .8K - R$$

and the solution to this problem[3] is $K = \frac{25}{4}$, $G = \frac{5}{2}$, $W = \frac{5}{2}$, $\frac{W}{G} = 1$, and $\pi = 5 - R$. So the firm's gain from the innovation under command-and-control is the profit differential $(5-R)-3.2 = 1.8-R$. Comparing this with the gain from innovation under Pigovian taxes $(\frac{4}{3} - R)$, it can be seen that incentives for innovation are *higher* under the command-and-control policy. In particular, if R is greater than $\frac{4}{3}$ but less than 1.8, the firm will adopt the innovation under the command-and-control policy but not under the economic instrument.

An interesting (and, as will be shown later, crucial) aspect of this example is that the innovation leads to an *increase* in the firm's emissions under the command-and-control policy. However, this result does not suggest that the innovation under consideration is not an "environmental" innovation. For one thing, scrubber improvements are archetypal pollution-control innovations. More importantly, while the individual firm's emissions may increase because of the innovation, emissions from the industry as a whole may decrease. For an example of this, assume that the pre-innovation situation features a large number of identical firms, each producing $G = 1$ units of the good and $W = 1.2$ units of emissions, and each making zero profit. With free entry and exit, the innovating firm's increased output (from $G = 1$ to $G = 2.5$) will drive 1.5 other firms out of the market, and the reduction in emissions from the exiting firms $(1.5 \cdot 1.2 = 1.8)$ will more than compensate for the increase in emissions from the innovating firm $(2.5 - 1.2 = 1.3)$.

3.3 General Results

The common argument in favor of economics 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

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[3] The solution turns out to be the unconstrained maximum.

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 substitutions, e.g., the use of low-sulphur coal).[4]

Although the previous section shows that this argument does not apply universally, its logic is nonetheless valuable. Consider, for example, 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?[5]

In order to focus on the effect of the innovation, 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:

$$\pi^0_{\text{max}}(\text{C\&C}) = \pi^0_{\text{max}}(\text{tax}) + p_W W^0, \tag{3.1}$$

where p_W is the Pigovian tax rate, W^0 is the firm's emissions level (under both policies), and $\pi^0_{max}(x)$ is the maximum profit for a firm that is using technology T^0 and facing regulatory policy x.

Making a similar definition for $\pi^1_{\text{max}}(x)$, the firm's gain from innovation (i.e., from the switch from technology T^0 to T^1) under policy x can be expressed as

$$\Delta\pi(x) = \pi^1_{\text{max}}(x) - \pi^0_{\text{max}}(x). \tag{3.2}$$

One can now determine the conditions under which economic instruments unambiguously provide (weakly) superior incentives for innovation than direct controls, i.e.,

$$\Delta\pi(\text{C\&C}) \leq \Delta\pi(\text{tax}). \tag{3.3}$$

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[4] For example, Bohm and Russell [5, p. 449] note that "[i]ncentives 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."

[5] The discussion that follows applies equally to other types of economic instruments, and to a wide variety of direct control; all that is assumed 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 [1, p. 191].

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

$$\pi^1_{\max}(\text{C\&C}) = \pi^1_{W^1}(\text{tax}) + p_W W^1. \tag{3.4}$$

As explained below, subtracting Equation 3.1 from Equation 3.4 produces

$$\begin{aligned}
\pi^1_{\max}(\text{C\&C}) - \pi^0_{\max}(\text{C\&C}) &= \pi^1_{W^1}(\text{tax}) - \pi^0_{\max}(\text{tax}) \\
&\quad + p_W(W^1 - W^O) && (3.5) \\
&\leq \pi^1_{W^1}(\text{tax}) - \pi^0_{\max}(\text{tax}) && (3.6) \\
&\leq \pi^1_{\max}(\text{tax}) - \pi^0_{\max}(\text{tax}), && (3.7)
\end{aligned}$$

i.e., $\Delta\pi(\text{C\&C}) \leq \Delta\pi(\text{tax})$.

Of the two crucial inequalities in this proof, the first arises from the assumption that $W^1 \leq W^0$. The second inequality is essentially tautological: $\pi^1_{\max}(\text{tax})$ 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 inequality that encompasses the vaunted flexibility of economic instruments: as long as $W^1 \leq W^0$, 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. Similar proofs for other economic instruments (Pigovian subsidies, auctioned permits, and grandfathered permits) lead to the following general result.

Proposition 1 *Assume that an economic instrument and a command-and-control policy yield identical firm behavior prior to innovation. Then the incentive for innovation from the economic instrument is greater than or equal to the incentive from the command-and-control policy as long as the innovation does not lead the firm to increase its emissions under the command-and-control policy.*

The proof above also identifies the problem that arises when $W^1 > W^0$: mimicry becomes problematic because economic instruments impose an additional burden on the firm (namely, the cost of additional emissions) that does not exist under the regulatory policy. 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.[6] For $W^1 > W^0$, the inequality used to move from step (3.5) to step (3.6) in the proof of Proposition 1 no longer holds; the proof breaks down, leading to counter-examples such as the one in the previous section.

3.4 Conclusion

This chapter has shown that economic instruments provide (weakly) superior incentives for innovation *as long as the innovation does not increase emissions under direct controls.* 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.

What types of innovations—and in combination with what types of direct controls—are likely to increase firm emissions? In terms of innovations, it appears that almost any type of innovation *may* increase firm emissions under certain circumstances: the counter-example given above features scrubbers, a classic end-of-pipe abatement technology. But one interesting case centers on the production-process innovations that Porter and van der Linde [34, quoted earlier] call “resource-enhancing innovations” (for example, improving the performance of a generator so that power plants can produce more energy from each ton of coal). Such innovations are likely to increase the marginal benefits of emissions, and therefore lead individual firms to increase emissions in a wide variety of circumstances. So the assertion that economic instruments provide stronger incentives for this type of innovation remains unproven.

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[6] 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.

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. As noted previously, however, this policy—which has been the focus of previous analyses—does not dominate the policy landscape. More prevalent are limits on emissions per unit output, or direct specifications of technology. *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 [5], Jaffe, Newell, and Stavins [14], and Magat [20]. For example, Bohm and Russell (quoted above in footnote 4) note that "[a]t the other extreme [in terms of dynamic incentives], a design standard leaves no room for innovation." This statement is partly true: it holds for 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. (If such an innovation increases firm emissions under a Pigovian tax, and if the firm facing the Pigovian tax chooses to adopt the scrubber both before and after innovation, then the analysis in Section 3.3 is reversed: the firm facing direct controls can mimic the firm facing Pigovian taxes, so the incentive for innovation under direct controls is greater than or equal to the incentive for innovation under a Pigovian tax.)

This is not to say that dynamic considerations actually favor direct controls; technology-based standards, for example, have obvious long-term shortcomings that unnecessarily limit opportunities for innovation.[7] But it is to say that the dynamic case for economic instruments must be more nuanced than the simple assertion that they provide stronger incentives for innovation. Upon reflection, this is perhaps as it should be, since providing strong incentives for innovation may not be the ultimate goal of environmental or social policy. As noted by Parry [30, p. 14], Jaffe, Newell, and Stavins [14, p. 23], and others, resources

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[7] The limited empirical work on this subject also favors economic instruments; see Jaffe, Newell, and Stavins [14] and Jaffe and Stavins [15].

devoted to R&D in scrubber technology cannot be devoted to other types of R&D, or to valued consumption goods. Balancing these competing interests cannot be accomplished by focusing on *maximal* incentives for innovation, but only by considering *optimal* incentives for innovation. This is an important area for future research.

Chapter 4

LIMITATIONS OF THE STANDARD APPROACH

The dominant framework for studying innovation in pollution control is the graphical approach shown in Figure 4.1 on page 25. (Papers in this tradition include Downing and White [7], Milliman and Prince [24], Palmer, Oates, and Portney [28], and Jung, Krutilla, and Boyd [16]. Algebraic analogues include Biglaiser and Horowitz [3] and Parry [29].) This dominant framework can be termed the "marginal" approach because of two of its principal components. First, innovation is modelled as a reduction in marginal abatement costs, e.g., from MAC to MAC^* in Figure 4.1. Second, the gains from innovation are identified as areas in that same figure. In a canonical example, the gains to a firm facing a Pigovian tax of p_B are described by Palmer, Oates, and Portney [28] as follows:

> [Figure 4.1] 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 this 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).

This marginal approach goes back at least as far as Zerbe [45] and Wenders [44]. Comparing these two papers identifies a definitional issue with important ramifications for later

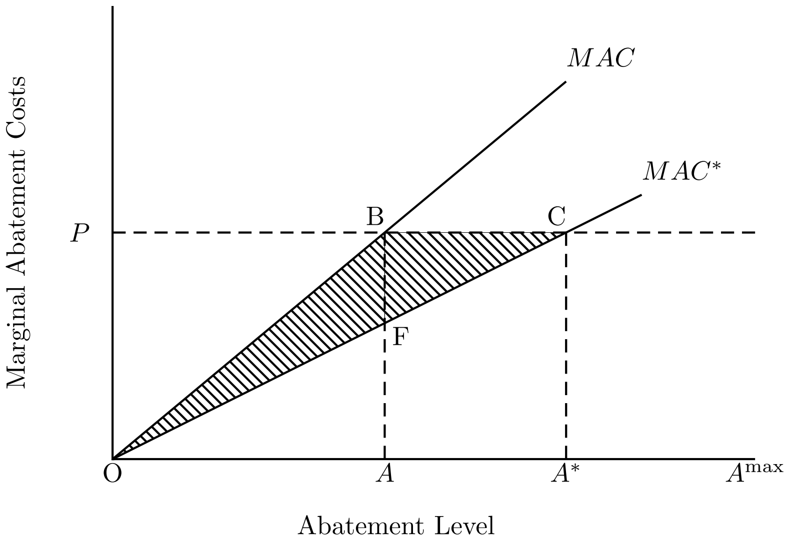

Figure 4.1: The marginal approach, with shaded area $OFCB$ representing the gain from innovation under a Pigovian tax of P

work: both authors discuss "innovation in pollution control," but they do not entirely agree on the meaning of this phrase. Wenders clearly limits his analysis to innovations in end-of-pipe abatement technologies; Zerbe focuses on these, too, but also (on p. 371) brings up fuel switching, thereby extending the scope of his analysis to include innovations in production processes.

Later papers adopted the phrase "innovation in pollution control," but for the most part failed to clarify the intended scope of this phrase. In many cases it is not clear whether the authors were 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 [11, p. 13n] cite Milliman and Prince [24] in asserting that "[i]ncentive-based policies have been shown to be more effective in inducing technological innovation and diffusion. . . than conventional command-and-control approaches." An even clearer example is Palmer et al.'s [28, quoted above] use of the marginal approach; their paper is a rebuttal of Porter and van der Linde's [34] defense of the Porter Hypothesis, a defense which repeatedly emphasizes the importance of production process innovations.

The next two sections show that, although the marginal approach has been frequently applied to production process innovations, it is in fact only valid for improvements in end-of-pipe technology.

4.1 Cost Minimization and Profit Maximization

The first limitation of the marginal approach comes from its focus on minimizing abatement costs. Firms have a broader focus—profit maximization—and failure to attend to this broader focus 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 the same problem, and the graphical approach correctly quantifies the gain from innovation. With production process innovations, however, cost minimization cannot substitute for profit maximization. In these cases, the marginal approach is inappropriate; it correctly identifies the optimal amount of abatement activity, but it incorrectly measures the gain from innovation.

To see this mathematically, consider again the conclusion drawn from figure 4.1, in which a firm faces a Pigovian tax of P. For expositional simplicity, assume that the innovation under consideration has no R&D costs or other fixed costs. In this case, the marginal approach indicates that the area $OFCB$ measures the *net* gain from innovation, i.e., the profit differential between the pre-innovation firm and the post-innovation firm.

Now, let $MAC(a)$ and $MAC^*(a)$ be the marginal abatement costs for the pre- and post-innovation firms, respectively. The marginal benefit of abatement is P, the per-unit Pigovian tax, so the net impact of an additional unit of abatement on π, the pre-innovation firm's profits, is $\frac{d}{da}\pi(a) = P - MAC(a)$. An identical result holds for the post-innovation firm's profits: $\frac{d}{da}\pi^*(a) = P - MAC^*(a)$. Making use of the Fundamental Theorem of Calculus yields

$$
\begin{aligned}
OFCB &= OFCP - OBP && (4.1)\\
&= \int_O^{A^*} [P - MAC^*(a)]\, da \;-\; \int_O^{A} [P - MAC(a)]\, da && (4.2)
\end{aligned}
$$

$$= \int_O^{A^*} \left[\frac{d}{da}\pi^*(a)\right] da \quad - \quad \int_O^{A} \left[\frac{d}{da}\pi(a)\right] da \tag{4.3}$$

$$= [\pi^*(A^*) - \pi^*(O)] - [\pi(A) - \pi(O)] \tag{4.4}$$

$$= [\pi^*(A^*) - \pi(A)] + [\pi(O) - \pi^*(O)]\,. \tag{4.5}$$

This shows that the area $OFCB$ is equal to the profit differential $\pi^*(A^*) - \pi(A)$ if and only if $\pi(O) - \pi^*(O) = 0$, i.e., if and only if firm profits at point O are equal before and after innovation.

Before investigating the implications of this result, recall that point O is not the point of zero production. On the contrary, it is the point of zero abatement, and therefore can reasonably be thought of as the point of "full production": a firm facing no regulations would operate at point O.

With that in mind, three comments are worth making. First, the term $\pi(O) - \pi^*(O)$ does not simply represent the innovation's fixed costs. In the example above, fixed costs are assumed to be zero, but that does not imply that $\pi(O) - \pi^*(O) = 0$. If, for example, the innovation is a production process improvement that enhances resource productivity (i.e., squeezes more good output out of any given combinations of inputs), profits after innovation will be higher at point O (and indeed at all other points at which the firm produces strictly positive amounts of output).

Second, profits at point O before and after innovation will be equal (i.e., $\pi(O) - \pi^*(O) = 0$) *if* the innovation is limited to end-of-pipe waste treatment technology. This is because point O represents the point of zero abatement, meaning that a firm producing at this level does not engage in any end-of-pipe waste treatment. Since there is no abatement activity and since there are assumed to be no R&D costs, the profit levels at point O before and after innovation must be equal.

Third and finally, profits at point O before and after innovation will (in general) be equal *only if* the innovation is limited to end-of-pipe waste treatment technology. If the innovation affects production processes (for example, in the case of fuel switching), there is every reason to think that profits at point O will be different: the firm may be using different inputs, or a different ratio of inputs, or may be squeezing more profits from its inputs. Indeed, the point O itself is likely to have moved.

4.2 Innovation and Margins

The previous section showed that the marginal approach does not (in general) correctly measure the gains from production process innovations. This section identifies an additional problem: the marginal approach inappropriately defines an innovation as a reduction in marginal abatement costs at all margins, as shown in figure 4.1.

The intuitive appeal of modelling innovation as lower marginal abatement costs is clear in the case of end-of-pipe innovations; the purpose of such innovations is, after all, to lower abatement costs. Even here, however, the assumption of *everywhere*-lower marginal abatement costs is unwarranted. As Downing and White [7, p. 19] point out, innovations might reasonably raise marginal abatement costs at some margins while lowering them at others. This point is ignored by most other authors, and Downing and White themselves dismiss it by noting that the “more commonly discussed” innovations are those which lower abatement costs at all margins. The connection between innovation and everywhere-lower marginal abatement costs is therefore tenuous even for innovations in end-of-pipe abatement technology.

In the case of production process innovations, this connection is in fact nonexistent. Such innovations are likely to increase marginal abatement costs at some margins, and in important cases will increase marginal abatement costs at *all* margins. A simple algebraic example will demonstrate these results.

Consider a firm with one input (coal, K, with market price p_K), one good output (electricity, G, with market price p_G) and one bad output (sulfur dioxide, B, which is unpriced in the absence of regulation). Consider further a simple production function for electricity, $G = \alpha G(K) = \alpha(10K - .5K^2)$ for some $\alpha \geq 1$. Production also creates pollution, $B = B(K) = \dfrac{1}{\omega}K$ for some $\omega \geq 1$. Imagine that the firm has no opportunities for end-of-pipe abatement of sulfur dioxide, so the only way it can reduce emissions is by reducing production.

For simplicity, choose units so that $p_G = p_K = 1$. In the absence of regulation, then, the firm's optimization problem can be expressed as choosing K to maximize profits, $\pi(K) = \alpha G(K) - K = (10\alpha - 1)K - .5\alpha K^2$. Since there is a one-to-one relationship between B and K given by $K = \omega B$, the firm's optimization problem can also be expressed as choosing B to maximize profits, $\pi(B) = (10\alpha - 1)\omega B - .5\alpha(\omega B)^2$. The derivative of this profit function with respect to B is

$$\text{MEB(B)} = \pi'(B) = (10\alpha - 1)\omega - \alpha\omega^2 B. \tag{4.6}$$

Equation 4.6 measures the firm's *marginal emissions benefits*. In the absence of regulation, the firm would choose to pollute until the point $B^{\max} = \dfrac{10\alpha - 1}{\alpha\omega}$ where the marginal emissions benefit equals zero.

As an aside, note that defining abatement A as $A = B^{\max} - B$ yields an equation for *marginal abatement costs*:

$$\text{MAC(A)} = \pi'(A) = (10\alpha - 1)\omega - \alpha\omega^2(B^{\max} - A). \tag{4.7}$$

Graphically, marginal abatement costs and marginal emissions benefits are mirror images: rotating the marginal abatement cost curves MAC and MAC^* from figure 4.1 around the line $A = A^{\max}$ yields the marginal emissions benefit curves MEB and MEB^* shown in figure 4.2. As shown in these figures, the traditional approach is to model innovation as a reduction in marginal abatement costs—or, equivalently, as a reduction in marginal emissions benefits. (Although the marginal abatement cost perspective dominates the literature, in what follows the focus will be on marginal emissions benefits. The symmetry described above allows for easy movement back and forth.)

To show the limitations of modelling innovation as a reduction in marginal emissions benefits, consider the effects of changes in α and ω on the marginal emissions benefits function in Equation 4.6. First envision an innovation that doubles ω; for simplicity, assume that the innovation is costless (e.g., involves no R&D expenditures). Since ω controls the relationship between B and K according to $B = \frac{1}{\omega}K$, a doubling in ω halves emissions per unit input. Intuitively, this innovation can be thought of as allowing for the substitution of otherwise identical low-sulfur coal for high-sulfur coal.

In the absence of regulation, the adoption of this innovation will provide no benefit to the firm. This is because nothing has changed in term of K: the firm will continue to purchase

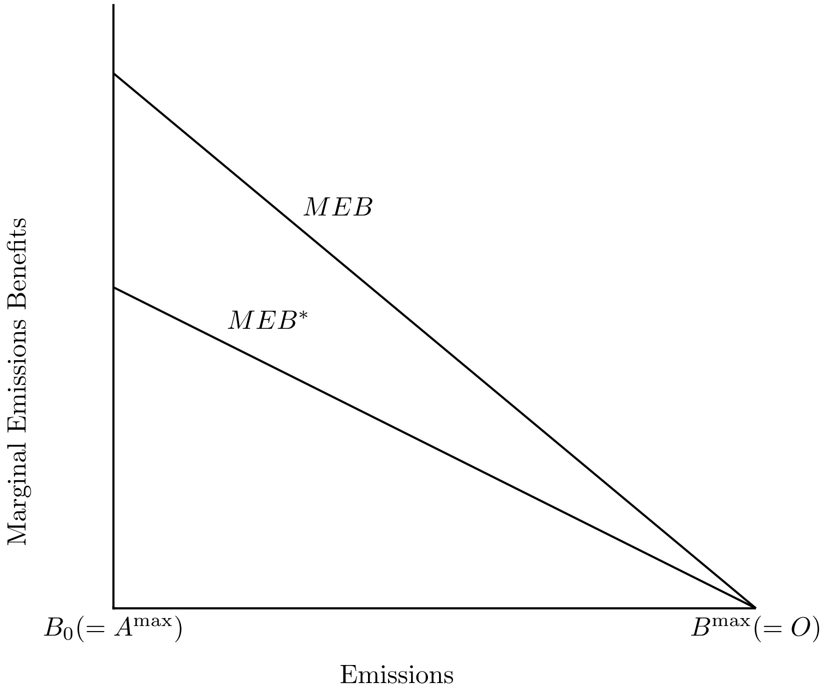

Figure 4.2: The marginal emissions benefit curves corresponding to the marginal abatement cost curves in Figure 4.1

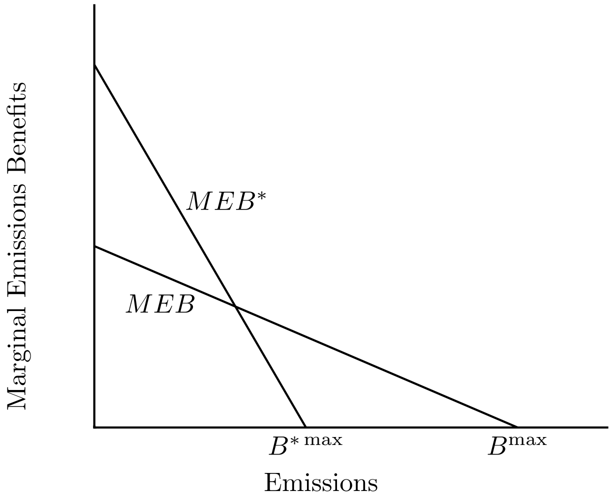

Figure 4.3: An innovation that "front-loads" demand for pollution

the same amount of K and produce the same amount of G. In terms of B, however, the innovation will "front-load" the benefits of emissions, i.e., increase benefits for initial units of emissions and reduce benefits for later units (as shown in figure 4.3). Intuitively, these results follow from the observation that each ton of sulfur corresponds to twice as much coal after the innovation as before. The initial unit of emissions, for example, provides a post-innovation benefit equal to the pre-innovation benefit of the first *two* units of emissions. (Mathematically, this can be seen by setting $B = 0$ in Equation 4.6: doubling ω doubles MEB.)

The reduction in benefits for later units of emissions results from the existence of diminishing marginal product of K and from the relationship between K and B. In terms of K, the marginal benefit of emissions equals zero at the same level before and after innovation; in terms of B, however, the marginal benefit of post-innovation emissions reaches zero twice as fast. (This can also be seen mathematically from Equation 4.6: if MEB originally equals zero at $B^{\max}$ then doubling ω results in MEB reaching zero at $B^{*\max} = \frac{1}{2}B^{\max}$.)

A final observation about figure 4.3 is that the areas under the two marginal benefit curves must be equal. This follows from the fact that the firm's profits are unaffected by the innovation in the absence of regulation.

This example shows that *pollution prevention* innovations are unlikely to lower marginal emissions benefits (or, equivalently, marginal abatement costs) at all margins. An even stranger result arises in the case of *resource-enhancing* innovations: these may *raise* marginal abatement costs at all margins.

For an example of this, consider an innovation that increases α; since α governs the relationship between K and G according to $G = \alpha G(K)$, an increase in α increases output per unit input. (An example would be an improved generator that produces more electricity for each ton of coal.) Intuitively, it makes sense that marginal emissions benefits should increase as a result of innovation, as shown in figure 4.4: each unit of emissions now corresponds to a greater amount of the good output, and is therefore more valuable to the firm.

To prove this result algebraically for the relevant interval (i.e., for $B < B^{\max} = \frac{10\alpha - 1}{\alpha\omega}$), differentiate Equation 4.6 with respect to α:

$$\frac{\partial MEB(B)}{\partial \alpha} = 10\omega - \omega^2 B \geq 10\omega - \omega^2 \left(\frac{10\alpha - 1}{\alpha\omega} \right) = \frac{\omega}{\alpha} > 0.$$

Since marginal abatement costs are equivalent to marginal emission benefits, it follows that marginal abatement costs are higher at all margins after the innovation. The intuition from the abatement cost perspective is that the only way to abate pollution is to reduce production, which is more costly with a leaner production process, i.e., with a higher α.

4.3 Conclusion

The above discussion has shown that a more general approach to innovation in pollution control is warranted. It also suggests a need to revisit previous efforts that were based on the marginal approach, most notably Milliman and Prince's [24] work on firm incentives for technological change. This is the subject of Chapter 5.

Especially noteworthy here are this chapter's implications for the conclusions of Parry, Pizer, and Fischer [32]. Disputing oft-repeated (but unsubstantiated) claims that dynamic issues in pollution control are more important than static ones, they conduct a theoretical analysis of potential gains from innovation and conclude that "the welfare gains from innovation tend to be *less* than those from optimal pollution control" (emphasis added). Because Parry, Pizer, and Fischer's analysis is based on the "marginal approach," the results of this

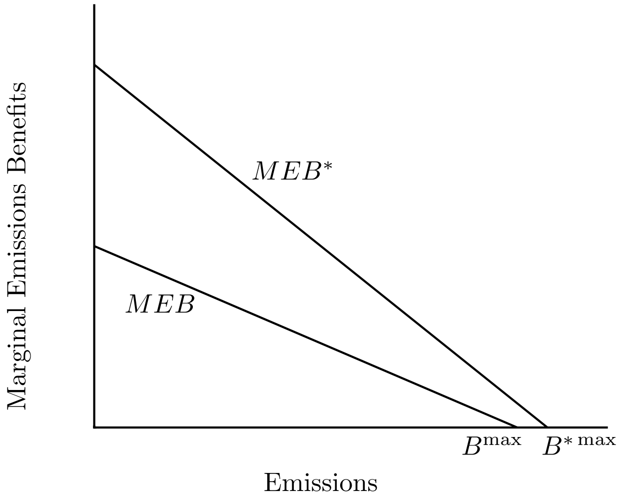

Figure 4.4: A resource-enhancing innovation that increases the marginal benefits of emissions at all margins

chapter put an important caveat on their conclusion: while their analysis is valid for innovations in end-of-pipe pollution control, it is not valid for production process innovations such as energy efficiency improvements. (In particular, the potential gains from production process innovations are not bounded above—as Parry, Pizer, and Fischer assume—by total abatement costs.) As a result, the focus of previous literature has arguably been on a type of innovation (end-of-pipe) that is of lesser importance from a dynamic perspective.

As a more general conclusion, the above examination of production process innovations suggests the need for integrating the analysis of innovation in pollution control into analyses of innovation more generally. (One such integrated approach is described in the next chapter.) After all, almost any innovation is likely to have environmental impacts. And, as for example in innovations which yield greater fuel efficiency in power plants or motor vehicles, it is not always easy to distinguish "environmental" innovation from other innovations. The process of identifying which innovations are "environmentally motivated"—or, similarly, which costs are "abatement costs"—is fraught with difficulty, and in the end may be of limited value.

Chapter 5

A GENERAL APPROACH TO FIRM INCENTIVES FOR TECHNOLOGICAL CHANGE IN POLLUTION CONTROL

The standard approach for analyzing incentives for innovation in pollution control is that taken in Milliman and Prince [24]. Technological change is divided into three stages: innovation (a single firm develops a new technology), diffusion (the new technology spreads across the industry), and optimal agency response (the regulatory body responds, e.g., by adjusting the rate of a Pigovian tax).

Milliman and Prince calculate the impact on firms of the transition from one stage to the next, and of various combinations of the stages. Most notably, they analyze the impact of the entire three-stage process and find that "emissions taxes and auctioned permits provide the highest firm incentives to promote technological change" (p. 247).[1]

This chapter examines the extent to which Milliman and Prince's conclusions carry over to a more general model of innovation. Motivation for this more general treatment comes from the problems identified in the previous chapter, and from a recent paper by McKitrick [23]. McKitrick shows that discontinuities are likely in marginal abatement cost curves, thereby highlighting the dangers of making assumptions about marginal abatement cost curves. Although Milliman and Prince do not assume continuous abatement cost curves, they do follow Downing and White [7] and others in assuming that innovation uniformly reduces marginal abatement costs. This chapter explores the ramifications of relaxing that assumption.

The structure of this chapter is as follows. Section 5.1 describes the new approach, which is an algebraic analogue of Milliman and Prince's geometric analysis. The next sections use

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[1] As in Milliman and Prince, this chapter's treatment of direct controls is limited to absolute emission limits. A possible area for future research is to further extend the model by considering a range of direct control policies.

this approach to calculate the gains from innovation, diffusion, and optimal agency response: Section 5.2 considers innovation, Section 5.3 considers diffusion in the absence of patents, Section 5.4 considers diffusion with patents, Section 5.5 considers optimal agency response in the absence of patents, and Section 5.6 considers optimal agency response with patents. The conclusion compares the results from this chapter with those of Milliman and Prince. As noted in the introductory chapter, it is important to caution against drawing policy implications from these results because of the model's restrictive assumptions.

5.1 The Model

Following Milliman and Prince, consider a competitive market with N identical profit-maximizing firms and divide the process of technological change into innovation, diffusion, and optimal agency response.

The baseline stage ($i = 0$) describes the situation prior to innovation. There are n potential inputs, $K_1, \ldots, K_n$, with prices $w_1, \ldots, w_n$. Each firm's production technology transforms these inputs into a good output $G = G^0(K_1, \ldots, K_n)$, with market price p_G, and a waste product $W = W^0(K_1, \ldots, K_n)$. Note that the inputs are *potential* inputs; for notational convenience, the model include inputs that are useless under the current technology but may prove useful after innovation. Also note that the list of potential inputs includes those that may be used in end-of-pipe abatement efforts. Such efforts (if they exist) are subsumed within the function W, i.e., $W^0(\cdot) = E^0(\cdot) - A^0(\cdot)$ where $E^0(\cdot)$ is initial emissions and $A^0(\cdot)$ is end-of-pipe abatement.

If there were no environmental regulations, the waste product would be unpriced and the firm's profits would be given by

$$\pi = p_G G - \sum w_i K_i. \tag{5.1}$$

Now consider imposing a limit on emissions and define $\pi^*(W)$ to be the firm's maximum profits subject to the constraint that emissions cannot exceed W. The derivative $\frac{d\pi^*}{dW}$ measures the firm's marginal emissions benefits, an example of which is shown in Figure 5.1. Note that reflecting this curve around the line $W = W^{\max}$ yields the firm's marginal abate-

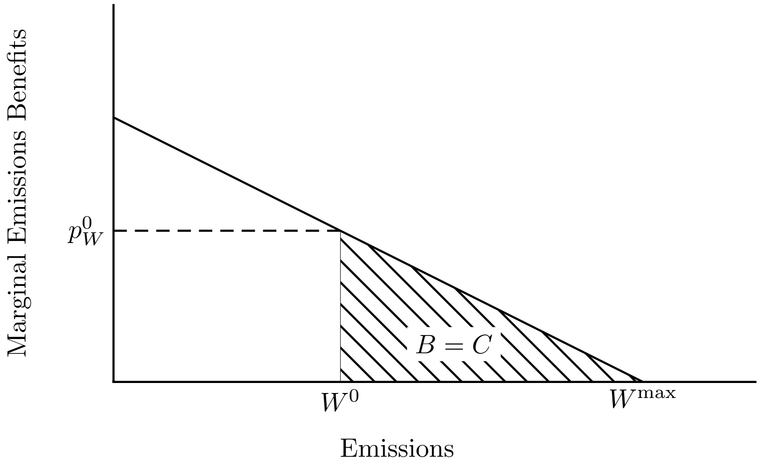

Figure 5.1: A marginal emissions benefit curve. The shaded area represents the total benefits B of extending an emissions limit from W^0 to $W^{\max}$ or, equivalently, the total costs C of reducing emissions from $W^{\max}$ to W^0. A firm facing a Pigovian tax of p_W^0 would choose to emit W^0 units of waste.

ment cost curve: the cost C of reducing emissions from $W^{\max}$ to W^0 is logically equivalent to the benefit B of being allowed to increase emissions from W^0 to $W^{\max}$.

The regulatory body maximizes social welfare by equating the social marginal benefit of emissions with the social marginal cost of emissions. The regulator's policy options are absolute emission limits (abbreviated "abs"), Pigovian subsidies ("sub"), free permits grandfathered in equal amounts to all firms ("gra"), auctioned permits ("auc"), and Pigovian taxes ("tax").

Assume that all of the policies are "properly designed" at stage 0, meaning that each firm produces the same (socially optimal) amount of waste—say, W^0—under the various policies. In order for this result to hold, the absolute emission limit must be W^0, the number of tradable permits issued or auctioned to each firm must be W^0, and the market price of these permits must be equal to the level of the Pigovian tax or subsidy (say, p_W^0).[2]

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[2] Throughout this chapter an assumption is made that the baseline $\overline{W}$ used for calculating the Pigovian subsidy is sufficiently high, e.g., $\overline{W} \geq W^{\max}$ in the example shown in Figure 5.1. This ensures that the policy always provides the appropriate marginal incentives.

In the innovation stage ($i = 1$), a single firm (the "innovating firm") adopts a new technology. The firm is assumed to be small enough that its actions have no impact on industry-wide variables such as the prices and aggregate amounts of inputs and outputs. In particular the firm is assumed to have no effect on aggregate emissions or on the market price of pollution permits if such a market exists.

As a final comment, note that our interest lies in comparing the effects of various policy instruments, so aspects (such as the cost of R&D) that are the same across the board hold little interest. Having said that, it is also worth noting that it is impossible to reconcile the current model with the idea of positive R&D costs: in the presence of immediate free-riding by other firms in the industry, no firm would spend money to pursue an innovation. In this chapter, therefore, we assume that R&D costs are zero. The next chapter relaxes this assumption by developing a temporal model that delays diffusion, thereby providing the innovating firm with the potential to gain from investing in R&D.

Define an "innovation" to be any change in the firm's technology, modeled as a change in the production functions from $G^0(\cdot)$ and $W^0(\cdot)$ to $G^1(\cdot)$ and $W^1(\cdot)$.[3] This definition may be overly general in other contexts, but it serves current purposes well. It includes innovations in end-of-pipe abatement efforts (which are subsumed within the function W) as well as innovations in production processes (which will likely affect both G and W). It also includes innovations that are not specifically "environmentally related," or even environmentally related at all. This means that the results from this chapter can be used to analyze the role of environmental policy in promoting non-environmental innovations.[4]

In the diffusion stage ($i = 2$), the other firms in the industry (the "non-innovating firms") adopt the innovation. (Sections 5.3 and 5.5 assume that the innovation is non-patentable, i.e., a public good; Sections 5.4 and 5.6 consider innovations that are patentable by firms inside or outside the industry.) Diffusion may change industry-wide variables relating to emissions, such as aggregate emissions and the market price of pollution permits. By as-

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[3] Recall that the potential inputs $K_1, \ldots, K_n$ include all relevant inputs for these production technologies.

[4] Since most innovations are likely to have environmental impacts, the concept of "environmental" or "environmentally related" innovation may in fact be of limited value. Is an innovation that allows more electricity to be generated from each ton of coal an "environmental" innovation or not, and is the distinction relevant?

sumption, however, no other industry-wide variables are affected: other input and output prices remain constant, and firms do not enter or exit the industry. Though restrictive, these assumptions follow those made explicitly or implicitly in Milliman and Prince.

The final stage ($i = 3$) is optimal agency response. Here the regulatory agency becomes aware of the new technology and responds with an appropriate policy adjustment, e.g., a change in the Pigovian tax rate that re-equates the social marginal benefit and social marginal cost of emissions. (As at stage 0, the various policies are "properly designed" at stage 3 in that each firm produces the socially optimal amount of waste—say, W^3—under the various policies.) Again following Milliman and Prince, this change in regulatory policy can affect industry-wide variables relating to emissions, but other industry-wide variables remain constant.

The following sections consider innovation, diffusion, and optimal agency response. The analysis is based on calculating profit differentials between the various stages. For example, $\Delta\pi_I^{01}$ measures the change in the innovating firm's profits between stages 0 and 1, i.e., the change in profits resulting from innovation. (The subscript I denotes the innovating firm; N denotes a non-innovating firm.) Similarly, $\Delta\pi_I^{12}$ measures the change in the innovating firm's profits resulting from diffusion.

Although the model breaks down technological change into different stages, there is no explicit discount rate and (as in Milliman and Prince) the model is fundamentally atemporal. (Chapter 6 develops a temporal model.) The various stages of technological change are best thought of not as points in time but as different "worlds" or scenarios: $\Delta\pi_I^{01}$ measures the change in innovator profits between the "before innovation" scenario and the "after innovation" scenario; $\Delta\pi_I^{12}$ measures the change in innovator profits between "innovation only" and "innovation plus diffusion"; and $\Delta\pi_I^{02}$ measures the change in profits between the baseline and "innovation plus diffusion." It follows that multi-stage profit differentials can be broken down additively, e.g., $\Delta\pi_I^{02} = \Delta\pi_I^{01} + \Delta\pi_I^{12}$.

The atemporal nature of the model leads to the following important result, which will be used frequently.

Proposition 2 *In the absence of patents, the gains from innovation plus diffusion are* *identical for innovating and non-innovating firms,*[5] *and the same is true for the gains from innovation plus diffusion plus optimal agency response, i.e.,*

$$\Delta\pi_I^{02} = \Delta\pi_N^{02} \overset{\text{call}}{=} \Delta\pi^{02} \tag{5.2}$$

$$\Delta\pi_I^{03} = \Delta\pi_N^{03} \overset{\text{call}}{=} \Delta\pi^{03} \tag{5.3}$$

Proof. In the absence of patents, there is no difference between innovating and non-innovating firms at stage 0 (before innovation, at which point nobody has the new technology), stage 2 (after diffusion, at which point everybody has the new technology), or stage 3 (after optimal agency response, at which point everybody is subject to the new regulatory policy). It follows that innovating and non-innovating firms will have identical profits in each of these three stages, and therefore that their profit differentials will be identical. As a result, the subscripts can be removed and the profit differentials can be called $\Delta\pi^{02}$ and $\Delta\pi^{03}$.

5.2 Innovation

This section examines a single firm that develops an innovation. It is assumed that there are no R&D costs or other fixed costs associated with the innovation, and that the firm is small enough relative to the industry that industry-wide variables will be unaffected by the innovation.

If we define $R(W)$ to be the regulatory cost of emitting W units of waste,[6] then a profit-maximizing firm would choose $K_1, \ldots, K_n$ to maximize

$$\pi = p_G G - R(W) - \sum w_i K_i. \tag{5.4}$$

If $\pi^0_{\max}(x)$ and $\pi^1_{\max}(x)$ are, respectively, the innovator's maximum profits before and after innovation under policy x, then the gain from innovation under policy x is the difference

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[5] Although Milliman and Prince do not explicitly point out this result, it can be seen from their results in Tables I and II.

[6] An absolute emission limit of W^0 can be represented by $R(W) = 0$ for $W \leq W^0$ and $R(W) = \infty$ for $W > W^0$. A Pigovian subsidy with baseline $\overline{W}$ and subsidy rate p^0_W corresponds to $R(W) = p^0_W(W - \overline{W})$, i.e., to a negative cost. As noted in Section 5.1, it is assumed that $\overline{W}$ is sufficiently high to avoid complications.

between these terms:

$$\Delta\pi_I^{01}(x) = \pi_{\max}^1(x) - \pi_{\max}^0(x). \tag{5.5}$$

Two results follow immediately.

Proposition 3 *Incentives for innovation are identical under a variety of properly designed economic instruments (taxes, subsidies, and tradable permits):*

$$\Delta\pi_I^{01}(\text{tax}) = \Delta\pi_I^{01}(\text{sub}) = \Delta\pi_I^{01}(\text{auc}) = \Delta\pi_I^{01}(\text{gra}) \overset{\text{call}}{=} A.$$

As described in Section 5.1, "properly designed" means Pigovian taxes with tax rate p_W^0, Pigovian subsidies with subsidy rate p_W^0, and auctioned or grandfathered tradable permits with market price p_W^0; all of these induce the pre-innovation firm to emit W^0 units of waste.

Proof. All of these policies have the form $R(W) = p_W^0 W + c$, where c is some constant. Pigovian taxes correspond to $c_{\text{tax}} = 0$, as do auctioned permits; W^0 grandfathered permits correspond to $c_{\text{gra}} = -p_W^0 W^0$; Pigovian subsidies with baseline $\overline{W}$ correspond to $c_{\text{sub}} = -p_W^0 \overline{W}$.

Since the constant term c doesn't affect the firm's profit-maximizing choices of $K_1, \ldots, K_n$, any differences in firm profits between these various policies at stages 0 or 1 can be attributed entirely to differences in the magnitude of c. For example,

$$\pi_{\max}^1(\text{tax}) \quad = \quad \pi_{\max}^1(\text{gra}) - p_W^0 W^0 \tag{5.6}$$

$$\pi_{\max}^0(\text{tax}) \quad = \quad \pi_{\max}^0(\text{gra}) - p_W^0 W^0 \tag{5.7}$$

Subtracting the second equation from the first yields $\Delta\pi_I^{01}(\text{tax}) = \Delta\pi_I^{01}(\text{gra})$, which is one of the desired results. The other results follow from identical proofs: the constant c drops out when computing $\Delta\pi_I^{01}$ for the various policies.

Proposition 4 *The incentive for innovation under a properly designed absolute emission limit is less than or equal to the incentive under the economic instruments discussed previously:*

$$\Delta\pi_I^{01}(\text{abs}) = A - B \text{ for some } B \geq 0.$$

As described in Section 5.1, "properly designed" absolute emission limit means an emission limit of W^0 that corresponds to the other policies at stage 0.

Proof. Intuitively, this is true because firms facing economic instruments can always mimic the behavior of firms facing an absolute emission limit; deviations from this mimicry offer the possibility of higher payoffs.

Mathematically, assume for simplicity that under an absolute emission limit the profit-maximizing choice for the post-innovation firm is to emit the maximum allowable amount of pollution, W^0.[7] The post-innovation firm could choose to emit W^0 units of emissions under a Pigovian tax, too; calling the resulting profits $\pi^1_{W^0}(\text{tax})$ yields

$$\pi^1_{\max}(\text{abs}) = \pi^1_{W^0}(\text{tax}) + p^0_W W^0. \tag{5.8}$$

Next: the policies are "properly designed" at stage 0, so

$$\pi^0_{\max}(\text{abs}) = \pi^0_{\max}(\text{tax}) + p^0_W W^0. \tag{5.9}$$

Subtracting the second equation from the first produces

$$\begin{aligned} \pi^1_{\max}(\text{abs}) - \pi^0_{\max}(\text{abs}) &= \pi^1_{W^0}(\text{tax}) - \pi^0_{\max}(\text{tax}) && (5.10) \\ &\leq \pi^1_{\max}(\text{tax}) - \pi^0_{\max}(\text{tax}), && (5.11) \end{aligned}$$

i.e., $\Delta\pi^{01}_I(\text{abs}) \leq \Delta\pi^{01}_I(\text{tax})$. The crucial inequality here arises tautologically: $\pi^1_{\max}(\text{tax})$ is by definition the maximum profit under a Pigovian tax.

5.2.1 Summary

The results are shown in Table 5.1. Note that absolute emission limits never provide a greater incentive than economic instruments, and in fact provide an equal incentive if and only if $B = 0$. Proposition 4 shows that $B = 0$ if and only if $\pi^1_{W^0}(\text{tax}) = \pi^1_{\max}(\text{tax})$, i.e., if and only if the innovation doesn't change the firm's optimal level of pollution under a Pigovian tax. The relative rankings assume that the inequality $B \geq 0$ is a strict inequality.

5.3 Diffusion in the Absence of Patents

This section examines the diffusion of an innovation across an entire industry. It is assumed that patents are not available, so that the innovation becomes a public good that is adopted

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[7] The same result can be reached without this assumption via a similar but notationally cumbersome proof.

Table 5.1: The gains from innovation. For clarity, the relative ranking assumes that the inequality constraint $B \geq 0$ is a strict inequality.

	Abs	Subsidy	Free permits	Auctioned permits	Tax
$\Delta\pi_I^{01}$	$A - B$	A	A	A	A
Rank	5	1	1	1	1

by all of the firms in the industry. Although the innovation may change industry-wide variables relating to emissions (e.g., the market-clearing price for pollution permits), the analysis follows Milliman and Prince in assuming that other industry-wide variables (e.g., output price) are unaffected. The results are given in the next three results.

Proposition 5 *In the absence of patents, the innovating firm is unaffected by diffusion under taxes, subsidies, or absolute emission limits. Under these policies, non-innovating firms make a gain from diffusion equal to the innovating firm's gain from innovation:* $A - B$ *under absolute emission limits,* A *under taxes or subsidies.*

Proof. Diffusion occurs prior to agency response, so tax rates, subsidy rates, and absolute emission limits are unaffected by diffusion; in the absence of patents, it follows that the innovating firm is not affected by diffusion under taxes, subsidies, or absolute emission limits, i.e., $\Delta\pi_I^{12} = 0$. Its profit differentials $\Delta\pi^{02}$ under these policies are therefore A, A, and $A - B$, respectively. Proposition 2 can now be applied to assert that the same profit differentials $\Delta\pi^{02}$ accrue to non-innovating firms. Since the gain from innovation for non-innovating firms is zero ($\Delta\pi_N^{01} = 0$), it follows that $\Delta\pi_N^{12} = \Delta\pi_I^{01}$ under taxes, subsidies, or absolute emission limits.

Proposition 6 *Under grandfathered permits, the non-innovating firm's gain from diffusion in the absence of patents is* $A - B$*. It follows that the innovating firm suffers a loss of* B *from diffusion.*

Proof At stages 0 and 2 all the firms are identical, so there will be no permit trades. If each firm receives W^0 permits, this situation is identical to an absolute emission limit of

W^0. So tradable permits and absolute emission limits are equivalent policies at stages 0 and 2, meaning that $\Delta\pi^{02}(\text{gra}) = \Delta\pi^{02}(\text{abs})$, which the previous proposition showed to be equal to $A - B$. Since the non-innovating firms make no gain from innovation, they must gain $A - B$ from diffusion. Propositions 2 and 3 can now be used to back out the impact of diffusion on the innovating firm: innovation produces a gain of $\Delta\pi_I^{01} = A$, and innovation plus diffusion produces a gain of $\Delta\pi^{02} = A - B$, so diffusion must yield $\Delta\pi_I^{12} = -B$.[8]

Proposition 7 *Under auctioned permits, the non-innovating firm's gain from diffusion in the absence of patents is $A - B \pm C$ for some $C \geq 0$. It follows that the innovating firm's gain from diffusion is $-B \pm C$.*

Proof If p_W^2 is the market price of permits at stage 2, profits under grandfathered and auctioned permits at stage 2 are related by

$$\pi_{\max}^2(\text{auc}) = \pi_{\max}^2(\text{gra}) - p_W^2 W^0. \tag{5.12}$$

Similarly,

$$\pi_{\max}^0(\text{auc}) = \pi_{\max}^0(\text{gra}) - p_W^0 W^0. \tag{5.13}$$

Subtracting the second equation from the first yields

$$\begin{aligned}
\Delta\pi^{02}(\text{auc}) &= \Delta\pi^{02}(\text{gra}) + (p_W^0 - p_W^2)W^0 && (5.14)\\
&= A - B \pm \left| p_W^0 - p_W^2 \right| W^0 && (5.15)\\
&\overset{\text{call}}{=} A - B \pm C. && (5.16)
\end{aligned}$$

Since the non-innovating firms make no gain from innovation, this must be their gain from diffusion. The innovating firm has a gain of A from innovation, so Proposition 2 can be used to back out $-B \pm C$ as its gain from diffusion.

5.3.1 Summary

Table 5.2 summarizes these results. The table lists the innovation results $\Delta\pi_I^{01}$ from Table 5.1, and then lists (for two different cases) the innovator's gains from diffusion ($\Delta\pi_I^{12}$)

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[8] The intuition behind this result is discussed in Section 5.7.

and from the combined effect of innovation plus diffusion ($\Delta\pi^{02}$). Since non-innovating firms are unaffected by innovation, their gain from diffusion is $\Delta\pi_N^{12} = \Delta\pi^{02}$.

The two cases concern the impact of diffusion on the market price (or shadow price) of permits. If, under grandfathered or auctioned permits, the permit price falls ($p_W^2 < p_W^0$), the results are shown in the middle rows of Table 5.2; intuitively, this can be thought of as the case in which the innovation *decreases* demand for pollution. If the permit price rises ($p_W^2 > p_W^0$), the results are shown in the bottom rows of Table 5.2; intuitively, this can be thought of as the case in which the innovation *increases* demand for pollution.[9]

The relative rankings (which assume strict inequalities) are established in the following proposition.

Proposition 8 *Auctioned permits provide either the maximum or the minimum incentive for innovation plus diffusion in the absence of patents.*

Proof. Since the various policies are "properly designed" at stage 0, profits under taxes and auctioned permits are equal at stage 0:

$$\pi_{\max}^0(\text{auc}) = \pi_{\max}^0(\text{tax}). \tag{5.17}$$

At stage 2, however, the price of auctioned permits diverges from the Pigovian tax rate. If the permit price goes down ($p_W^2 < p_W^0$), Equation 5.4 confirms what intuition suggests: firm profits are higher under auctioned permits than under Pigovian taxes:

$$\pi_{\max}^2(\text{auc}) > \pi_{\max}^2(\text{tax}). \tag{5.18}$$

Subtracting the first equation from the second yields $\Delta\pi^{02}(\text{auc}) > \Delta\pi^{02}(\text{tax})$, i.e., $A - B + C > A$. The conclusion is that auctioned permits provide the greatest incentive if diffusion reduces the permit price.

On the other hand, if the permit price goes up ($p_W^2 > p_W^0$) then the gain under auctioned permits is $A - B - C$, which is lower than $A - B$ or A.

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[9] If the permit price stays the same, all the policies are equal because $B = C = 0$. Intuitively, this corresponds to the case in which the innovation produces no change in the demand for pollution.

Table 5.2: The gains from innovation, diffusion, and innovation plus diffusion in the absence of patents. For clarity, the relative ranking assumes that all inequality constraints are strict inequalities.

	Abs	Subsidy	Free permits	Auctioned permits	Tax
$\Delta\pi_I^{01}$	$A - B$	A	A	A	A
Rank	5	1	1	1	1
$p_W^2 < p_W^0$ ("Decreased demand" for emissions)					
$\Delta\pi_I^{12}$	0	0	$-B$	$-B + C$	0
Rank	2	2	5	1	2
$\Delta\pi^{02}$	$A - B$	A	$A - B$	$A - B + C$	A
Rank	4	2	4	1	2
$p_W^2 > p_W^0$ ("Increased demand" for emissions)					
$\Delta\pi_I^{12}$	0	0	$-B$	$-B - C$	0
Rank	1	1	4	5	1
$\Delta\pi^{02}$	$A - B$	A	$A - B$	$A - B - C$	A
Rank	3	1	3	5	1

5.4 Diffusion with Patented Discoveries

So far we have assumed that innovations could not be patented and that the innovating entity was the firm. This section examines two cases of patented discoveries. The first concerns an invention that is patented by a firm outside the industry. (Note that in this case the innovation stage simply does not exist: the outside firm profits by diffusing its technology across the industry.) The second concerns an invention that is patented by a firm inside the industry. (In this case the benefits from the innovation stage are unchanged by the existence of patents.)

In both cases, the goal of this section is to extend Milliman and Prince's analysis to include the more general types of innovation discussed earlier in this chapter. As such, we follow Milliman and Prince in assuming that the patents allow the patenting firm to capture a fraction z, $0 \leq z \leq 1$, of the benefits that accrue to other firms. If $z = 0$ patents are worthless and all the benefits of diffusion accrue to the non-innovating firms; the results here are identical to those in the previous section (on diffusion in the absence of patents). If $z = 1$ patents are all-powerful and all the benefits of diffusion accrue to the innovating firm. And if $0 < z < 1$ then patents allow the innovating firm to gain some but not all of the gains from diffusion.[10]

5.4.1 Patenting by a Firm outside the Industry

Since there are N firms in the industry, it follows that the outside firm's gain from diffusion will be $z \cdot N$ times the per-firm gain from diffusion ($\Delta\pi^{02}$ in Table 5.2 on page 45). The results and relative rankings are listed in Table 5.3. Comparing Table 5.3 with Table 5.2, the relative rankings of the various policy instruments are identical. Note also that the relative rankings are identical for the non-innovating firms: their gains from diffusion under each policy are simply reduced by the fraction $(1 - z)$ in the presence of patents.

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[10] Chapter 2 contains information on other approaches to modelling gains from patents.

Table 5.3: The gains from innovation, diffusion, and innovation plus diffusion for a discovery patented by a firm outside the industry. For clarity, the relative ranking assumes that all inequality constraints are strict inequalities.

	Abs	Subsidy	Free permits	Auctioned permits	Tax
$p_W^2 < p_W^0$ ("Decreased demand" for emissions)					
$\Delta\pi^{02}$	$zN(A-B)$	$zN(A)$	$zN(A-B)$	$zN(A-B+C)$	$zN(A)$
Rank	4	2	4	1	2
$p_W^2 > p_W^0$ ("Increased demand" for emissions)					
$\Delta\pi^{02}$	$zN(A-B)$	$zN(A)$	$zN(A-B)$	$zN(A-B-C)$	$zN(A)$
Rank	3	1	3	5	1

5.4.2 Patenting by a Firm inside the Industry

Since there are $N-1$ non-innovating firms, we will let $z^* = z(N-1)$. It follows that the innovating firm's gain from diffusion will be the sum of its own gain from diffusion ($\Delta\pi_I^{12}$ in Table 5.2 on page 45) and its portion of the gains from diffusion accruing to the other firms in the industry ($z^* \cdot \Delta\pi^{02}$, where $\Delta\pi^{02}$ comes from that same table). The results and relative rankings are listed in Table 5.4.

As expected, the availability of patents increases the gain from diffusion for the innovating firm. Comparing Table 5.4 with Table 5.2, the relative rankings of the various policy instruments are almost identical.[11]

5.5 Optimal Agency Response in the Absence of Patents

This section examines optimal agency response in the absence of patents and then consider all three steps—innovation, diffusion, and optimal agency response—together. Since firms

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[11] The only difference is the poorer performance of absolute emission limits in terms of $\Delta\pi_I^{12}$, the innovating firm's gain from diffusion. The intuition here is that the patent is less valuable under absolute emission limits, so the innovating firm receives a smaller royalty.

Table 5.4: The gains from innovation, diffusion, and innovation plus diffusion for a discovery patented by a firm inside the industry. For clarity, the relative ranking assumes that all inequality constraints are strict inequalities.

	Abs	Subsidy	Free permits	Auctioned permits	Tax
$\Delta\pi_I^{01}$	$A - B$	A	A	A	A
Rank	5	1	1	1	1
$p_W^2 < p_W^0$ (“Decreased demand” for emissions)					
$\Delta\pi_I^{12}$	$z^*(A - B)$	$z^*(A)$	$z^*(A - B)$ $-B$	$z^*(A - B + C)$ $-B + C$	$z^*(A)$
Rank	4	2	5	1	2
$\Delta\pi_I^{02}$	$(z^* + 1) \cdot$ $(A - B)$	$(z^* + 1) \cdot$ (A)	$(z^* + 1) \cdot$ $(A - B)$	$(z^* + 1) \cdot$ $(A - B + C)$	$(z^* + 1) \cdot$ (A)
Rank	4	2	4	1	2
$p_W^2 > p_W^0$ (“Increased demand” for emissions)					
$\Delta\pi_I^{12}$	$z^*(A - B)$	$z^*(A)$	$z^*(A - B)$ $-B$	$z^*(A - B - C)$ $-B - C$	$z^*(A)$
Rank	3	1	4	5	1
$\Delta\pi_I^{02}$	$(z^* + 1) \cdot$ $(A - B)$	$(z^* + 1) \cdot$ (A)	$(z^* + 1) \cdot$ $(A - B)$	$(z^* + 1) \cdot$ $(A - B - C)$	$(z^* + 1) \cdot$ (A)
Rank	3	1	3	5	1

can lobby in favor of or in opposition to agency response, our focus will be on whether firms gain or lose from agency response.

Following Milliman and Prince, the agency's response is allowed to change industry-wide variables relating to emissions (e.g., the market-clearing price for pollution permits), but it is assumed that other industry-wide variables (e.g., output price) are unaffected. It is also assumed that the benchmark for pollution subsidies—the emissions level below which emissions reductions are subsidized—remains unchanged, and is high enough that all emissions reductions are subsidized. Finally, again following Milliman and Prince, it is assumed that entry and exit are not allowed.

As Section 5.3 suggests, the results will depend on the impact of innovation and diffusion on the "demand" for pollution, i.e., on the market price (or shadow price) of permits. The next two subsections below address these two cases.[12] Both of them make use of the following result.

Proposition 9 *In the absence of patents, the combined effect $\Delta\pi^{03}$ of innovation, diffusion, and optimal agency response under absolute emission limits must be equal to that under free permits, and the combined effect under Pigovian taxes must be equal to that under auctioned permits.*

Proof In the absence of patents, all firms are identical at stages 0 and 3, so there are no permit trades. Since the regulator is behaving optimally at both stages under the various policies, the number of free permits it issues at either stage must be equal to the absolute emission limit, and the price and quantity of auctioned permits must be equal to the results under taxes.

5.5.1 Reduced Demand for Pollution Control

First assume that innovation and diffusion reduce the demand for pollution control, meaning that the intersection of the marginal environmental damage curve and the marginal emissions benefit curve occurs at a lower price. Figure 5.2 shows an example, with MEB^0

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[12] As discussed in footnote 9, all policies are identical if the demand for pollution is unchanged by innovation and diffusion.

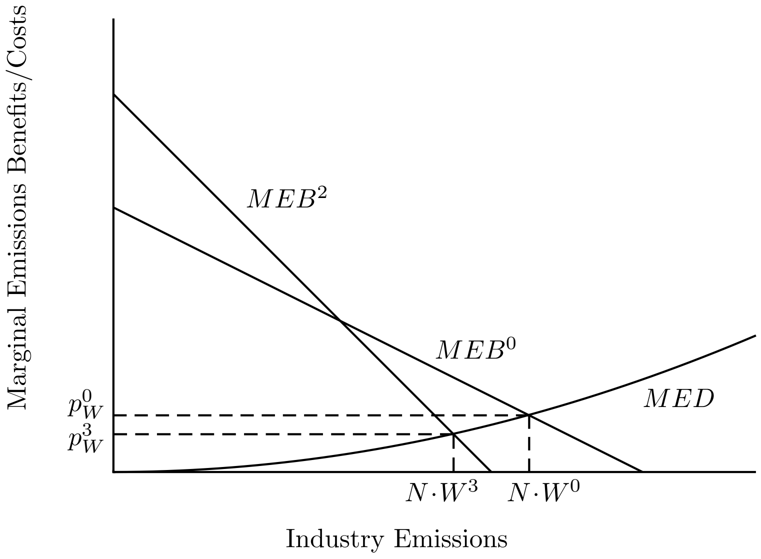

Figure 5.2: An innovation that *decreases* demand for pollution at the margin. The curves represent marginal environmental damages and marginal emissions benefits at stages 0 (before innovation) and 2 (after diffusion).

and MEB^2 representing industry-level marginal emissions benefits with the old and new technologies, respectively, and MED representing marginal environmental damage.[13] The social optimum with the old technology features emissions of W^0 per firm (and so $N \cdot W^0$ for the entire industry) and a shadow price for emissions of p_W^0. The social optimum with the new technology features emissions of $W^3 < W^0$ per firm and a shadow price for emissions of $p_W^3 < p_W^0$.

Accordingly, the optimal agency response is to tighten the absolute emission limit, reduce the number of permits issued or auctioned, or lower the rate for emissions taxes or subsidies. These adjustments will harm the firms in the industry under all policies except emissions taxes. If $-D < 0, -E < 0$, and $F > 0$ are the impacts of agency response under

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[13] This innovation can be thought of as a technology that allows the firm to substitute low-sulphur coal for high-sulphur coal, thereby “front-loading” the benefits of emissions onto the initial units of emissions. Similar shifts would occur in the demand for gasoline in the case of a consumer who switches to a car with high gas mileage, or in the demand for electricity in the case of a consumer who switches to compact flourescent lights.

Table 5.5: The gains from innovation, diffusion, optimal agency response, and combinations of the three, assuming that diffusion *decreases* demand for pollution and that there are no patents. For clarity, the relative ranking assumes that all inequality constraints are strict inequalities.

	Abs	Subsidy	Free permits	Auctioned permits	Tax
$\Delta\pi_I^{01}$	$A-B$	A	A	A	A
Rank	5	1	1	1	1
$\Delta\pi_I^{12}$	0	0	$-B$	$-B+C$	0
Rank	2	2	5	1	2
$\Delta\pi^{02}$	$A-B$	A	$A-B$	$A-B+C$	A
Rank	4	2	4	1	2
$\Delta\pi^{23}$	$-D$	$-E$	$-D$	$B-C+F$	F
Rank	2–5	2–5	2–5	2–5	1
Lobby	Oppose	Oppose	Oppose	Oppose	Favor
$\Delta\pi^{03}$	$A-B-D$	$A-E$	$A-B-D$	$A+F$	$A+F$
Rank	3–5	3–5	3–5	1	1

absolute emission limits, subsidies, and taxes, respectively, then the previous proposition (Proposition 9) yields all of the results in Table 5.5 (on page 51). Section 5.7 discusses the ambiguity concerning the relative ranking of subsidies and absolute emission limits/free permits.

5.5.2 Increased Demand for Pollution Control

Now assume that innovation and diffusion increase the demand for emissions, meaning that the intersection of the marginal environmental damage curve and the marginal emissions benefit curve occurs at a higher price. An example is shown in Figure 5.3.

The optimal agency response in this case is to loosen the absolute emission limit, increase the number of permits issued or auctioned, or increase the rate for emissions taxes or subsidies. These adjustments will benefit the firms in the industry under all policies except

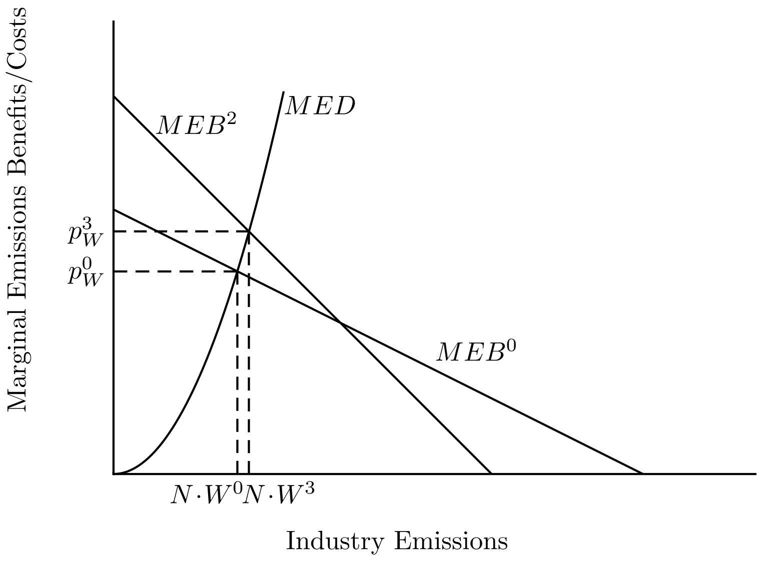

Figure 5.3: An innovation that *increases* demand for pollution at the margin. The curves represent marginal environmental damages and marginal emissions benefits at stages 0 (before innovation) and 2 (after diffusion).

emissions taxes. If $D > 0, E > 0$, and $-F < 0$ are the impacts on each firm of agency response under absolute emission limits, subsidies, and taxes, respectively, then Proposition 9 yields all of the results in Table 5.6 (on page 53) except the following:

Proposition 10 *In the absence of patents, auctioned permits and taxes provide the weakest incentive for innovation, diffusion, and optimal agency response.*

Proof. Auctioned permits are clearly inferior to subsidies because $A - F < A + E$ for $E > 0$ and $F > 0$. Proposition 9 now shows that the desired result will follow if it can be shown that auctioned permits (which are equivalent to taxes) are inferior to grandfathered permits (which are equivalent to absolute emission limits). Intuitively, this makes sense because auctioned permits impose an additional cost on firms, namely, the higher price of permits. Mathematically,

$$\pi^3_{\max}(\text{gra}) = \pi^3_{\max}(\text{auc}) + p^3_W W^3 \tag{5.19}$$

$$\pi^0_{\max}(\text{gra}) = \pi^0_{\max}(\text{auc}) + p^0_W W^0. \tag{5.20}$$

Table 5.6: The gains from innovation, diffusion, optimal agency response, and combinations of the three, assuming that diffusion *increases* demand for pollution and that there are no patents. For clarity, the relative ranking assumes that all inequality constraints are strict inequalities.

	Abs	Subsidy	Free permits	Auctioned permits	Tax
$\Delta\pi_I^{01}$	$A-B$	A	A	A	A
Rank	5	1	1	1	1
$\Delta\pi_I^{12}$	0	0	$-B$	$-B-C$	0
Rank	1	1	4	5	1
$\Delta\pi^{02}$	$A-B$	A	$A-B$	$A-B-C$	A
Rank	3	1	3	5	1
$\Delta\pi^{23}$	$+D$	$+E$	$+D$	$B+C-F$	$-F$
Rank	1–4	1–4	1–4	1–4	5
Lobby	Favor	Favor	Favor	Favor	Oppose
$\Delta\pi^{03}$	$A-B+D$	$A+E$	$A-B+D$	$A-F$	$A-F$
Rank	1–3	1–3	1–3	4	4

Subtracting the second equation from the first and rearranging yields

$$\Delta\pi^{03}(\text{gra}) - \Delta\pi^{03}(\text{auc}) = p_W^3 W^3 - p_W^0 W^0. \tag{5.21}$$

The right hand side here is positive since $p_W^3 > p_W^0$ and $W^3 > W^0$. The conclusion is that auctioned permits provide the weakest incentive.

5.6 Optimal Agency Response with Patented Discoveries

As in Section 5.4, we assume that the patenting firm captures a fraction z, $0 \leq z \leq 1$, of the benefits that accrue to other firms. As in that section, we consider patenting by an outside firm as well as by a firm inside the industry.

The results, summarized in Table 5.7, depend on whether the innovation increases or decreases the demand for emissions (or, equivalently, for pollution control). In each case, the first row of the table, copied from the previous section, indicates the lobbying stance of firms in the absence of patents. The second row indicates the lobbying stance of an outside firm that patents a discovery, and the final row the lobbying stance of an inside firm that patents a discovery.

For patents by an outside firm, the results are as follows. If the discovery decreases demand for emissions, the optimal agency response is to tighten the absolute emission limit, reduce the number of permits issued or auctioned, or lower the rate for emissions taxes or subsidies. The first three of these actions will increase the value of the patented discovery; the last two will decrease the value of the patented discovery. If the discovery increases demand for emissions, the optimal agency response is to loosen the absolute emission limit, increase the number of permits issued or auctioned, or increase the rate for emissions taxes or subsidies. The first three of these actions will decrease the value of the patented discovery; the last two will increase the value of the patented discovery.

For patents by a firm inside the industry, the impact of agency response will be two-fold. In addition to the impact on the firm's profits from production, there will be an indirect impact on the firm's profits from royalties. This produces two extreme cases. If $z = 0$, patents have no value and the results will be identical to those in Section 5.5 (and in the first rows of Table 5.7). The other extreme case occurs when z and N are such that $z \cdot N$ is so large that the royalty effect dominates the production effect; here the results will be similar to those identified in the previous subsection (and shown in the second rows of Table 5.7) for patenting by a firm outside the industry. The results are indeterminate except when the two effects point in the same direction.

5.7 Conclusion

The first order of business is to compare the results above with those of Milliman and Prince. It is difficult to compare the quantitative results because of the different approaches (algebraic versus geometric).[14] *Qualitatively*, however, this chapter's results (e.g., in terms of

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[14] The two approaches should yield identical quantitative results as long as the innovation is limited to end-of-pipe abatement technologies and results in an everywhere-lower marginal abatement cost curve.

Table 5.7: Firm attitudes toward agency response with and without patents

	Abs	Subsidy	Free permits	Auctioned permits	Tax
$p_W^2 < p_W^0$ ("Decreased demand" for emissions)					
No patents	Oppose	Oppose	Oppose	Oppose	Favor
Patent by outside firm	Favor	Oppose	Favor	Favor	Oppose
Patent by inside firm	Uncertain	Oppose	Uncertain	Uncertain	Uncertain
$p_W^2 > p_W^0$ ("Increased demand" for emissions)					
No patents	Favor	Favor	Favor	Favor	Oppose
Patent by outside firm	Oppose	Favor	Oppose	Oppose	Favor
Patent by inside firm	Uncertain	Favor	Uncertain	Uncertain	Uncertain

relative rankings) for the innovation stage (i.e., $\Delta\pi_I^{01}$) agree exactly with those in Milliman and Prince, and the results for diffusion and optimal agency response are in agreement in cases where the innovation *lowers* the demand for emissions at the margin. This is a significant extension of Milliman and Prince's results to other types of innovation.

Where this chapter's results for diffusion and optimal agency response differ from those in Milliman and Prince are cases where the innovation *increases* the demand for emissions at the margin. Here the analysis above comes to almost the reverse of Milliman and Prince's conclusion. For example, Table 5.6 shows that taxes and auctioned permits provide the weakest incentive for the entire process of technological change.[15]

These results therefore muddy the waters concerning the impact of environmental policies on firm incentives for technological change. Loosening the model's restrictive assumptions—e.g., allowing for changes in input or output prices—would likely complicate matters even further. There are, however, a few bright spots.

First, the analysis in this chapter suggests that the study of "environmental" innovations can be integrated more closely with the study of innovations more generally. This might be a promising area for future research, especially when the topic under consideration is *socially optimal* incentives rather than simply *maximal* incentives. Social welfare gains can come from both "environmental" and "non-environmental" innovations, suggesting that a socially optimal incentive structure must balance the rewards for these different types of innovation.

Second, this chapter highlights the role of marginal environmental damages in ranking environmental policies. For example, consider an innovation that "front-loads" the benefits of emissions onto the initial units of emissions, such as the use of low-sulphur coal instead of high-sulphur coal or compact flourescent lights instead of incandescent. Such an innovation is pictured in Figures 5.2 and 5.3, both of which show the same shift in the industry marginal emissions benefit curve. But taxes and auctioned permits provide the strongest incentive for technological change in Figure 5.2 and the weakest incentive in Figure 5.3. The difference is the location of the marginal environmental damage curve: MED is relatively low in

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[15] Milliman and Prince suggest such a result in their sixth comment, on page 259.

Figure 5.2 and relatively high in Figure 5.3. This suggests that, in the case of "front-loading" innovations, taxes and auctioned permits are good instruments for providing incentives if and only if marginal emissions damages are relatively small.

Third, the above analysis underscores the importance of the baseline $\overline{W}$ in determining the incentive effects of Pigovian subsidies. As shown in Tables 5.5 and 5.6, subsidies cannot be definitively ranked above or below absolute emission limits (or free permits) in terms of the entire process of technological change. Intuitively, this relative ranking should depend on the size of the baseline, a result captured in

Proposition 11 *If the subsidy baseline $\overline{W}$ is relatively large compared to a firm's optimal choice of emissions, subsidies will provide a lower incentive than absolute emission limits if $p^3_W < p^0_W$ and a higher incentive if $p^3_W > p^0_W$. The reverse is true if the baseline is relative small.*

Proof. Absolute emission limits and subsidies are related by

$$\begin{aligned} \pi^3_{\max}(\text{abs}) &= \pi^3_{\max}(\text{sub}) - p^3_W(\overline{W} - W^3) & (5.22) \\ \pi^0_{\max}(\text{abs}) &= \pi^0_{\max}(\text{sub}) - p^0_W(\overline{W} - W^0) & (5.23) \end{aligned}$$

Subtracting the second equation from the first and rearranging yields

$$\Delta\pi^{03}(\text{abs}) - \Delta\pi^{03}(\text{sub}) = p^3_W W^3 - p^0_W W^0 + (p^0_W - p^3_W)\overline{W}. \tag{5.24}$$

If the benchmark $\overline{W}$ is very large, the subsidy payment term $(p^0_W - p^3_W)\overline{W}$ will dominate the right hand side. If the subsidy rate decreases ($p^3_W < p^0_W$), subsidies will provide less of an incentive than an absolute emission limit; Table 5.2 shows that subsidies will then provide the weakest incentive of all the instruments. If the subsidy rate increases ($p^3_W > p^0_W$), subsidies will provide more of an incentive than absolute emission limits; Table 5.3 shows that subsidies will then provide an intermediate level of incentives (greater than absolute emission limits, less than taxes).

The reverse is true if the subsidy baseline is small. For example, if the innovation reduces demand for pollution and $\overline{W} = W^0 = \max\{W^0, W^3\}$ then Equation 5.24 simplifies to

$$\Delta\pi^{03}(\text{abs}) - \Delta\pi^{03}(\text{sub}) = p^3_W(W^3 - W^0) < 0, \tag{5.25}$$

showing that in this case subsidies provide a stronger incentive than an absolute emission limit. If the innovation increases demand for pollution and $\overline{W} = W^3 = \max\{W^0, W^3\}$ then Equation 5.24 simplifies to

$$\Delta\pi^{03}(\text{abs}) - \Delta\pi^{03}(\text{sub}) = p_W^0(\overline{W} - W^0) > 0, \tag{5.26}$$

showing that in this case subsidies provide a weaker incentive than an absolute emission limit.

A fourth result is the consistently poor performance of free permits in terms of diffusion. Free permits always provide either the lowest or the second-lowest incentive for diffusion ($\Delta\pi_I^{12} = -B$). To see the intuition behind the unambiguous loss for the innovating firm, recall that at stage 2 (after diffusion) all of the firms will be the same, so there will not be any trades and the innovating firm will simply use its alloted permits to earn profits of, say, $\hat{\pi}$. At stage 1 (after innovation but before diffusion), the innovating firm could also choose to not make any trades, and if it did so it would earn profits of $\hat{\pi}$. Any trades that the innovating firm makes at stage 1, then, must raise its profits above $\hat{\pi}$. Diffusion eliminates those trading opportunities, and therefore hurts the firm regardless of whether the innovating firm is a net buyer of permits or a net seller of permits at stage 1.

A fifth result concerns the superiority of economic instruments (taxes, subsidies, permits) over absolute emission limits in terms of innovation ($\Delta\pi_I^{01}$). The analysis above shows that economic instruments never provide weaker incentives for innovation, and provide strictly stronger incentives as long as innovation reduces the firm's optimal level of emissions. This result holds for all kinds of innovation: end-of-pipe innovations, production process innovations such as those championed by Porter and van der Linde [34], even "non-environmental" innovations that nonetheless affect emissions levels.

As a final comment, it is important to emphasize the restrictive assumptions—in particular, the *ceteris paribus* assumption—that underlie the model in this chapter (and the model in Milliman and Prince). These restrictive assumptions make it unwise to draw policy conclusions from this analysis.

Chapter 6

A CLOSER LOOK AT DYNAMICS

The analysis in the previous chapter, like the analysis of Milliman and Prince, is open to criticism because of its treatment of dynamics. As noted on page 38, the model is fundamentally atemporal. The various stages of technological change in the analysis so far are best thought of not as points in time but as different "worlds" or scenarios: $\Delta\pi_I^{01}$ measures the change in innovator profits between the "before innovation" scenario and the "after innovation" scenario; $\Delta\pi_I^{12}$ measures the change in innovator profits between "innovation only" and "innovation plus diffusion"; and $\Delta\pi_I^{02}$ measures the change in profits between the baseline and "innovation plus diffusion."

The atemporal nature of the model is only one way in which its treatment of dynamics is lacking. Other problems stem from the model's focus on partial equilibrium rather than general equilibrium: there is no entry or exit into the market, and technological change is not allowed to change output price or most other industry-wide variables.

This chapter will address one of these shortcomings by introducing a more realistic time element into the model. The issues of output effects and entry/exit, however, are left for future research; while the other issues can be incorporated into the existing model, addressing output effects or entry/exit requires the development of an entirely new approach.

The difficulty with these issues stems from the fact that output effects are inconsistent with the fundamental premise of the existing model. As described above, the model measures gains from technological change relative to a pre-innovation baseline; in doing so, *a crucial assumption is that that baseline is the same under all the different policies.* In other words, all relevant variables—including input prices, output prices, and the number of firms in the industry—are assumed to be the same.

This *ceteris paribus* methodology has both positives and negatives. The good news is that holding everything else constant focuses attention on the differences between the various policy instruments. The bad news is that everything else is in fact not constant; taxes and subsidies, for example, will result in radically difference output prices and industry size.

In brief, then, the situation is that (1) the existing approach begins by assuming away output effects and entry/exit, which (2) renders it incapable of incorporating these issues later in the model, meaning that (3) a new approach will be needed if output effects or entry/exit are to be accounted for. Developing such a new approach is beyond the scope of this dissertation. What is not beyond the scope of this dissertation is extending the existing model to include time.

6.1 Time

This section develops a continuous-time model that incorporates temporal issues into the previous chapter's analysis. Assume that innovation, diffusion, and optimal agency response occur at times $t_0 = 0, t_1$, and t_2, respectively. Further assume that interest is compounded continuously, with r being the per-period (e.g., per-year) discount rate. Finally, assume that the present value of R&D costs (which are incurred prior to time t_0) are $R \geq 0$.[1]

Adapting the analysis in the previous chapter for use in a temporal model, assume that profits (excluding R&D costs) are zero prior to innovation.Let $\Delta\pi^{01}$ be the *per period* profit differential post-innovation but pre-diffusion. Since this differential exists for the time between $t_0 = 0$ and t_1, the present value of this profit differential is

$$\int_0^{t_1} \Delta\pi^{01} e^{-rt} dt = \frac{\Delta\pi^{01}}{r}\left(e^{-r\cdot 0} - e^{-rt_1}\right) = \frac{\Delta\pi^{01}}{r}\left(1 - e^{-rt_1}\right).$$

Similarly, the present value of the extra profits between diffusion and agency response ($\Delta\pi^{02}$ per period) is

$$\int_{t_1}^{t_2} \Delta\pi^{02} e^{-rt} dt = \frac{\Delta\pi^{02}}{r}\left(e^{-rt_1} - e^{-rt_2}\right).$$

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[1] Unlike in the previous chapter, this chapter takes an approach that is robust enough to allow for positive R&D costs. Since there is a time lag between the various stages of technological change—and in particular between innovation and diffusion—firms that innovate can come out ahead of firms that simply wait for diffusion. The presence of this first-mover advantage allows the model to incorporate R&D costs. As in the previous chapter, however, the focus on relative performance means that this issue is of little importance in terms of the model's results.

Finally, the present value of extra profits post–agency response ($\Delta\pi^{03}$ per period) is

$$\int_{t_2}^{\infty} \Delta\pi^{03} e^{-rt} dt = \frac{\Delta\pi^{03}}{r} \left(e^{-rt_2} - e^{-r\cdot\infty} \right) = \frac{\Delta\pi^{03}}{r} \left(e^{-rt_2} \right).$$

Note that the post–agency response period lasts indefinitely.

We can now determine the present value of the entire process of technological change by summing up the present values of extra profits in the various stages, yielding

$$-R + \int_0^{t_1} \Delta\pi^{01} e^{-rt} dt + \int_{t_1}^{t_2} \Delta\pi^{02} e^{-rt} dt + \int_{t_2}^{\infty} \Delta\pi^{03} e^{-rt} dt$$

$$= -R + \frac{1}{r} \left[\Delta\pi^{01} \left(1 - e^{-rt_1} \right) + \Delta\pi^{02} \left(e^{-rt_1} - e^{-rt_2} \right) + \Delta\pi^{03} \left(e^{-rt_2} \right) \right]. \tag{6.1}$$

6.1.1 A Re-Examination of Previous Conclusions

We can now combine the above result with the results from Tables 5.5 and 5.6 to see how the inclusion of time into the model affects the relative rankings of the various policies. (For comparison purposes we assume that $R = 0$, i.e., that R&D is costless.)

Overall, a time-sensitive model makes it more difficult to conclusively rank the policies. The only scenario in which one policy necessarily provides stronger incentives than another is when the former is dominant during each of the three time periods. This occurrence is rare with patented discoveries because of the uncertainty surrounding the effects of agency response, but it does occur on a number of occasions in the absence of patents. When diffusion decreases demand for emissions (as in Table 5.5), auctioned permits are the strongest policy, followed by taxes. Also, free permits are stronger than absolute emission limits. When diffusion increases demand for emissions (as in Table 5.6), subsidies are stronger than taxes, which in turn are stronger than auctioned permits. Also, free permits are stronger than either auctioned permits or absolute emission limits. These conclusions are summarized (to the extent possible) in Table 6.1.

Two additional points are worth making. First, as discussed in Section 5.7, the subsidy baseline plays a crucial role in determining the relative rank of subsidies; additional assumptions about this baseline would allow for additional results. Second, the inclusion of time in the model highlights the importance of the order of events. In particular, since innovation is the first stage, it carries the greatest weight, all else equal. The superiority of

Table 6.1: The gains from the entire process of technological change in the absence of patents. The first row shows the results when diffusion *decreases* demand for pollution, the second when diffusion *increases* demand for pollution. All inequality constraints are strict inequalities.

	Abs	Subsidy	Free permits	Auctioned permits	Tax
Decreased	4/5	3/4/5	3/4	1	2
Increased	2/3/4/5	1/2/3	1/2/3	4/5	1/2/3/4

economic instruments over absolute emission limits in terms of innovation therefore carries even more weight in a time-inclusive framework.

Chapter 7

CONCLUSION

This dissertation makes a number of contributions to the theoretical literature on incentives for innovation in pollution control. Chapter 3 highlights the pitfalls of the common assumption that direct controls are equivalent to absolute limits on emissions. The analysis shows that relaxing this assumption can reverse some of conclusions that are often found in the literature, most notably the conclusion that economic instruments always provide greater incentives for innovation than direct controls. This is not an issue of merely academic importance: actual public policies feature a wide variety of direct controls, including limits on emissions per unit output or technology standards that mandate use of, e.g., Best Available Control Technology. This dissertation makes a small step toward extending the theoretical analysis of incentives for innovation in pollution control to include a menu of direct controls that is as varied as the menu of economic instruments.

Chapter 4 highlights limitations in the tradition approach to analyzing innovation in pollution control. It shows that the traditional approach is inappropriate for production process innovations and that the traditional definition of innovation in pollution control—a definition that equates innovation with lower marginal abatement costs—is too narrow to include production process innovations such as fuel switching or energy-efficiency measures.

The problems identified in Chapter 4 are addressed in Chapter 5. This chapter follows the analysis of Milliman and Prince [24], but uses a different analytical approach that encompasses production process innovations as well as innovations in end-of-pipe abatement technology. An important result here is that Milliman and Prince's qualitative conclusions are supported in cases where innovation lowers abatement costs at the margin but are reversed in cases where innovation increases abatement costs at the margin. Chapter 6 attempts to address some of the shortcomings of the model in Chapter 5 by incorporating dynamic aspects, in particular by creating a temporal model and by considering the possibility of entry and exit.

There are a variety of areas that might be fertile ground for future research. For example, the analysis in Chapter 5 does not address the criticisms in Chapter 3 concerning the various types of direct controls; ending the monopoly on direct controls held by absolute limits on emissions would be one way of improving the analysis. Another option would be reconsidering the approach to patents and diffusion used in Milliman and Prince, for example along the lines of Fischer, Parry, and Pizer [8]. A third possibility would be to replicate the analysis in a non-competitive setting.

Deeper issues that provide opportunities for future research are the unrealistic assumptions that underlie the model used in this dissertation. Most notable is the *ceteris paribus* assumption that the context for innovation (the market price, the number of firms in the industry, etc.) is the same under different policies.[1] An alternative approach here might be to assume that the context is the same prior to implementing the various policies, but that the context changes once the policies are in place. It would then be possible to study the impacts of different policies in a general equilibrium setting. Such a treatment would allow for full consideration of issues such as entry and exit and output effects.

Another deep issue here concerns the attractiveness of providing incentives for technological change in pollution control. *Greater* incentives are not always *better* incentives: resources directed toward innovation in pollution control cannot, for example, be used for innovation in other areas. From the perspective of social welfare, then, the relevant issue is not *maximal* incentives but *optimal* incentives. Downing and White [7] is one of the few papers that discusses this issue in any detail, so the opportunity certainly exists for a significant contribution. Any attempt, however, must deal with the second-best nature of this issue resulting from well-known problems concerning innovation in general (and not just innovation in pollution control): spillover effects can result in incentives for innovation that are too low, while patent races can result in incentives for innovation that are too high.

The previous two paragraphs highlight the hazards in deriving policy implications from this dissertation. For example, the theory of environmental economics indicates that Pigo-

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[1] Other unrealistic assumptions are that firms are all identical and that there is no entry and exit. This last issue is related to the *ceteris paribus* assumption.

vian taxes would lead to a higher market price and a smaller number of firms than Pigovian subsidies. The *ceteris paribus* assumption ignores this result—assuming instead that the context for innovation is identical under these and other policies—and therefore leads to some unlikely conclusions, most notably that taxes and subsidies can have identical effects. Basing policy recommendations on these conclusions would be unwise. And, even if the foundations of the analysis were more realistic, sound policy recommendations would require a shift in focus from maximal incentives to optimal incentives.

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