Free-Market Incentives for Innovation: A Closer Look at the Case of Pollution Control

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June 4, 2004

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JEL Codes: Q20, O30

Keywords: Conservation and Pollution; Technological Change and Innovation

*Thanks to Gardner Brown, Robert Halvorsen, and Karl Seeley for helpful comments on this paper. The views expressed herein are solely those of the author.

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Abstract

Dynamic considerations are often advanced as an important reason to prefer free markets to command-and-control policies. This paper takes a closer look at the theoretical support for this claim in the area of pollution control in competitive markets, where market-based instruments such as Pigovian taxes are argued to provide stronger incentives for innovation than direct controls. Counter to established theory, we find that commonly used forms of direct control—such as limits on emissions per unit output—can provide greater incentives for innovation than Pigovian taxes. After providing a numerical example of this result, we identify general conditions under which dynamic considerations do favor market-based instruments for environmental protection.

1 Introduction

William J. Baumol (2002, p. viii) has recently written that "what differentiates the prototype capitalist economy most sharply from all other economic systems is free-market pressures that force firms into a continuing process of innovation. . . The static efficiency properties that are stressed by standard welfare economics are emphatically *not* the most important qualities of capitalist economies."

Baumol's writings echo (and were perhaps influenced by) the work that he and others have done on the economics of pollution control. In that field, assertions of the importance of dynamic considerations and the superiority of market-based instruments over direct controls in providing incentives for innovation have appeared steadily for almost 30 years[1] and are supported by an extensive theoretical literature that examines incentives for innovation in competitive market settings (Zerbe 1970; Wenders 1975; Downing and White 1986; Milliman and Prince 1989; Jung, Krutilla, and Boyd 1996).

Recent developments in the economics of pollution control have focused even more attention on dynamics. Most notably, the debate on the so-called double dividend hypothesis has called into question the "static efficiency properties"

[1] For example, Kneese and Schultze (1975, 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"; Orr (1976, 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"; and Bohm and Russell (1985, 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. . . "

of market-based instruments. These questions are of such a serious nature that Parry and Oates (1998, p. 10) feel the need to assert that they "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.

The intent of this paper is to indicate a need for caution when making such claims in the realm of pollution control in competitive markets (and perhaps in more general competitive market contexts as well). We will show that the dynamic superiority of market-based environmental policies over direct controls is not as clear-cut as the theoretical literature suggests. The difficulty is that previous studies—while examining a variety of market-based instruments (Pigovian taxes, Pigovian subsidies, auctioned or grandfathered permits)—focus almost exclusively on only one type of command-and-control regulation: absolute emissions limits, i.e., limits on total firm emissions.

This focus on absolute emissions limits is puzzling. Direct controls can also rely on other types of *performance standards*—such as limits on emissions per unit output or per unit input—or on *technology standards* such as scrubber requirements. Helfand (1991) and Bohm and Russell (1985, p. 419) indicate that technology standards and limits on emissions per unit input or output are common forms of regulation, and Keohane, Revesz, and Stavins (1998, p. 313n) note that they are more common in practice than absolute emissions limits.[2]

Despite this, most papers in the theoretical literature make no mention of any direct control policies other than absolute emissions limits. One noteworthy exception in the literature on competitive markets is Parry (1998), which considers a limit on emissions-per-unit-output combined with an industry-wide cap on total production.[3] It is not entirely clear how this industry-wide cap affects individual firms—it appears from the analysis that each firm essentially faces its own cap—but in any case Parry concludes (in Proposition 5.2) that incentives for innovation are lower under this policy than under Pigovian taxes. Although we do not consider instrument combinations, our paper comes to a different conclusion: limits on emissions-per-unit-output can lead to greater incentives for innovation than Pigovian taxes.

The remainder of this paper re-examines dynamic considerations in competitive markets using a more inclusive view of command-and-control policies. Section 2 identifies conditions under which market-based instruments can (and can not) be shown to provide stronger dynamic incentives in competitive markets. Section 3 discusses the limitations and implications of this result. Section 4

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[2] The real-world effectiveness of absolute emissions limits may be hampered by "smurfing", a term that traditionally refers to efforts by money launderers to break down large cash transactions (which financial institutions are required to report to the U.S. Treasury) into multiple small transactions that are not subject to federal scrutiny. In the context of pollution control, smurfing could be used to circumvent absolute emissions limits, e.g., by making polluting factories smaller or spinning off each factory as its own company.

[3] Montero's (2002) analysis of incentives for innovation in an oligopoly is another exception, one which we discuss below.

provides a numerical example showing that market-based instruments *do not* always provide the strongest incentives for innovation. The conclusion argues that dynamic aspects of pollution control policies (and perhaps economic policies more generally) remain a wide-open field for investigation.

It is important to note that the focus of this paper is on competitive markets. Montero's (2002) analysis of incentives for innovation in an oligopoly finds that standards can provide greater incentives than market-based instruments. These results, however, depend on the strategic interactions between firms, so they do not directly contradict the competitive-market claims discussed above. In contrast, this paper fits exactly into the competitive-market context of many previous analyses (Zerbe 1970; Wenders 1975; Downing and White 1986; Milliman and Prince 1989; Jung, Krutilla, and Boyd 1996).

It is also important to understand some of the subtleties of that competitive-market context. In order to compare the incentives created by different policy instruments, we follow the *ceteris paribus* approach of previous authors: we assume that firm behavior under different policies (say, a tax and a standard) are identical prior to innovation, and then examine the changes in behavior resulting from innovation. Section 3 considers this assumption in more detail.

2 A General Result

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—market-based instruments give firms the freedom to take maximum advantage of innovations.[4] More formally, the argument is that the set of options S_D available to a firm facing direct controls is a proper subset of the set of options S_E available to a firm facing market-based 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 market-based instruments *include but are not limited to* the use of that scrubber; the firm therefore has the flexibility to take advantage of new types of scrubbers or other innovations.

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, we will assume that firm behavior under the two policy regimes is identical prior to innovation. In particular, we assume that the direct controls (abbreviated C&C) lead the firm to emit W^0 units of waste, the same emissions level induced by a Pigovian tax of p_W. Profits under the two policies will therefore differ only by the Pigovian tax

[4] For example, Bohm and Russell (1985, 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] We will show that the results that follow applies equally to other types of market-based instruments. It also applies to a wide variety of direct controls; all we assume about these policies is that they act by imposing constraints on firm behavior rather than by changing the firm's objective function.

payment:

$$\pi^0_{\max}(\text{C\&C}) = \pi^0_{\max}(\text{tax}) + p_W W^0, \tag{1}$$

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 using technology T^0 and facing regulatory policy x.

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

$$\Delta\pi(x) = \pi^1_{\max}(x) - \pi^0_{\max}(x). \tag{2}$$

We will now determine the conditions under which market-based instruments unambiguously provide superior incentives for innovation than direct controls, i.e.,

$$\Delta\pi(\text{C\&C}) \leq \Delta\pi(\text{tax}). \tag{3}$$

The key issue turns out to be the post-innovation firm's behavior under direct controls, and in particular the magnitude of emissions post-innovation (W^1) relative to emission pre-innovation (W^0). If $W^1 \leq W^0$, then incentives for innovation will be higher under Pigovian taxes because the firm facing the Pigovian tax has the option of *mimicry*: it could choose to mimic the behavior of a firm facing direct controls, choosing the same production process and identical amounts of inputs and outputs (including W^1 units of emissions). To see the importance of this option, call the profits from mimicry $\pi^1_{W^1}(\text{tax})$. Then we have

$$\pi^1_{\max}(\text{C\&C}) = \pi^1_{W^1}(\text{tax}) + p_W W^1. \tag{4}$$

Subtracting equation 1 from equation 4 produces

$$\pi^1_{\max}(\text{C\&C}) - \pi^0_{\max}(\text{C\&C}) \quad = \quad \pi^1_{W^1}(\text{tax}) - \pi^0_{\max}(\text{tax})$$

$$
\begin{aligned}
& +p_W(W^1 - W^0) && (5)\\
\leq\ & \pi^1_{W^1}(\text{tax}) - \pi^0_{\max}(\text{tax}) && (6)\\
\leq\ & \pi^1_{\max}(\text{tax}) - \pi^0_{\max}(\text{tax}), && (7)
\end{aligned}
$$

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

Of the two crucial inequalities in this proof, the first arises from our assumption that $W^1 \leq W^0$; we will discuss this more below. The second inequality is tautological: $\pi^1_{\max}(\text{tax})$ is by definition the maximum profit under a Pigovian tax, so it must be at least as good as any of the firm's other options.

It is this second inequality that encompasses the vaunted flexibility of market-based 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 demonstrate the same result for auctioned and grandfathered permits and for Pigovian subsidies. For a general proof, replace the terms $p_W W^0$ in equation 1 and $p_W W^1$ in equation 4 with $p_W(W^0 - c)$ and $p_W(W^1 - c)$, respectively, and note that the proof goes through exactly as before because the constant c cancels when one equation is subtracted from the other. Setting $c = 0$ provides the desired result for Pigovian taxes and for auctioned permits (with market price p_W); setting $c = W^0$ provides the desired result for grandfathered permits (again with market price p_W); and setting $c = \widetilde{W}$ provides the desired result for a Pigovian subsidy paying p_W for each unit of emissions below a baseline of $\widetilde{W}$. (In the case of auctions, note that innovation does not change the market price of emissions because of the competitive market assumption discussed at the end of section 1.) These lead to the following general result.

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

3 Limitations and Implications

Proposition 1 is significantly limited by its assumption that the market-based instrument and the command-and-control instrument yield identical firm behavior prior to innovation. This assumption limits the applicability of the result to the full range of command-and-control instruments. Scrubber requirements, for example, lead to different marginal conditions—and therefore to different firm behavior—than market-based instruments, even in those cases when the market-based instrument leads the firm to adopt the same type of scrubber. Helfand (1991) shows that other types of command-and-control policies also affect input and output choices in ways that are likely to make firm behavior under these instruments incommensurable with their behavior under market-based instruments.

Despite this, Proposition 1 and its proof make three important contributions to the literature. First, the proof explicitly shows the key role that mimicry plays in the argument that market-based instruments provide greater incentives for innovation than command-and-control instruments.

Second, the proposition highlights a previously unidentified hole in that argument: when the innovation leads the firm to increase its emissions under the command-and-control policy (i.e., when $W^1 > W^0$), the argument fails. In such cases, mimicry becomes problematic because market-based instruments impose an additional burden on the firm (namely, the cost of additional emissions) that does not exist under direct controls. The set of *profit options* available to the firm under direct controls is no longer a proper subset of the set of profit options available to the firm under market-based instruments.[6]

Third, the proposition generalizes previous results (e.g., Downing and White (1986)) concerning firm-level incentives for innovation. Although the limitation discussed at the beginning of this section (which applies to previous results as well as our result) shows that this generalization is less than complete, it does make advances on two fronts. One concerns the types of innovation under consideration: Proposition 1 holds for production-process innovations as well as the innovations in end-of-pipe abatement technology that Bauman (2003) shows to be the focus of previous research. The second concerns the types of policy instruments under consideration: although Proposition 1 allows for only brief forays outside of that domain, those brief forays contradict the conventional wisdom about incentives for innovation. We return to this point in the conclusion; first, however, we provide a numerical example showing that incentives for a quintessential pollution control innovation—an improvement in scrubber technology—can be stronger under command-and-control policies than under market-based instruments.

[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 market-based 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.

4 A Numerical Example

Consider a simple model of a coal-burning power plant in a competitive market. 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 we will consider is one which reduces α, e.g., an improvement in scrubber technology. The innovation has fixed R&D costs of R and no marginal costs. Because of the competitive market assumption, the firm's behavior has no impact on the market prices of inputs or outputs.

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 we will compare are Pigovian taxes and a limit on emissions per unit output. 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 our example, we will set $p_G = 4$, $p_W = 1$, $p_K = .8$, and $\alpha = 1.2$. So 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 $\pi = 2$.

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

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

which 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 $\left(\frac{10}{3} - R\right) - (2) \approx 1.33 - R$.

Now consider a limit on emissions per unit output 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 the previously 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.[7]

After the innovation reduces α to .4, profits are

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

and the solution to this constrained maximization problem is $K = 6.25$, $G = 2.5$, $W = 2.5$, $\frac{W}{G} = 1$, and $\pi = 5 - R$.[8] So the firm's gain from the innovation under

[7] This normalization is part of the standard approach, e.g., Milliman and Prince (1989); Malueg (1989) shows that incentive structures can differ if the firm's pre-innovation behavior is different under the two policies.

[8] As Proposition 1 makes clear, a crucial aspect of this example is that the innovation leads to an *increase* in the firm's emissions under the command-and-control policy.

command-and-control is the profit differential $(5 - R) - (3.2) = 1.8 - R$.

Comparing the gain from innovation under direct controls $(1.8 - R)$ with the gain from innovation under Pigovian taxes $(1.33 - R)$, we see that incentives for innovation are higher under the command-and-control policy. In particular, if R is such that $1.33 < R < 1.8$, the firm will pursue the innovation under the command-and-control policy but not under the market-based instrument.

5 Conclusion

The argument presented in this paper would be unexceptional were it not for an unusual set of circumstances that magnify its policy implications. As noted by Jaffe, Newell, and Stavins (2003), there is a dearth of empirical evidence on the incentive effects of different types of policy instruments.[9] A variety of complications—including the counterfactual nature of the topic—suggest that the heavy reliance on theoretical results is likely to continue.

Also likely to continue is the focus on dynamics and incentives for innovation. In part this is because (as the Parry and Oates quote in the introduction shows) the double-dividend debate is calling into question the static efficiency properties that originally dominated the economist's case for market-based instruments. But the topic of incentives for innovation is also a force in its own right.

Together, these observations show that the case for using market-based instruments—an issue that has arguably been *the* policy focus of environmental economics—rests heavily on a rather narrow theoretical foundation. This paper questions the strength of that foundation: the idea that market-based instruments are superior to direct controls in providing firm-level incentives for

[9] Some exceptions include Jaffe and Stavins (1995) and Newell, Jaffe, and Stavins (1999).

innovation in competitive markets is not the bedrock result that it appears to be.

Of course, firm-level results are only the first step in the process of technological change, a process that can also include diffusion of the innovation to other firms in the industry. But aggregation has no effect on the main result of this paper: as in Milliman and Prince (1989), Fischer, Parry, and Pizer (2003), and elsewhere, the industry-level effect of diffusion is simply a multiple of the firm-level effect for direct control policies, Pigovian taxes, and grandfathered permits.[10] Even at the industry level, then, it is possible for direct controls to provide stronger incentives for technological change than market-based instruments.

It is more complicated to include the possibility of regulatory response, e.g., a lowering of the emissions-per-unit-output standard, and this is one possible topic for future research.[11] Our results emphasize, however, that a more important topic for future research is to focus on *optimal* incentives for innovation rather than *maximal* incentives. Resources allocated to pollution control R&D cannot be allocated to other types of R&D, or to increased production of consumption goods; it follows that more is not always better when it comes to incentives for

[10]This is not the case for auctioned permits because of an additional industry-level effect stemming from the effect of diffusion on the equilibrium price for permits.

[11]Such a response seems especially plausible if an increase in per-firm emissions—as was crucial in the numerical example in Section 4—translates into an increase in industry-wide emissions. Industry-wide emissions will definitely increase if demand for the product in question is perfectly elastic, as assumed in much of the literature. If demand is perfectly elastic, however, a decrease in emissions-per-unit-output for one firm will translate into *lower* industry-wide emissions because the number of firms in the industry will shrink.

innovation in pollution control. This paper shows that economic instruments do not always provide "more"; whether or not they provide "better" is an open question.

References

Bauman, Yoram. 2003. "The Effects of Environmental Policy on Technological Change in Pollution Control." Ph.D. diss., University of Washington.

Baumol, William J. 2002. *The Free-Market Innovation Machine: Analyzing the Growth Miracle of Capitalism*. Princeton University Press.

Bohm, Peter, and Clifford S. Russell. 1985. "Comparative Analysis of Alternative Policy Instruments." In *Handbook of Natural Resource and Energy Economics*, edited by Allen V. Kneese and James L. Sweeney, Volume 1. North-Holland.

Downing, Paul B., and Lawrence J. White. 1986. "Innovation in Pollution Control." *Journal of Environmental Economics and Management* 13:18–29.

Fischer, Carolyn, Ian W.H. Parry, and William A. Pizer. 2003. "Instrument Choice for Environmental Protection When Technological Innovation is Endogenous." *Journal of Environmental Economics and Management* 45:523–545.

Helfand, Gloria E. 1991. "Standards versus Standards: The Effects of Different Pollution Restrictions." *American Economic Review* 81:622–634.

Jaffe, Adam B., Richard G. Newell, and Robert N. Stavins. 2003. "Technological Change and the Environment." In *Handbook of Environmental*

Economics, vol 1: *Environmental Degradation and Institutional Responses*, edited by Karl-Goran Mäler and Jeffrey R. Vincent. North-Holland.

Jaffe, Adam B., and Robert N. Stavins. 1995. "Dynamic Incentives of Environmental Regulations: The Effects of Alternative Policy Instruments on Technology Diffusion." *Journal of Environmental Economics and Management* 29:S–43–S–63.

Jung, Chulho, Kerry Krutilla, and Roy Boyd. 1996. "Incentives for Advanced Pollution Abatement Technology at the Industry Level: an Evaluation of Policy Alternatives." *Journal of Environmental Economics and Management* 30:95–111.

Keohane, Nathaniel, Richard Revesz, and Robert Stavins. 1998. "The Choice of Regulatory Instruments in Environmental Policy." *Harvard Environmental Law Review* 22:313–367.

Kneese, Allen V., and Charles L. Schultze. 1975. *Pollution, Prices, and Public Policy.* The Brookings Institution.

Lipsey, R.G., and Kelvin Lancaster. 1956. "The General Theory of the Second Best." *Review of Economic Studies* 24:11–32.

Malueg, David A. 1989. "Emission Credit Trading and the Incentive to Adopt New Pollution Abatement Technology." *Journal of Environmental Economics and Management* 16:52–57.

Milliman, Scott R., and Raymond Prince. 1989. "Firm Incentives to Promote Technological Change in Pollution Control." *Journal of Environmental Economics and Management* 17:247–265.

Montero, Juan-Pablo. 2002. "Permits, Standards, and Technology Innovation." *Journal of Environmental Economics and Management* 44:23–44.

Newell, Richard G., Adam B. Jaffe, and Robert N. Stavins. 1999. "The Induced Innovation Hypothesis and Energy-Saving Technological Change." *Quarterly Journal of Economics* 114:941–975.

Orr, Lloyd. 1976. "Incentive for Innovation as the Basis for Effluent Charge Strategy." *American Economic Review* 66:441–447.

Parry, Ian W.H. 1998. "Pollution Regulation and the Efficiency Gains from Technological Innovation." *Journal of Regulatory Economics* 14:229–254.

Parry, Ian W.H., and Wallace E. Oates. 1998. "Policy Analysis in a Second-Best World." Resources for the Future discussion paper 98-48.

Wenders, John T. 1975. "Methods of Pollution Control and the Rate of Change in Pollution Abatement Technology." *Water Resources Research* 11:393–396.

Zerbe, Richard O. 1970. "Theoretical Efficiency in Pollution Control." *Western Economic Journal* 8:364–376.