Prices, Quantities, and Two-Part Tariffs: Optimal Environmental Policy with Endogenous Technical Change

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Abstract

Theoretical research has failed to uncover simple rules for environmental policy instrument choice when technical change is endogenous. This is somewhat surprising, given the well-known equivalence of price and quantity instruments under conditions of certainty and the simple relative-slopes rule developed by Weitzman (1974) in a model of uncertainty.

This paper seeks to bridge that gap. I consider a simplified version of Weitzman's model to analyze how the prescriptions of that model change when technical change is endogenous. The results depend on the costs of developing new techniques relative to the benefits from society of the innovations. For intermediate values of research costs, the model suggests that a quantity instrument may be strictly preferred to a price instrument, because it reduces the potential for inefficient adoption.

I then turn to optimal regulatory policies, and show that a simple two-part instrument, combining a menu of unit emissions taxes with levies or subsidies on adoption, can simultaneously achieve the efficient levels of adoption and abatement, for any set of techniques available as a result of research and development. Such an instrument could achieve efficient adoption and abatement even when the regulator does not know in advance the set of new techniques that will be available, the costs of research and development, or the probability that research will be successful.

The implications for environmental policy may be surprising. To take the example of energy efficiency, my model suggests that a regulator ought to impose *levies,* rather than subsidies, on more energy-efficient technologies, and offer subsidies for *less* energy-efficient ones.

1 Introduction

Over two decades ago, Allen Kneese and Charles Schultze argued that the extent to which an environmental policy instrument encourages innovation in pollution control technology is, "over the long haul, perhaps the single most important criterion on which to judge environmental policies" (Kneese and Schultze 1978). If anything, their claim has gained credence in the years since. The long time horizons of emerging issues such as global climate change mean that the implications of environmental policy for technological change are likely to take on a relatively more important role in policy debates.

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Despite a substantial amount of attention devoted to the topic, theoretical research has failed to uncover simple rules for policy instrument choice when technical change is endogenous. This is somewhat surprising, given the well-known equivalence of price and quantity instruments under conditions of certainty and the simple relative-slopes rule developed by Weitzman (1974) in a model of uncertainty.

This paper seeks to bridge that gap. I consider a simplified version of Weitzman's model to analyze how the prescriptions of that model change when technical change is endogenous. The model suggests that when the costs of developing a new technique are low relative to the net benefits to society from the use of the technique, the Weitzman model still applies exactly as before, even with endogenous technical change. When costs are high enough so that the potential new technique becomes irrelevant, the model reduces to the certainty case. For intermediate values of research costs, however, the choice of policy instrument matters. In such cases, the model suggests that a quantity instrument may be strictly preferred to a price instrument, because it reduces the potential for inefficient adoption. I offer some conjectures for how these conclusions might extend to a more general setting.

I then propose an instrument that has not been previously discussed in the environmental economics literature, but which is superior to the pure price and quantity instruments usually considered. I show that a simple two-part instrument, combining a menu of unit emissions taxes with levies or subsidies on adoption, can simultaneously achieve the efficient levels of adoption and abatement, for any set of techniques available as a result of research and development. A similar two-part instrument could be constructed using a menu of quantity standards along with adoption levies and subsidies. These instruments achieve efficient adoption and abatement even when the regulator does not know in advance the set of new techniques that will be available, the costs of research and development, or the probability that research will be successful. This two-part tariff closely resembles the monopolistic screening results common in the industrial organization literature on optimal monopoly regulation or public procurement.

The implications for environmental policy are surprising. The optimal two-part tariff imposes a levy on the adoption of lower-marginal-cost techniques, while at the same time compensating the firm with lower taxes. Likewise, the optimal policy involves a subsidy for higher-marginal-cost techniques (along with higher unit taxes). Consider the case of energy efficiency – a policy realm where adoption subsidies for energy-efficient technologies are often proposed. My model suggests that a regulator ought to impose *levies,* rather than subsidies, on more energy-efficient technologies, and offer subsidies for *less* energy-efficient ones. Of course, the levies would be paired with lower emissions taxes, and the subsidies with higher emissions taxes. Nonetheless, the prescription runs strongly counter to the current of the literature on energy efficiency policies, which considers adoption subsidies for energy efficient techniques among the set of possible instruments.

An appropriate starting point for any discussion about technological change is the framework introduced by Schumpeter (1939). He distinguished three phases: invention (in which the creation of a new product or process is conceptualized); innovation (in which the new product or process is brought to market); and diffusion (in which the product or process is adopted by users in an industry or the economy). In this paper, I focus for the most part on the third step – more specifically, on the individual adoption decisions that together make up diffusion of a technology. Even if innovative activity is thought to be the long-run impetus of technological change, the incentives created for firms to adopt new techniques will be crucial in shaping the incentives for innovating firms to invest in research and development. Moreover, the effects of environmental regulations such as emissions standards or taxes necessarily work through the adoption stage, by influencing the choices firms make about how to control pollution. "Upstream" effects – for example, innovation of lower-cost abatement techniques – are indirect, mediated by the demand for new technologies that is created by the environmental regulation.

Because I focus on the choices made by firms who face a particular set of available techniques, and only indirectly examine the incentives for other firms to invest in innovative effort, I consider "techniques" rather than "technologies," and similarly write of "technical" rather than "technological" change. This follows the lead of Binswanger (1978), who usefully distinguished between technical change, defined as "changes in techniques of production at the firm or industry level that result both from research and development and from learning by doing" (p. 18), and *technological* change, which he considered to involve broader applications of knowledge.

In my own words, and in the current context, I consider techniques to be specific methods of controlling pollution emissions. For example, a technique might be a model of catalytic converter on a car, or a certain type of "scrubber" removing sulfur dioxide from the flue gases of an electric power plant, or a way of switching to a cleaner fuel. Note that a given technique, in this interpretation, can involve varying combinations of emissions and input costs, and thus can be defined by its own possible convex cost function.

The next section reviews the theoretical work in the environmental economics literature, focusing on comparisons between price and quantity instruments and on discussions of optimal policy instrument choice. In Section 3, incorporate technique choice into the well-known Weitzman model. In Section 4, I introduce the two-part instrument, and show that it can induce optimal outcomes in the modified Weitzman model. Section 5 extends the results to a more general model of technique choice. Section 6 concludes.

2 Previous literature

I begin by reviewing the theoretical work in the environmental economics literature on endogenous technical change and policy instrument choice.[1] The predominant theoretical framework has involved what could be called the "discrete technique choice" model: firms contemplate the use of a certain technology which reduces marginal costs of pollution abatement and which has a known fixed cost associated with it (Downing and White 1986; Jung, Krutilla, and Boyd 1996; Milliman and Prince 1989; Zerbe 1970). While some of these authors present this approach as a model of innovation,[2] it seems more useful as a model of adoption. The adoption decision is one in which a firm faces a given technique (or set of techniques) with a known fixed cost and certain consequences, and must decide whether or not to use it; this corresponds precisely to the discrete technique choice model.

Innovation, on the other hand, inherently involves choices about research and development expenditures, with some uncertainty over the technology that will result and the costs of developing it.[3] In this paper, therefore, I will consider the discrete model to be one of adoption rather than

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[1] For a comprehensive review of technological change and the environment, see Jaffe, Newell, and Stavins (2001).

[2] Zerbe (1970) couches his research in terms of adoption. Downing and White (1986) frame their work in terms of innovation. Milliman and Prince (1989) use one model to discuss both diffusion and innovation, the latter being defined essentially as the initial use of the technology by the "innovating" firm. Jung, Krutilla, and Boyd (1996) present their model as one of either adoption or innovation (see their note, p. 97).

[3] For various examples of models of innovation in pollution abatement technology, see Biglaiser and Horowitz 1995;

innovation.

The theoretical literature has focused on the cost savings from adopting a lower-cost technology under various policy instruments. Several researchers have found that the incentive for the adoption of new technologies is greater under an emissions tax than under direct regulation, when the instruments are chosen to be equivalent under some *ex ante* technique (Downing and White 1986; Jung, Krutilla, and Boyd 1996; Milliman and Prince 1989; Zerbe 1970).[4] This result is explained by the fact that under the standard abatement is fixed, while under the tax the firm increases its abatement after adoption, since its marginal costs have fallen. Hence under the tax the cost savings include savings not only on the abatement that was being performed under the old technology, but also savings on the increase in abatement (since by increasing abatement it pays less in taxes). It follows that if there is a fixed cost to adopt the new technology, adoption should be more likely under the tax. Some of these studies (Jung, Krutilla, and Boyd 1996; Milliman and Prince 1989) have simply analyzed which policy instruments provide greater incentives for adoption, without regard to whether such incentives are efficient.

Somewhat more generally, Keohane (2003) extends this result to show that the cost savings from an improved technique (and hence the incentive to adopt it) are always greater under a price instrument than under a quantity instrument that is equivalent *ex ante*. This holds regardless of the nature of the improvement – *i.e.,* whether or not the cost savings are from lower marginal costs or lower capital costs. Like the conclusions of previous studies, however, this result is a positive rather than normative one.

Normative analyses have proved less clear-cut. Downing and White (1986) compare taxes, tradeable permits, subsidies, and standards, and conclude that each instrument provides either too much or too little incentive for adoption relative to the socially optimal outcome. A similar ambiguity emerges from Parry (1998) and Fischer, Parry, and Pizer (1998). The latter consider emissions taxes, auctioned permits, and freely allocated permits, and find that conditions exist for *each* of these three instruments, under which it generates a higher welfare gain than the other two.[5]

Biglaiser, Horowitz, and Quiggin (1995) compare taxes and tradeable permits in a dynamic model in which firms can reduce their marginal abatement costs through investment, and the regulator can respond by adjusting its policy. They find that tradeable permits are not generally time-consistent, and thus may not achieve the social optimum, while a tax achieves the first best outcome. The latter result is hardly surprising, because they assume constant marginal damages.[6]

Three key points can be made about the normative analyses in the literature. First, in general they restrict the set of instruments they consider to the "textbook" instruments of taxes, subsidies, tradeable permits, and standards, but do not explain why they do so.[7] When technical change is

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Fischer, Parry, and Pizer 2003; Magat 1978, 1979; and Parry 1998.

[4] The normalization of the instruments with respect to the *ex ante* technique is crucial. Magat (1979), comparing a standard with a tax that is adjusted to be equivalent at every point in time, found (not suprisingly) that the two instruments had the same consequences for technical change.

[5] These conditions include the relative slopes of marginal benefit and cost curves, the appropriability of innovation, and the ability of the regulator to adjust policies in response to innovation.

[6] This is simply a special case of the broader point that a nonlinear tax that perfectly replicates the marginal benefit schedule will achieve the first-best outcome.

[7] An exception is Biglaiser and Horowitz (1995). They find that the regulator's optimal policy will include a technology standard requiring firms to adopt a certain "best available technology," but this result depends critically on two assumptions: first, that firms are identical *ex ante* (and thus are affected identically by a given technology; second, that research is a random lottery, independent of any firm effort – a fixed cost C earns one draw from a known distribution. As a result, the luckiest firm ends up with a technique that is superior for every firm, but does

endogenous, the regulator simultaneously faces the tasks of inducing the optimal choice of technique and efficient abatement, let alone inducing optimal innovative effort; why should the regulator not cast her net wider than the usual set of instruments?

Second, even though they essentially restrict themselves to a comparison of price and quantity instruments, these studies do not relate their results to Weitzman's (1974) well-known model of policy instrument choice under uncertainty, which yields a simple rule for the preferred choice of instrument.[8]

Third, the existing literature in general assumes that the regulator fixes the policy instruments equivalent to each other under some initial technique, even though other techniques will potentially be developed in the future.[9] This is true even though several studies focus attention on the possibility that the regulator can adjust policies *ex post* in response to changes in pollution abatement technology (Downing and White 1986; Milliman and Prince 1989; Parry 1998).

While understandable for analyses that simply analyze the relative magnitude of adoption incentives, this assumption is fundamentally at odds with a normative analysis. The literature does not explain why a welfare-maximizing regulator should fail even to consider the possibility of technical change in setting policy – say, by formulating an expectation about potential future techniques. To choose a policy in such a way, the regulator must be either uninterested in welfare (aims to achieve something other than maximizing net social benefits), myopic (does not anticipate the possibility of technical change), or ignorant (has no information whatsoever on the possible direction or rate of technical change). At the very least, such a regulator might charitably be called "naive."

The two-part instruments considered here require an expansion of the regulator's choice set and powers of observation beyond the assumptions usually made in the theoretical literature. But there seems to be no compelling reason, when technical change is endogenous, to constrain the analysis of optimal policy to a consideration of "textbook" instruments. While comparisons among conventionally considered instruments – e.g., prices versus quantities – can provide deep insights, they can also be limiting. This is especially true when the literature just summarized suggests that none of the conventional instruments is optimal in general, while I can identify an optimal instrument outside the set.

Moreover, while a menu of tariffs would in the limit (as the number of possible techniques goes to infinity) bear some resemblance to a nonlinear tax schedule, the criticism often leveled at such tax schedules (namely, that it would be impossible for a regulator to charge a different marginal tax on each unit of emissions) does not apply, since for any given technique chosen by the firm the tax would be constant per unit of emissions. Indeed, the attraction of the two-part

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not cost any more than any other technique.

[8] A notable exception is an early paper by Mendelsohn (1982), who seeks to incorporate endogenous technical change into Weitzman's original model. Mendelsohn concludes that endogenous technical change leads to a bias towards the quantity instrument, compared to Weitzman's original result. However, while the gist of his conclusion is correct, his modeling approach appears to have significant drawbacks, and his article does not quite pin down the source of the difference between price and quantity instruments.

Mendelsohn's model assumes conditions such that the firm's expected investment in research is zero under the quantity standard, which seems a strong result. A related issue is that the cost and benefit functions are centered around the expected optimal quantity, $\hat{q}$. However, this quantity in fact depends on marginal cost and hence on research effort, so that in general it is not determined independently of the instrument chosen. Mendelsohn also appears to mis-specify the regulator's optimization problem. As a result, one can show that the term Mendelsohn derives for the comparative advantage of prices over quantities is not quite correct, although it has the right sign.

[9] Two exceptions are Biglaiser and Horowitz (1995) and Biglaiser, Horowiz, and Quiggin (1995).

instruments considered here is that they could replicate the first best outcome of a nonlinear tax, in a much simpler fashion. As discussed in the review of Section 2, several models in the existing literature explicitly consider the possibility that a regulator responds to technique adoption *ex post*, for example by reducing the emissions tax. My proposal of a set of taxes corresponding to a set of available techniques differs only because in my model the regulator has the foresight to announce it in advance.

3 Endogenous technical change in the Weitzman model

As just discussed, models of the dynamic effects of policy design generally reach a sharp conclusion on the effects of policy instruments: a price instrument always provides a strictly greater spur to the adoption of new techniques by the regulated firm than a quantity instrument does, when the instruments are normalized to be equivalent under some "benchmark" technique. On the other hand, Weitzman (1974) showed in a seminal paper that when the regulator is uncertain about the marginal costs of abatement, and seeks to maximize expected social welfare, either a price instrument or a quantity instrument may be optimal, depending on the relative slopes of the marginal benefit and cost functions. In this section, I explore the apparent contradiction between these two results.

Part of the explanation for the different results lies in the framework of analysis. As already pointed out, the prior section sought to understand how different policy instruments might affect technique choices by firms, but did not analyze the relative welfare effects of those instruments. More adoption is not necessarily better, so the result that a price instrument produces a greater response in technique choice does not necessarily contradict Weitzman's finding that a quantity instrument may be optimal.

However, as already noted, some studies *have* addressed the optimal choice of policy instrument when technical change is endogenous, but have still failed to come up with an analytically clean solution. The contrast between the clarity of Weitzman's rule and the relative muddle of recent results beg the question: does the basic message of the Weitzman model need to be changed in the case of endogenous technical change?

The answer turns out to be, "it depends." To demonstrate that conclusion, I develop a greatly simplified version of Weitzman's model that incorporates endogenous technical change. The point of the exercise is to gain some intuition into how the optimal choice of price or quantity varies when I introduce technique choice into a Weitzman-style model, while retaining the rest of the model structure.

I first show how the policy instrument may matter in this setting. If the cost of adoption is low enough, firms always adopt any innovation that becomes available, and the Weitzman relative-cost prescription goes through unchanged. This corresponds to a case in which research and development, and thus technique adoption, is cheap. This is a somewhat notable result, since it suggests that endogenous technical change does not *always* make a difference to the optimal choice of policy.

Similarly, if firms never adopt an innovation (because its development is too expensive), the model of technical change presented here reduces to a world of certainty, restoring the basic equivalence between price and quantity instruments.

Unless the marginal benefit function is perfectly flat, however, some intermediate cases exist between these two extremes. In those cases, the firm's adoption decision differs under price and quantity instruments. Hence the Weitzman analysis does not apply. Instead, I show that if the regulator is restricted to a choice between a price instrument and a quantity instrument, a quantity instrument is always strictly preferred. The intuition is that in this case adoption is inefficient, and the quantity instrument (because of the lower cost savings it creates relative to the price) ensures that the firm does not adopt.

As noted throughout this discussion, my model is a very simple one. However, I suggest at the conclusion of this section why the intuition developed here might carry over to a more general setting.

I start by presenting a simplified version of Weitzman's (1974) model. I assume that there is only one firm, which takes prices as given and has some fixed output.[10] The firm is governed by a regulator who seeks to maximize social welfare but has only limited knowledge of the firm's abatement cost functions. The firm's marginal abatement cost function is linear,[11] and its slope is known to the regulator; but the true marginal cost function is shifted up or down around the expected cost function according to a stochastic function.

Weitzman allows the stochastic parameter to be distributed according to some density function, with known mean and variance. I simplify his model by assuming that there are only two possible marginal cost functions, each equally likely, each with slope c, each lying a vertical distance θ above or below the expected marginal cost function. The essence of Weitzman's model is retained, although its generality is diminished.

Figure 1 illustrates the model. The true marginal cost function is either MC_0 or MC_1, with the expected marginal cost function EMC in the middle. The marginal benefit function is known and equal to MB, with slope $-b$.[12] The regulator can either require the firm to abate some quantity q, or can impose a per-unit tax on emissions of p.[13] However, she must make her decision without knowing the true marginal cost function. Moreover, her decision will be fixed for some period of time during which the firm operates with the actual cost function.

In this model, the regulator's optimal choice of quantity q_W and price p_W correspond to the quantity and price at the expected optimum (given by the intersection of the MB and EMC curves). In both cases, some deadweight loss is inevitable, since the true marginal cost function will never be EMC. Nonetheless, choosing p_W or q_W minimizes the *expected* deadweight loss for a price or quantity instrument, respectively. Importantly, the expected deadweight loss differs under the two policy instruments. Weitzman's well-known result is that a price (quantity) instrument is

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[10] To keep the analysis close to Weitzman's original model, we will revert to abatement rather than emissions, and to considering costs and abatement in level terms, rather than rates per unit output. Thus, given our discussion on cost functions earlier, we adopt the assumption that the firm's output is fixed.

[11] To be precise, Weitzman assumes that the total cost and benefit functions are quadratic in the neighborhood of the optimal point, using a second-order Taylor approximation of some arbitrary functions as justification. Note that in our adaptation of the model to incorporate endogenous technical change, we draw the marginal cost functions as extending to the vertical axis, which is inconsistent with Weitzman's intepretation for linear marginal cost functions. Extending the functions in this way is convenient, because it allows us to specify the areas under the marginal cost functions in a simple way. Doing so does not affect the results, because the only the areas in the neighborhood of the optimum are calculated by relying on the linearity assumption. (Looking ahead to Figure 2, the area $abcxh$ (for example) is included in several terms, such as area $abcf$; but the size of its area is never calculated directly, and so the assumption that MC_0 and MC_1 are linear all the way to the vertical axis has no bearing on the results.)

[12] Independent uncertainty in the marginal benefit function would not affect the optimal choice of policy instrument (Weitzman 1974), while a positive correlation in cost and benefit uncertainty will tend to favor the quantity instrument, although Weitzman's rule is not necessarily reversed (Stavins 1996).

[13] As Weitzman pointed out, a nonlinear tax that followed the marginal benefits schedule would always achieve the efficient outcome. However, Weitzman argued persuasively that such a nonlinear tax was implausible in the real world, justifying a focus on linear unit taxes.

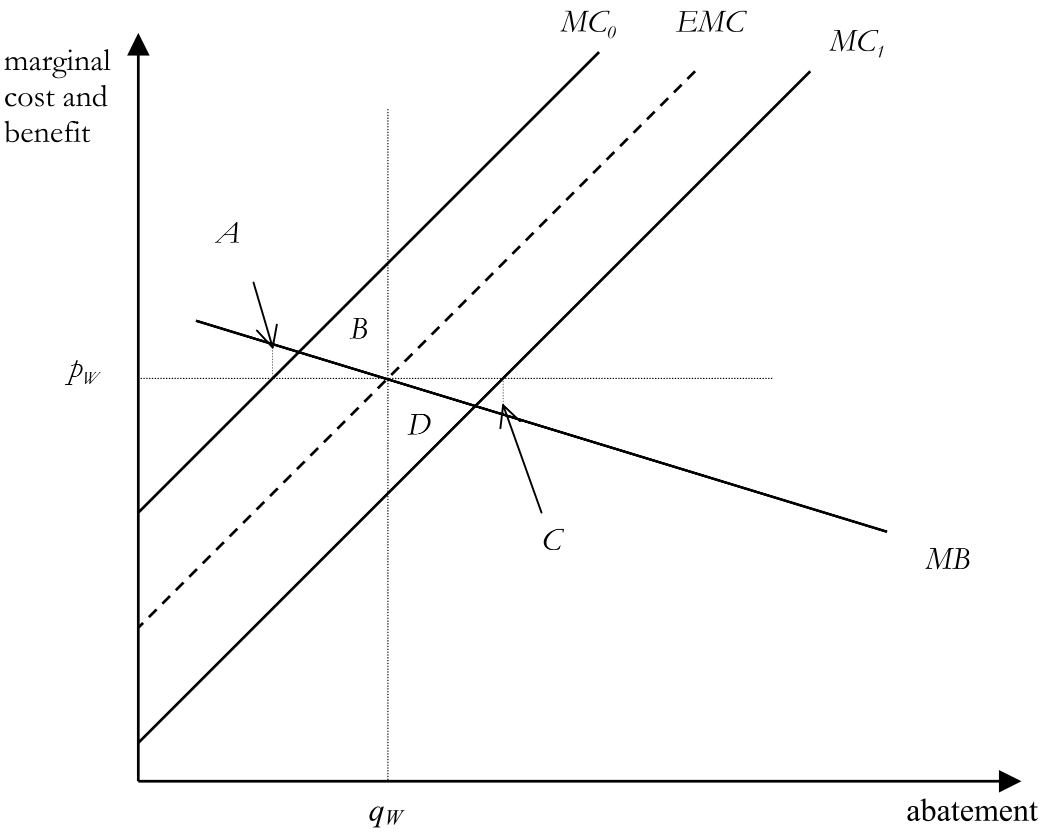

FIGURE 1 -- The simplified Weitzman model.

preferred if the slope of marginal benefit is less (greater) than the slope of marginal cost. Intuitively, a nearly flat marginal benefit function can be closely approximated by a tax, while a steep marginal benefit function can (somewhat more loosely) be approximated by a quantity instrument.

In Figure 1, as drawn, the marginal cost curve is steeper than marginal benefit (i.e., $c > b$). The expected deadweight loss under the price p_W is the area of triangle A (its area equals the average of the areas of triangles A and C), which is smaller than the area of triangle B (the expected deadweight loss using the quantity q_W).[14]

Weitzman presents his model as representing one of two possibilities: the case in which the firm knows its true marginal cost from the start, but cannot be induced truthfully to reveal it, or the case in which the firm only discovers its marginal cost after the regulator has decided on an instrument. Note that his model assumes that only *one* of the possible marginal cost functions is realized: that is, the firm does not have a choice of technique. Thus it might also be viewed as a model of *exogenous* technical change. In this interpretation, research is going on behind the scenes, which will produce either cost function MC_0 or cost function MC_1, but not both.

The basic premise of the literature on *endogenous* technical change, however, is that firms may have a choice of technique. If I allow the firm to choose between $MC_1$and MC_0, I can find conditions under which Weitzman's relative-costs rule of thumb no longer holds.

I incorporate endogenous change into the model in a natural but simple way. I expand the model to three periods. In the first, the regulator sets the price or quantity instrument; in the second, an innovating firm chooses whether or not to do research; and in the third, still governed by the price and quantity instrument announced in period 1, the polluting firm chooses a technique and a level of abatement.

I assume as before that there are two possible techniques, with cost functions MC_0 and MC_1; but I now assume that they *both* may be available in the third period, with the firm choosing the technique that entails the lowest compliance costs. In particular, I suppose that MC_0 is available with certainty, but that MC_1 will only be available with probability 1/2. When the regulator sets a price or quantity instrument in the first period, she must do so without knowledge of whether or not MC_1 will be available.

Here the technique with marginal cost function $MC_1$is the potential result of research and development. In this simple case of one possible technique, I assume a simple and direct R&D policy which ensures that polluting firm pays, and the innovator receives, the *ex ante* expected costs of research. I make this assumption on R&D policy in order to focus clearly on the effects of price and quantity instruments on adoption.

In particular, I suppose that a risk-neutral outside firm specializes in innovation.[15] In the second period this innovator, having observed the regulator's choice of instrument, has the option to invest $k/2$ in research to develop new abatement techniques. With probability 1/2 the firm is successful, produces the MC_1 technique, and offers it for sale at price k in the third period.[16] Thus k, the cost

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[14] The difference between these two areas is $\Delta B - \Delta A = \frac{\theta^2}{2}\frac{(c-b)}{c^2}$; this corresponds to Weitzman's general formula if we replace θ^2 with its more general counterpart, the variance of the stochastic parameter shifting marginal cost.

[15] This third party could alternatively be another branch of government; or the government could subsidize research done by the polluting firm itself.

[16] Our model of innovation reflects the assumption that the government can observe the cost of such research, and implements an enlightened R&D policy – essentially, an unassailable patent with a regulated price set so that on average the firm just breaks even.

We are also ignoring discounting. This does not affect the results substantially, as long as the payment made to the successful innovator is then adjusted for discounting (so that the innovator still breaks even in expectation).

of the new technique to the polluting firm, represents the expected cost of developing it.[17]Given these assumptions, note that the innovator is willing to invest in R&D (research and development) if and only if the polluter will adopt the new technique if it becomes available. Without loss of generality, since the choice of technique hinges on relative costs, I assume that the cost to the firm of choosing MC_0 is zero.

In this section, the regulator is assumed to know k, as well as both marginal cost functions (although she does not, of course, know whether or not MC_1 will actually be available). I shall refer to the model described by these assumptions as "the modified simple Weitzman model with endogenous technical change."

The outcome of the model hinges on the size of the adoption cost k, as might be expected from the results of the prior section. First, suppose that $k = 0$, so that the firm chooses MC_1 if it is available. Then the firm's actual marginal cost function is MC_0 with probability 1/2 and MC_1 with probability 1/2, and my model reduces to the Weitzman-style model above.

In fact, the model yields the same outcome as the Weitzman model as long as the firm will always opt for MC_1 if it is available – that is, as long as the adoption cost k is less than the variable cost savings from using MC_1 rather than MC_0. To see this, consider Figure 2, which replicates the marginal cost and benefit functions drawn in Figure 1.[18] Suppose that the regulator implements the Weitzman quantity q_W. If MC_1 is available, the firm saves $S_q \equiv$ area $(abeh)$ in variable costs by using it instead of MC_0. Similarly, if the regulator implements the Weitzman price p_W, the firm's variable cost savings from using MC_1 (relative to MC_0) is $S_W^p \equiv \text{area}(abcf)$. By the assumed linearity of the marginal cost and benefit curves, area$(cex) =$area(xfh), hence $S_W^q = S_W^p \equiv S_W$. Because the regulator chooses the price or quantity corresponding to the expected optimum, the cost savings from the new technique MC_1 are unaffected by the policy instrument. This result is in contrast to that of the prior section, where the price or quantity were fixed by the initial technique (here MC_0) without taking into account the possibility of MC_1.

Hence if $k < S_W$ and the regulator follows the Weitzman prescription, the firm will choose MC_1 if it is available, regardless of the policy instrument.[19] Thus incorporating endogenous technical change into the simple Weitzman model has no effect on the optimal choice of price or quantity instrument if the adoption cost is low enough that the firm makes the same choice under either instrument.[20]

Note also that under either p_W or q_W the savings S_W to the firm from adopting technique 1 equals the net gain to society. The social net gain is just the difference in net benefits between the optimal abatement level under MC_1 and that under MC_0. In Figure 2, this is given by area$(abdg)$, which equals area$(abcf)$ (or area$(abeh)$) by symmetry. Hence under p_W and q_W the firm has the

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[17] We are implicitly assuming here that the only capital cost is research and development – i.e., that the capital cost of installing either technique is zero. That assumption is harmless, however, The results would be identical if technique 0 had some positive installation cost k_0, technique 1 had some adoption cost k_1 that included both an installation cost and the cost of research and development (adjusted for the probability of success, as in the text), and we redefined $k \equiv k_1 - k_0$.

[18] Note that the "expected marginal cost function" EMC, is now in fact the expected MC function conditional upon the superiority of MC_1. By the "Weitzman instruments," we mean the instruments that would be recommended in the Weitzman model, "as if" that model applied (that is, taking the conditional expected marginal cost curve to be simply the expected marginal cost curve). As discussed below, if the adoption cost k is sufficiently high, the firm does not adopt MC_1 even if it is available.

[19] Because the polluter will buy MC_1 if it is available, the innovator will find it worthwhile to invest in research and development.

[20] The expected net social benefits are greater here than in Weitzman's model, however, by an amount $\frac{1}{2}(S_W - k)$.

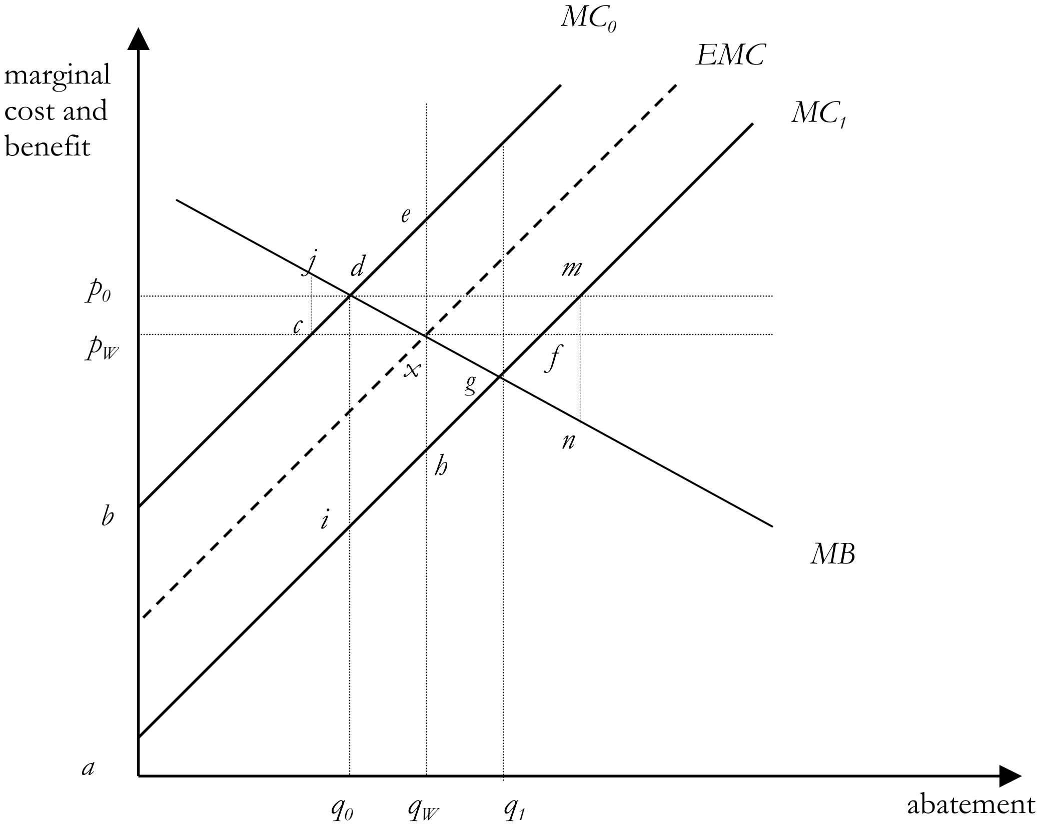

FIGURE 2 -- The simplified Weitzman model incorporating endogenous technical change.

correct incentive to adopt the new technique.[21]

Now suppose that $k \geq S_W$. In this case, adoption of technique MC_1 is socially undesirable. If the regulator imposes q_W or p_W, the firm will choose MC_0. Because there is no possibility that the realized cost function will be MC_1, the Weitzman analysis does not apply, and neither q_W or p_W is the best choice of price or quantity instrument.

The best quantity instrument in this case is easy to determine: it is q_0, the efficient quantity under the initial technique MC_0. If the regulator chooses q_0, the firm's variable cost savings from adopting MC_1 are S_0^q =area($abdi$), which is less than or equal to than the adoption cost since $S_0^q \leq S_W$ and $S_W \leq k$. Hence the firm will always choose MC_0, and abatement q_0 will be efficient. In fact, since q_0 discourages the adoption of the inefficient technique, the quantity instrument achieves the "first best" outcome, regardless of the uncertainty over the realization of research. Let the net social benefits under q_0 be denoted NB_0.

It might first appear, in this case, that a price instrument p_0 will be equivalent to q_0. If the regulator chooses p_0, the firm's variable cost savings from using MC_1 are $S_0^p =$ area($abdm$). This savings is *larger* in general than the cost savings under price p_W, because under the higher tax the firm saves more by adopting the lower-marginal-cost technique. In the figure, area($abdm$) is *larger* than the area($abcf$) by area($cdmf$), which corresponds to the extra savings on tax payments due to adoption when the tax is higher.[22]

Note that if marginal benefits are constant, so that the MB curve is perfectly flat, then $p_0 = p_W = MB$ and $S_0^p = S_W$. In this case, either a price p_0 or quantity q_0 can achieve the efficient outcome when $k \geq S_W$.[23]

If marginal benefits vary, however, then $S_0 > S_W$. Even so, if $k \geq S_0^p$, the firm does not adopt MC_1 even under price p_0. In this case, technique MC_1 is essentially irrelevant, and everything is identical to the case in which the cost function is certain and equal to MC_0. Price and quantity instruments are perfectly equivalent, and p_0 and q_0 both achieve the efficient level of abatement.

On the other hand, if $S_0^p > k \geq S_W$, then under the tax p_0 the firm will adopt MC_1 if it is available, even though it would not adopt under q_0. Thus with probability 1/2, the net social benefits are less than NB_0 by area(gmn) $+ k - S_W$. This deadweight loss has two parts. First, the firm produces too much abatement even given cost function MC_1, because of the high tax; this loss is given by area(gmn). Second, the firm adopts the technique when doing so is not socially desirable, producing loss $k > S_W$.

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[21] This equivalence also depends on our assumption that technique MC_1 is available with probability 1/2, which ensures symmetry. It is straightforward to show that if the probability of successful research is greater than a half, the Weitzman prescription (which still calls for setting the price or quantity instruments at the expected optimum) would produce a larger cost savings to adoption under the quantity than under the price instrument, while a probability of less than one half would produce the opposite result. This is simply because the higher the probability of successful research, the lower is p_W and the higher is q_W.

For small values of k, the firm would adopt in both cases, and the Weitzman analysis would still go through. For $k > S_W$, the analysis in the text would also go through. However, the Weitzman instruments would no longer induce adoption in all cases where adoption is desirable (i.e., where $k < S_W$). Relative slopes would enter in to these cases, along with the probability of successful research.

Since the model is so simple to begin with, it seems hardly worthwhile to pursue the implications of various probabilities. Instead, at the end of the section we sketch how our assumptions might carry over to a more general model.

[22] It is straightforward to show that the variable compliance cost savings under a tax are increasing in the size of the tax.

[23] Indeed, in this case the price instrument $p = MB$ will always achieve the first-best outcome, regardless of the regulator's lack of knowledge ofabatement cost.

Of course, p_0 is not in general the best price instrument possible in this case. The preferred price is a price $\tilde{p} \in [p_W, p_0)$ chosen so that the resulting variable cost savings from adopting MC_1, say $S(\tilde{p})$, equal k. Since $S(\tilde{p}) = k$, the firm will choose MC_0. For any price $p' > \tilde{p}$, $S(p') > k$ and the firm adopts MC_1 if available, abating too much and yielding high deadweight losses; for any $p'' < \tilde{p}$, the firm still chooses MC_0, but the resulting deadweight loss (relative to the efficient point where $MC_0 = MB$) is bigger than under $\tilde{p}$.

Nonetheless, even under $\tilde{p}$ a deadweight loss is assured, since $\tilde{p} \neq p_0$. Thus in this case of intermediate adoption costs, the price instrument either encourages inefficient adoption of the new technique, or misses the optimum under the old.

I conclude that for such intermediate values of the capital cost, the choice of policy instrument can affect the firm's choice of technique, even in a Weitzman-style model. In these cases, a quantity instrument is strictly preferred to a price instrument. Indeed, q_0 can achieve the efficient outcome.

I summarize my discussion in the following proposition, using the definitions of S_W and S_0^p given above.[24]

Proposition 1 *In the modified simple Weitzman model with endogenous technical change, we can distinguish three cases, depending on the size of the adoption cost relative to the variable cost savings from operating technique MC_1 rather than MC_0. If $k < S_W$, the optimal policy rule is identical to Weitzman's relative-slopes rule. If the adoption cost is very large, so that $k \geq S_0^p$, price and quantity instruments (p_0 and q_0) are equivalent. For intermediate values of $k \in [S_W, S_0^p)$, however, the optimal choice of price or quantity instrument is a quantity instrument, set at q_0; and this is strictly preferred to any price instrument.*

Again, note that the intermediate case is possible only when $b > 0$, so that marginal benefits are not constant.

Proposition 1 shows that for some values of k there is a *strict* preference for the quantity instrument over the price instrument, even though the price instrument (as shown in the previous section) generates greater private cost savings and hence a larger adoption incentive. But more adoption is not better, if the cost savings to the firm do not reflect gains in net social benefits.

In this simple model, the choice of policy instrument only matters if the adoption cost k is greater than the net benefit to the society from adoption. Thus if the adoption cost is high enough to drive a wedge between the price and quantity instruments, it is also socially undesirable. That is why the quantity instrument becomes optimal.

Because this model represents such a special case, it is worth considering whether the intuition it presents carries over into more general models. The key simplification is the assumption of a discrete outcome of research, and the related assumption that the regulator there is a single expected cost of research k, known to the regulator. Suppose instead that the new marginal cost function MC_1 depends on research effort in some continuous way, and hence that k is no longer known *ex ante*. A full analysis of this case would be desirable; it would require careful attention to the choice of how to model the costs and outcomes of research.[25] I do not provide a full analysis, but I can sketch some general conclusions as long as the regulator has some information about the magnitude of the costs relative to the social benefits from innovation.

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[24] We rely on the graphical proof developed in the discussion above. An algebraic proof is entirely straightforward, using the assumption of linear marginal cost and benefit curves.

[25] Note that such a model begins to blur the distinction maintained in this paper between adoption and innovation.

If the cost of research and development is known to be sufficiently low, so that the firm uses any innovation that is developed (and it is socially desirable for it to do so), then the choice of instrument will not affect the choice of technique. In this case the Weitzman prescription will continue to apply. Hence one can loosely conclude that the Weitzman analysis would continue to hold when innovations are "large" and the expected costs of research and development are "small." Put another way, the Weitzman analysis will continue to hold when there is a high social return on investment in research and development.

In general, however, I might expect that some kind of preference for a quantity instrument will remain. The reason is that the price instrument tends to encourage "too much" adoption, while the quantity instrument might not encourage enough. Simply comparing the choice of technique, either instrument might seem preferable. However, the price instrument amplifies the effect of technique choice on the resulting level of abatement. Indeed, this flexibility lies at the heart of Weitzman's original insight: with exogenous technical change, the regulator gains by taking advantage of the greater response by firms to a price instrument, when that response is kept in check by the slope of the marginal cost function.

Because the price instrument incorporates such flexibility, the social costs of the firm choosing the "wrong" technique will be amplified. Consider again Figure 2. By imposing a price of p_0 (or any price greater than $\tilde{p}$), the regulator induces the firm to adopt a socially inefficient technique. This error is then compounded by the fact that under the new technique, the firm expands abatement beyond even what would be efficient for that technique.

The likely result in a more general model is thus that the optimal choice of instrument will still depend on the relative slopes of marginal benefit and cost, but that quantity instruments are relatively more attractive than in the case of exogenous technical change.[26]

A general model along these lines would be a valuable contribution. However, it turns out that if the regulator's choice set of policy instruments is enlarged somewhat, I can immediately identify a relatively simple policy that achieves the first-best outcome, even when the regulator lacks knowledge in advance about the costs of research and development or the probabilities of success.

4 Two-part instruments in the modified Weitzman model

4.1 Overview

The remainder of the paper demonstrates that the regulator can achieve the efficient choices of adoption and abatement by combining a menu of price or quantity instruments with levies or subsidies on technology adoption, even when she has very limited knowledge about the costs and potential payoffs of innovation. In this section, I develop intuition, remaining within the simplified Weitzman model just presented. In Section 5, I demonstrate the results in a more general model of technique choice.

At the outset, it is important to acknowledge that two-part tariffs depart from the Weitzman model in two important ways. First, they represent an expansion of the regulator's set of feasible instruments. After all, a two-part tariff in the original Weitzman model with exogenous marginal cost functions is akin to a kind of nonlinear tax schedule, which he rejected as implausible. It is

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[26] Indeed, this discussion suggests Mendelsohn (1982) arrived at the right conclusion, although perhaps for the wrong reasons. See note 8 above.

straightforward to show that allowing such instruments in that model would allow the regulator to achieve the first-best outcome using either prices or quantities.[27]

Second, to implement the two-part tariffs proposed here, the regulator must observe the firm's choice of technique, and must know the resulting marginal abatement cost function. Again, this represents a considerable departure from the Weitzman model, which was based on the premise that the marginal abatement costs were unobservable by the regulator.

Nonetheless, this approach is a reasonable one in the context of endogenous technical change. The spirit of the Weitzman model – the regulator lacks key information *ex ante* about the pollution control technology that the regulated firm will use – remains intact. In Weitzman's model, the missing information is the true marginal cost curve; indeed, this is the only source of uncertainty. In the current model, it is the set of techniques that will be available (along with their costs of development and production), and the specific choice the firm will make, that is unknown to the regulator.

I have in mind something like the following scenario. Suppose that when the regulatory regime is announced, there are several research projects underway to develop new pollution control techniques. The regulator has some notion of what projects are underway, and what the outcome of each project will be if successful – that is, what the marginal abatement cost function will be for each project. However, the regulator has no idea of how likely success is in each case, or how much it will cost to develop and to install at the firm. In the model proposed below, the regulator announces ahead of time a menu of taxes and adoption levies (or subsidies), with a different tax-and-levy combination corresponding to each of the projects. The regulator then observes the firm's choice of technique – for example, observes which of the innovating companies the firm purchased its pollution control equipment from. In response to that choice, the regulator assigns the firm the appropriate tax and levy from the announced menu.

For most of the analysis, I continue to consider the simple case of a single representative regulated firm. I subsequently sketch an extension of the model to an industry of heterogeneous firms. In that model, I suggest, the tax rate would be constant among firms (indeed, it would have to be, to satisfy the necessary condition for cost-effectiveness), but the subsidies or levies would vary among firms depending on their choices of technique.

4.2 The Weitzman model with two-part instruments

I start by considering the same modified Weitzman model with endogenous technical change as I considered above, with two changes. First, I now suppose that the regulator does not know k when she chooses the policy in period 1. Second, I allow that the regulator somewhat more leeway in choosing policy instruments: she can now assign the firm a different fixed quantity or unit price depending on the firm's choice of technique, and is also allowed to impose a levy or offer a subsidy on the adoption of technology MC_1. I thus assume that the regulator can observe the choice of technique by the firm, and can respond by collecting the pre-announced levy or paying the pre-announced subsidy. In this case, a two-part instrument – a combination of a price or quantity

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[27] In the Weitzman model, firms never choose to "adopt" a given cost function, so the optimal adoption levy or subsidy would be zero.

Note that allowing a regulator to announce a menu of quantities or prices is not conceptually identical to a true nonlinear tax schedule, because for any given technique chosen by the firm, the tax would be constant per unit of emissions. We argue that this distinction is worth taking into account in evaluating whether a two-part tariff of the kind considered here would have any practical implication.

instrument with a levy or subsidy on adoption – can achieve the optimal outcome, despite the regulator's lack of knowledge about the costs of research or of adoption.

To see the intuition behind the adoption levy, consider the regulator's dilemma when she does not know k. She would like simultaneously to ensure two things: first, that the firm chooses technique MC_1 if and only if it is socially desirable for it to do so; second, that given its choice of the optimal technique the firm chooses the efficient level of abatement.

I already know, in this simple model, that the instruments p_W and q_W each ensure the optimal choice of technique, since the net private gain to the firm from adoption equals the net social benefits. However, such a price or quantity guarantees that abatement will be inefficient *ex post.* I also know that if the regulator must impose only one price or one quantity, but the marginal cost function is uncertain, she is unable to ensure efficient abatement – indeed, this is the whole premise of the Weitzman model. If the regulator can tailor the price or quantity to the technique, announcing *ex ante* that the tax will be p_0 (or the quantity q_0) if the firm adopts MC_0 and p_1 (or q_1) if the firm adopts MC_1, she can obviously induce efficient abatement. But these prices or quantities would create too much incentive for adoption. What the regulator would like to do is to employ a menu of prices or quantities and then use a levy or subsidy to ensure efficient adoption.

Suppose that the regulator offers the firm the following choice: "Use technique MC_0 and pay p_0 per unit of emissions; or use MC_1 and pay p_1 on each unit of emissions, *plus* a fixed amount A." Under the proposed policy, the firm's compliance costs with technique MC_0 are the area under MC_0 up to q_0 plus the rectangle of height p_0 from q_0 to the maximum quantity $q^{\max}$ (see Figure 3). If the firm adopts technique MC_1, its total compliance costs are the are under MC_1 up to q_1, plus the rectangle of height p_1 from q_1 to $q^{\max}$, plus adoption cost k, plus the adoption levy A.

The regulator can induce the optimal choice of technique by choosing A so that the net cost savings to the firm from adoption equal the net social benefits. In Figure 3, the optimal levy is $A = \text{area}(dsug)$. This optimal level is simply the part of the firm's private gains that is simply a savings in emissions taxes – and thus a transfer from the government to the firm, with no net gains for society. Note also that the same policy also achieves the efficient amount of abatement: if the firm's marginal cost function is MC_0, it faces a tax p_0 and so abates to q_0; if the firm's marginal cost function is MC_1, it faces a tax p_1 and so abates to q_1.

The fact that the optimal adoption levy is simply equal to the difference between the firm's tax savings and the gain in benefits from abatement suggests a connection to the early model of Downing and White (1986). In a model of a sole polluter, they considered the case in which the regulator adjusted the tax downward in response to adoption, as in the instrument proposed here. They concluded that in such a case a tax provided excess incentive for adoption, because "the decreases in *inframarginal* effluent fee payments are transfers from a social perspective but provide an incentive for the innovator" (p. 25). The adoption levy proposed here simply corrects for this excess incentive.[28]

In a similar way, the regulator can achieve the efficient amounts of abatement and technology adoption by combining a quantity instrument with an adoption levy. The regulator offers the firm a choice between two options: technique MC_0 and quantity standard q_0; or technique MC_1, quantity standard q_1, and adoption levy A'. The optimal adoption levy is again the excess of the firm's private gains from adoption over the social gains, which under the quantity instrument is area(deg) in Figure 3.

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[28] It also corrects for the tax savings the firm enjoys in excess of social benefits even under price p_0.

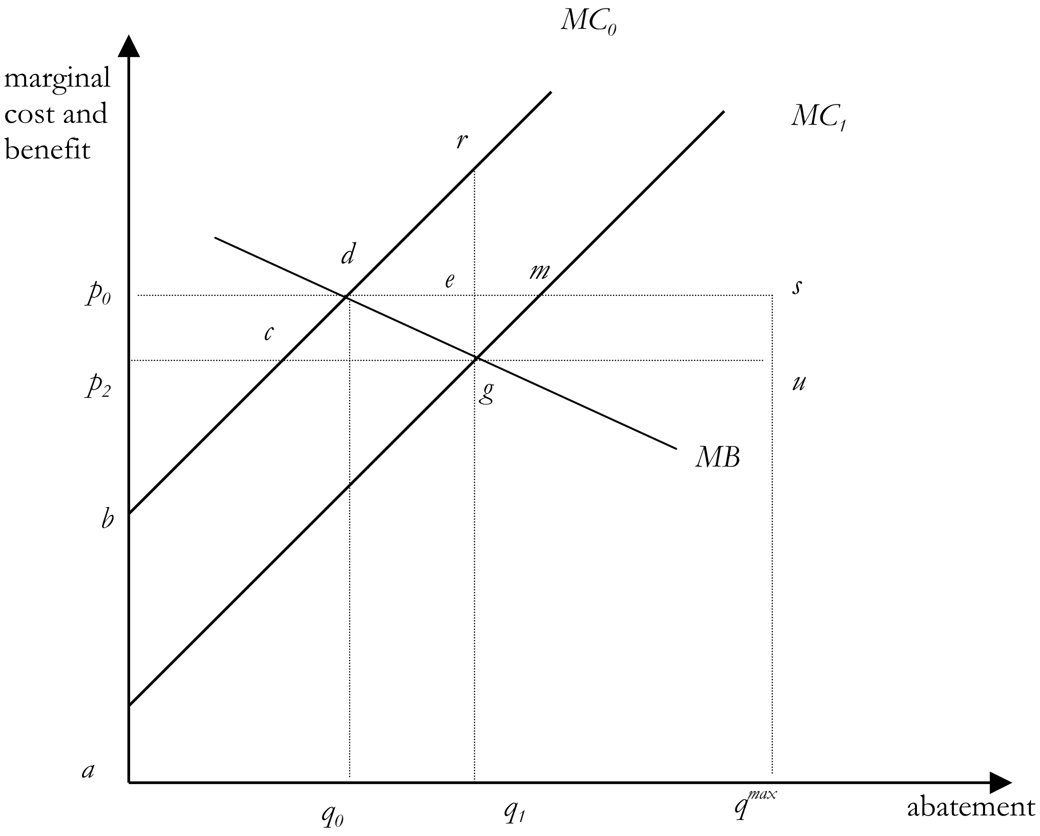

FIGURE 3 -- Two-part tariff in the modified Weitzman model.

In the cases considered so far, the regulator imposes a levy on adoption of MC_1, rather than offering a subsidy. Because technique MC_1 has a lower marginal cost, the optimal tax falls from p_0 to p_1. Because that fall in the tax yields an inefficiently high incentive to adopt the new technique, the regulator must offset it by charging the firm for the "privilege" of being offered the lower price. The result is akin to a monopolist that can charge customers a two-part tariff, and uses the fixed "access fee" to capture the consumer surplus; in this case, the regulator uses the adoption levy to capture the part of the gain from adoption that is solely a transfer in tax payments to the firm.

5 Optimal policies for efficient adoption and abatement

I now extend the result of the previous section to a more general model of technique choice. Even without knowledge of the costs of adopting different techniques, or of the research and development involved, the regulator can induce the optimal choice of technique by the firm and the efficient level of abatement, given the set of techniques available to the firm to choose from. She does this by implementing a system of two-part instruments, such as a combination of unit emissions taxes and subsidies or levies on adoption. If I further assume that there is an appropriate R&D policy in place as well, the two-part instruments proposed here also lead to efficient innovation.

5.1 A model of abatement technique choice

I contemplate a single representative regulated firm with unit output.[29] The firm is assumed to act like a cost-minimizing competitive firm. I discuss the consequences of relaxing this assumption at the end of this section.

Let the firm's emissions in the absence of any regulatory constraint – *e.g.,* the pollution resulting from burning its cheapest available fuel – be denoted by $\hat{m}$. The cost of reducing emissions below that level depends on emissions m, unregulated emissions $\hat{m}$, and the state of the firm's technology, which we will summarize by a parameter θ. Let the total cost of emitting $m \leq \hat{m}$ be given by $c(m, \hat{m}; \theta) + k_\theta$, where $c(\cdot)$ is the variable cost function and k_θ is the capital cost for technique θ.

We assume that costs per unit of output vary with the emissions rate in the usual way – namely, we assume that reductions in the emissions rate are costly, and become costlier as the emissions rate falls. By construction, moreover, the cost of emitting at rate $\hat{m}$ is zero (recall that $c(\cdot)$ represents the cost of reducing emissions below their unregulated level).

Assumption 1 The emissions rate variable cost function $c(m, \hat{m}; \theta)$ is convex in the emissions rate m: $c_m < 0, c_{mm} > 0$. Moreover, $c(m, \hat{m}; \theta) \equiv 0$.

Note that c_m is the marginal change in control cost from increasing emissions. The marginal cost of abatement is $-c_m$, which as usual is positive.

Assumption 2 states that a higher value of the technology parameter θ corresponds to higher costs, both in absolute terms and in terms of marginal reductions in emissions.

Assumption 2 $c_\theta > 0$ and $c_{m\theta} < 0$.

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[29] The assumption of unit output simplifies the analysis of benefits and hence of welfare. While the abatement cost function can reasonably be assumed to be homogeneous of degree one (see Keohane (2003)), making a unit output assumption unncessary, the homogeneity assumption is less attractive for the damages function.

A representative abatement cost function for an individual firm with a given technique is illustrated in Figure 4, where the emissions rate is on the horizontal axis and the cost per unit of output is on the vertical axis. Finally, note that $\hat{m}$ is independent of regulation, and hence (for our purposes) can be treated as a constant. For ease of exposition, we omit it from much of the following analysis.

Under an emissions standard, the regulator requires the firm to emit at rate $\bar{m}$; assuming perfect enforcement, the firm complies and bears cost $c(\bar{m};\theta)$. Since the firm is responsible only for the costs of abatement, its compliance costs per unit of output are simply $c^s \equiv c(\bar{m};\theta) + k_\theta$, where the superscript s denotes the standard.

Under an emissions tax t, the firm faces an effective price on each unit of emissions, for total emissions payments of tm. Its compliance costs are now the sum of abatement costs and emissions payments, or $c^t \equiv c(m;\theta) + k_\theta + tm$. The firm chooses the emissions rate m^* that minimizes its compliance costs:

$$\begin{aligned} m^* &= \arg\min_m c(m,\theta) + tm + k_\theta \\ &\Rightarrow -c_m(m^*;\theta) = t. \end{aligned} \tag{1}$$

This is the familiar prescription that "marginal abatement cost equals tax" at the cost-minimizing emissions level. Since equation (1) holds identically at m^* given technique θ, I can view the cost-minimizing emissions rate as a function of the technology parameter. Note that the firm's emissions rate is increasing in θ: $\frac{dm^*(\theta)}{d\theta} = -\frac{c_{m\theta}}{c_{mm}} > 0$.

In Figure 4, the cost-minimizing emissions rate m^* is the emissions rate at which a line with slope t is tangent to the cost function.[30] Note that the firm's total cost per unit of output – the sum of its emissions payments and variable abatement cost – is given by the vertical intercept of the tangent line at m^*. Somewhat loosely, I can view the cost function associated with a given abatement technique as a "quasi-isoquant" giving the trade-off between the emissions rate m and resources spent on abatement c.[31] The tangent line then plays a role analogous to an iso-cost line, with the height of the line an index of cost.

To this set of assumptions on cost, I add an assumption of convex damages from emissions.

Assumption 3 The total damages associated with total emissions m are given by $h(m) < 0$, with $h' < 0$ and $h'' < 0$.

Given my assumption on the damages function, I will find it easier to work with a *benefit* function defined as follows. Note that $h(\hat{m})$ represents the social damages (per unit of fixed output) from the firm's pre-regulation emissions rate $\hat{m}$. Reductions in the emissions rate reduce the harm from pollution. I can therefore define the *emissions reduction benefit function* as $b(m) \equiv h(\hat{m}) - h(m)$.[32]

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[30] It is straightforward to show that the firm will never choose a given technique if the tax is less than the minimum average cost (graphically, if the tangent line intersects the horizontal axis to the right of the unconstrained emissions rate $\hat{m}$). In other words, at such a low price the firm would prefer to emit at its unconstrained rate, and pay for all its emissions, rather than installing the given technique. The result is exactly analogous to the familiar result that a profit-maximizing firm will only produce positive output at prices above its minimum average cost.

[31] Because we are expressing emissions and abatement cost in per-unit-output terms, the function $c(\cdot)$ is not a true isoquant. On the other hand, we *could* draw a true isoquant relating total emissions M and the cost of abatement efforts.

[32] More precisely, $b(m)$ can be described as the benefits (per unit of fixed output) from reducing the emissions rate from $\hat{m}$ to m. With only one firm, $\hat{m}$ is fixed, and hence nothing is lost by suppressing the dependence of b on $\hat{m}$.

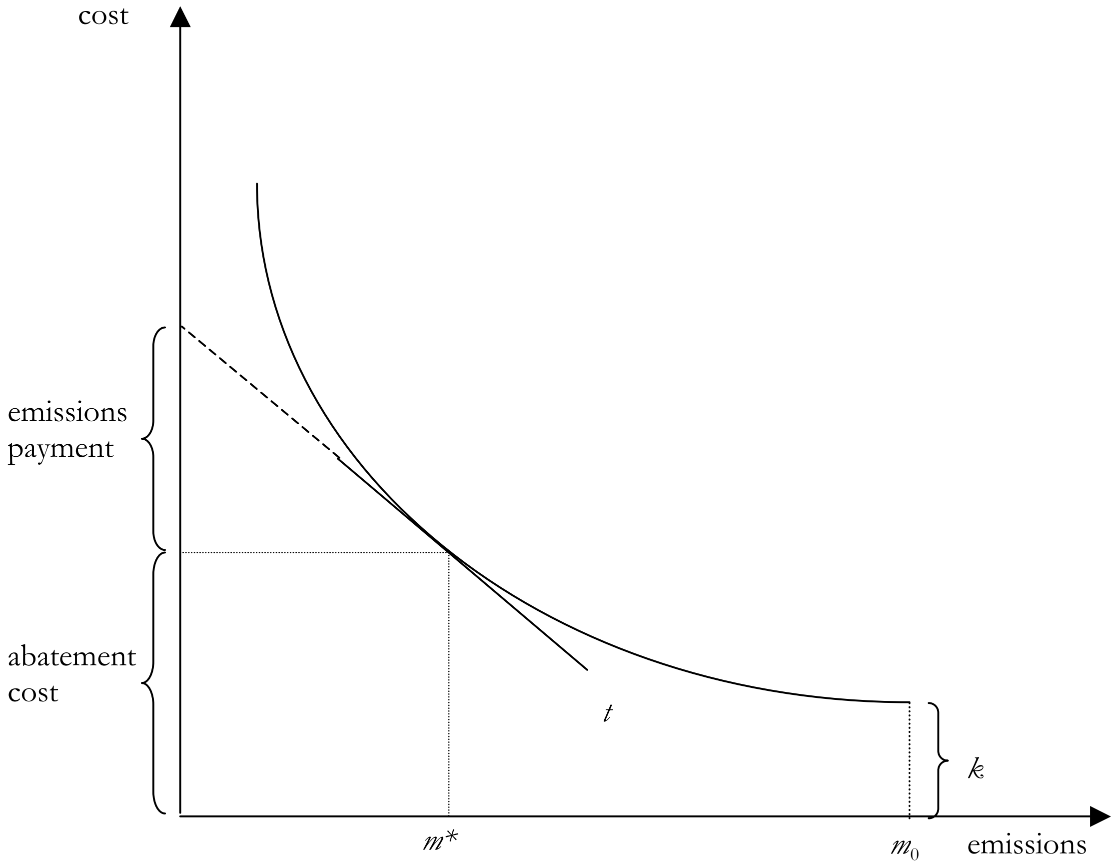

FIGURE 4 – Emissions cost function and optimal emissions rate given a tax.

From my assumptions on $h(m)$, the benefit function is positive, concave and decreasing in emissions: $b(m) > 0, b'(m) < 0, b''(m) < 0$. Note that the marginal benefit of abatement is simply $-b'(m)$, which is positive. Note also that I am assuming that total benefits from abatement are strictly concave. If marginal benefits were constant, the two-part tariff proposed here would reduce to a unit tax equal to marginal cost, which I already know is optimal in that special case.

The world lasts three periods, and there are three agents. In the first period, the regulator selects and announces a regulatory regime, which may include a schedule of prices or quantities that depend on the choice of technique, along with corresponding subsidies or levies on technique choice. I assume that the regulator chooses a regime to maximize social welfare. In the second period, after the regulator's announcement, each of a number of innovating firms chooses a project to invest in, as described below. In the third period, the polluting firm chooses a technique and an emissions rate.

After announcing the regime, the regulator must adhere to it. However, note that in period 2 the regulator, having identified the firm's chosen technique, can respond – in a pre-determined way – to that choice. Intuitively, this corresponds to a scenario in which the regulatory regimes – the frameworks within which the regulator operates – are "sticky;" but within a given regime the regulator can respond to developments according to fixed rules. Note also that since I am able to demonstrate that the instrument chosen here achieves the optimal outcome *ex post*, the assumption that the regulator cannot alter her policy *ex post* assumes less significance.[33]

I assume that the regulator has both the knowledge necessary to determine an appropriate price or quantity for a given technique, and the ability to observe the technique chosen by the firm.

Assumption 4 The regulator is able to observe the technique used by the firm, in the sense that the regulator can identify the variable cost parameter θ. The regulator also knows how the abatement cost function $c(m; \theta)$ varies with m and θ.

I assume that there exists a "benchmark technique," denoted technique 0, with variable cost parameter θ_0 and capital cost k_0. It could be taken to be the initial technique, or a standard one available to all firms in the industry. The regulator, the innovator, and the polluting firm are all assumed to know the costs of this technique. Other techniques may be developed through research by the innovating firms. I suppose that research results in some set of available techniques $\Theta = \{\theta_i\}$ which is not known *ex ante*. Each technique i has an associated adoption cost i, which represents the real costs of producing and installing the technique, given that it is in the available set Θ.

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[33] Indeed, in the case of an adoption levy, the policy proposed here is perfectly time-consistent, since the regulator retains an incentive to collect the levy if the firm adopts the new technique. On the other hand, the promise of an adoption subsidy might be time-inconsistent: if the regulator can change its policy in the second period, then it would like to "fool" the firm into adopting more efficient techniques, only to renege on the subsidy payment. This raises a host of well-traveled issues related to time-inconsistency, including the regulator's reputation (if the world does not end after two periods) and the so-called "ratchet effect"; see Biglaiser, Horowitz, and Quiggin (1995) for a discussion in the environmental-policy context.

Those authors frame this problem as one of regulatory "commitment," which implies that the "more plausible" assumption is that commitment is not feasible (even though it is typically desirable), since it would require some sort of bond posted by the regulator. However, it seems more natural to view the issue as one of real constraints on the regulator's behavior. In the real world, legislatures do not respond instantly to all developments, and regulators are often unable to change the fundamental structure of regulatory regimes "from the inside." Hence it seems eminently reasonable to assume some intertia in the regulatory regime, even if the regime itself defines some ways that the regulator can react to choices made by firms. That this assumption of "sticky regimes but rule-based responses" may in effect offer the regulator valuable commitment power is an interesting one, but one we shall not pursue further.

Note that the regulator does not have any specific information about the set of techniques that may be possible, other than the benchmark; nor does the regulator know the costs of research and development, or the probability such research will pay off.

5.2 Optimal regulation

Once research has been carried out, and the set Θ of techniques is available, social welfare is maximized if the polluter faces the actual costs of producing (*i.e.*, manufacturing) and installing the technique. Because I focus here on the effects of environmental policy instruments on adoption, I assume that this condition holds, so that the polluting firm pays exactly the cost of adoption k_i if it chooses technique i.[34] Given this assumption, under the two-part instruments proposed here the firm will choose the efficient technique from its available set, as I show below. Again, I am making a strong distinction between adoption and innovation, in an effort to arrive at clear results.[35]

The regulator does not know which techniques will be available to the polluter (since that depends on the costs of research and development). She therefore announces a menu of two-part tariffs applicable to any technique i. Let m_i^* denote the efficient choice of emissions rate for technique i; that is, m_i^* satisfies $c_m(m_i^*;\theta_i) = b'(m_i^*)$.

The regulator can achieve the efficient levels of adoption and abatement by offering the firm the following menu. If the firm uses technique θ_0, it pays a tax of $t_0 = -b'(m_0^*)$ on each unit of emissions. If the firm uses technique θ_i, it pays a unit emissions tax $t_i = -b'(m_i^*)$ and an adoption levy $A(\theta_i)$. (For convenience, I will often refer to a levy A_i, suppressing the dependence on θ.) For the optimal levy A_i^* derived below, this regime achieves the efficient choice of technique and efficient abatement given that technique, for any set of available techniques.

Note first that this menu ensures that the firm emits at the socially optimal rate given its choice of technique, since for each technique i it faces an emissions tax of $-b'(m_i^*)$. Intuitively, as with any two-part tariff, the tax rates $\{t_i\}$ ensure efficient abatement. The optimal adoption levy ensures efficient adoption, as I now show.

Now consider the firm's choice between technique 0 and some technique j that is available to it in the third period. The firm's adoption decision will be efficient if and only if the firm's net cost savings from using technique j coincide with the net benefits to society that result from adoption. The net social benefit from adoption is simply the difference between the net social benefits at m_0^* and those at m_j^*, minus the *ex ante* cost of research and development. Hence net social benefits

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[34] Note that in the simple model of section 4, there was only one possible technique, so the policy of charging the polluter its expected social cost if available was efficient. In general, however, given the existence of a set of techniques *ex post*, the choice of technique by the firm ought not to incorporate the sunk costs of research and development.

[35] Without specifying a model of innovation and R&D policy, we cannot conclude that the set of available techniques Θ will be optimal. Moreover, as is well known (see, *e.g.,* Tirole 1997, ch. 10), the *ex post* optimal cost of technique i to the polluting firm, k_i, will provide insufficient incentive *ex ante* for the innovators to engage in research. Of course, the cost paid by a firm that adopts technique i need not equal the amount received by the innovator that generates technique i. One particularly simple model of innovation is that it is government-financed, perhaps by a separate government "agency" with knowledge of the costs of research and probabilities of success. (We could suppose that that agency learned such information in period 2, after the announcement of the policy instrument in period 1.) Acting to maximize social welfare, the government would then invest optimally in research, and would provide the outputs of research (the available techniques) to the polluting firm at the *ex post* socially optimal cost k_i for each $i, \theta_i \in \Theta$.

from the adoption of technique j are given by:

$$\begin{aligned}NSB_j &= \big(b(m_j^*) - c(m_j^*;\theta_j)\big) - \big(b(m_0^*) - c(m_0^*;\theta_0)\big) - (k_j - k_0) \\ &= \big(c(m_0^*;\theta_0) - c(m_0^*;\theta_j)\big) + \big(b(m_j^*) - b(m_0^*)\big) - \big(c(m_j^*;\theta_j) - c(m_0^*;\theta_j)\big) \\ &\quad -(k_j - k_0) \\ &= \int_{\theta_j}^{\theta_0} c_\theta(m_0^*;\theta)d\theta + \int_{m_0^*}^{m_j^*} \left[b'(m) - c_m(m;\theta_j)\right] dm - (k_j - k_0). \qquad (2)\end{aligned}$$

The first term on the right-hand side of equation (2) is the cost savings from switching from technique 0 to technique j given emissions rate m_0^*; the second term is the increase in net social benefits from moving from emissions rate m_0^* to m_j^*, given technique j. Both terms are positive.

The firm's net private gain from adopting technique j rather than technique 0 is the difference in abatement costs, plus the reduction in tax payments, minus the adoption cost and adoption levy:

$$\begin{aligned}NPB_j &= c(m_0^*;\theta_0) - c(m_i^*;\theta_i) + (t_0 m_0^* - t_j m_j^*) - (k_j - k_0) - A_j \\ &= c(m_0^*;\theta_0) - c(m_0^*;\theta_j) + c(m_0^*;\theta_j) - c(m_j^*;\theta_j) + (t_0 m_0^* - t_j m_j^*) \\ &\quad -(k_j - k_0) - A_j \\ &= \int_{\theta_j}^{\theta_0} c_\theta(m_0^*;\theta)d\theta - \int_{m_0^*}^{m_j^*} c_m(m;\theta_j)dm + (t_0 m_0^* - t_j m_j^*) \qquad (3) \\ &\quad -(k_j - k_0) - A_j.\end{aligned}$$

The first term on the right-hand side of equation (3) is again the cost savings from using technique θ_j rather than θ_0 at m_0^*; the second term is the increase in the firm's costs to reduce its emissions rate from m_0^* to m_j^*, under technique θ_j; and the third term is the pure gain to the firm from the fall in the tax that accompanies its adoption of technique θ_j.

The abatement levy A_j that equalizes the firm's private gains with social benefits is therefore defined by equating (2) and (3). A little algebra then yields the optimal adoption levy. Defined for any technique i, the optimal levy is:

$$A_i^* \equiv (t_0 m_0^* - t_i m_i^*) - \int_{m_0^*}^{m_i^*} b'(m)dm. \qquad (4)$$

The right-hand side of equation (4) is the difference between the firm's tax savings and the benefits to society from increased abatement.[36] Note that the adoption levy A_0^* for the benchmark technique, of course, is zero.

The abatement levy is positive if and only if the new technique j has lower marginal costs than the benchmark technique 0. To see this, first consider the case of lower marginal costs, so that $\theta_j < \theta_0$ and hence $m_0^* > m_j^*$. I can separate the firm's tax savings $t_0 m_0^* - t_j m_j^*$ into two parts: the savings on the reduction in emissions from m_0^* to m_j^*, and the savings the firm enjoys on emissions m_j^*:

$$\text{Tax savings } = t_0(m_0^* - m_j^*) + (t_0 - t_j)m_j^*. \qquad (5)$$

Society gains some benefit from the firm's reduction in emissions. However, by construction the initial tax p_0 is equal to the marginal benefit of abatement at m_0^*, and by assumption the marginal

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[36] In terms of the model studied in section 4.2, this expression corresponds exactly to area($dsug$) in Figure 3.

benefit declines as emissions fall. Therefore, $t_0(m_0^* - m_j^*)$ is greater than $\int_{m_0^*}^{m_j^*} b'(m)dm$. Moreover, the firm's tax payments fall by $(t_0 - t_j)m_j^*$, a pure transfer that generates no social benefits. Hence the firm's tax payments fall by more than social benefits rise. The levy A_j^* equals the difference between the two. Intuitively, the regulator lowers the tax to achieve the efficient emissions rate given the lower marginal cost function. This requires that the regulator also charge the firm for adopting the technique, lest the firm adopt a technique that yields substantial private gains to the firm, but little or negative benefits to society.

Now suppose that the new technique j has *higher* marginal costs, so that $\theta_j > \theta_0$ and emissions rise after adoption of θ_j. In this case, social benefits from abatement fall, since the emissions rate increases. However, the increase in the firm's tax payments is larger than the fall in benefits. Indeed, equation (5) now represents the firm's tax *increase*, rather than its savings. By the concavity of the benefit function, $t_0(m_0^* - m_j^*) < \int_{m_0^*}^{m_j^*} b'(m)dm$ (note that both terms are negative). Moreover, $t_0 < t_j$. Hence $A_j^* < 0$. When the new technique has higher marginal costs, the efficient tax increases. To compensate the firm for the increase in tax payments, the regulator must offer a *subsidy* on adoption. As before, the magnitude of the subsidy equals the difference between the change in the firm's tax payments and the change in social benefits.

In both cases, the optimal abatement levy equals the excess gain the firm enjoys from adoption, beyond the net benefits to society. By capturing this excess gain through the abatement levy, the regulator aligns the firm's incentive to adopt a new technique with society's interests.

The instrument is exactly analogous to a two-part tariff charged by a discriminating monopolist, who charges price equal to marginal cost (to ensure efficient consumption) and uses a fixed charge to collect consumer surplus (Schmalensee 1982). Indeed, this two-part instrument is simply an instance of second-degree price discrimination by the regulator. It is also analogous to the screening models common in the literature on public regulation of monopolies or of firms contracted to supply to the government (Baron and Myerson 1982; Laffont and Tirole 1986). Indeed, note that my assumption that $c_{m\theta} < 0$ is equivalent to the "single-crossing" property proposed by Mirrlees (1971) and usually assumed in those moral hazard models. The key difference in my model, of course – and the reason that in this case the two-part instruments achieve the efficient outcome – is that the regulator is assumed able to observe the firm's technique, or its "type."[37]

Figure 5 illustrates the two-part tariff for the case in which the new technique has lower marginal costs. The figure depicts two abatement cost curves, corresponding to techniques $\theta_0 < \theta_j$, along with the benefit function $b(m)$. Also drawn are the tangent lines to the benefit and cost functions at the efficient emissions rates m_0^* and m_j^*.

The net social benefit under technique θ_0 is just the vertical distance between the benefit and cost curves; measured on the vertical axis, this equals distance $x + y$. Similarly, the net social benefit under θ_j is given by $y + z$. The increase in net social benefit from using technique θ_j rather than technique θ_0 is therefore $(y + z) - (x + y) = z - x$. Note that this takes into account the capital costs (including the cost of research and development) associated with the two techniques.

To induce the correct emissions rates, the regulator charges the optimal tax for each technique. However, as I have seen, the fall in the tax inflates the firm's cost savings from adopting technique

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[37] It would be interesting to extend our current model to one in which the regulator was uncertain about the firm's type. From the literature just cited, we would expect that such uncertainty would result in a loss due to the information rent demanded by the firm in return for revealing its type. Moreover, there would no distortion for the lowest-cost firms. Whether this would alter the firm's incentives for technique choice in a significant way is not obvious *a priori*, however.

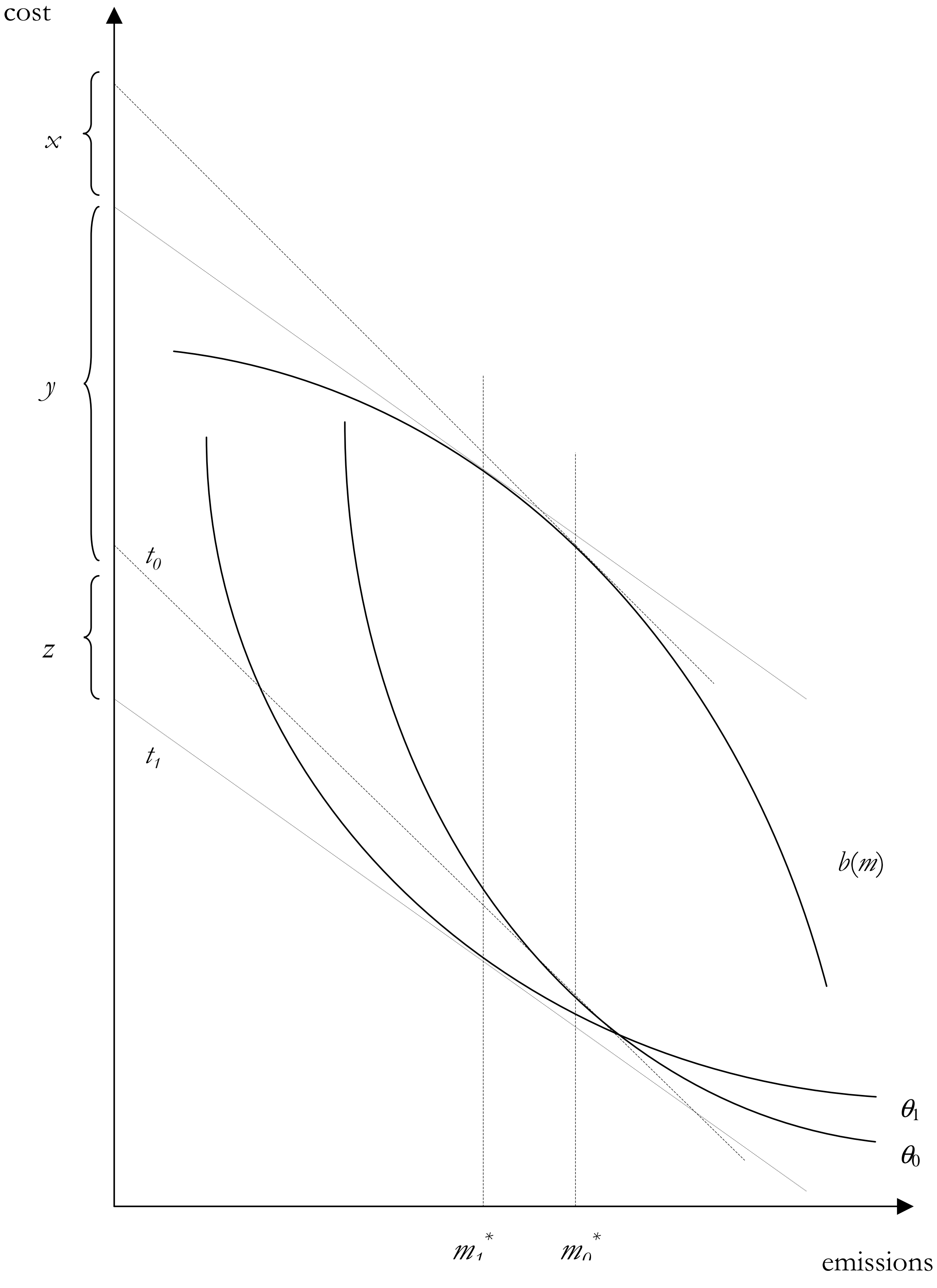

FIGURE 5 -- Optimal two-part tariff for a new technique with lower marginal costs.

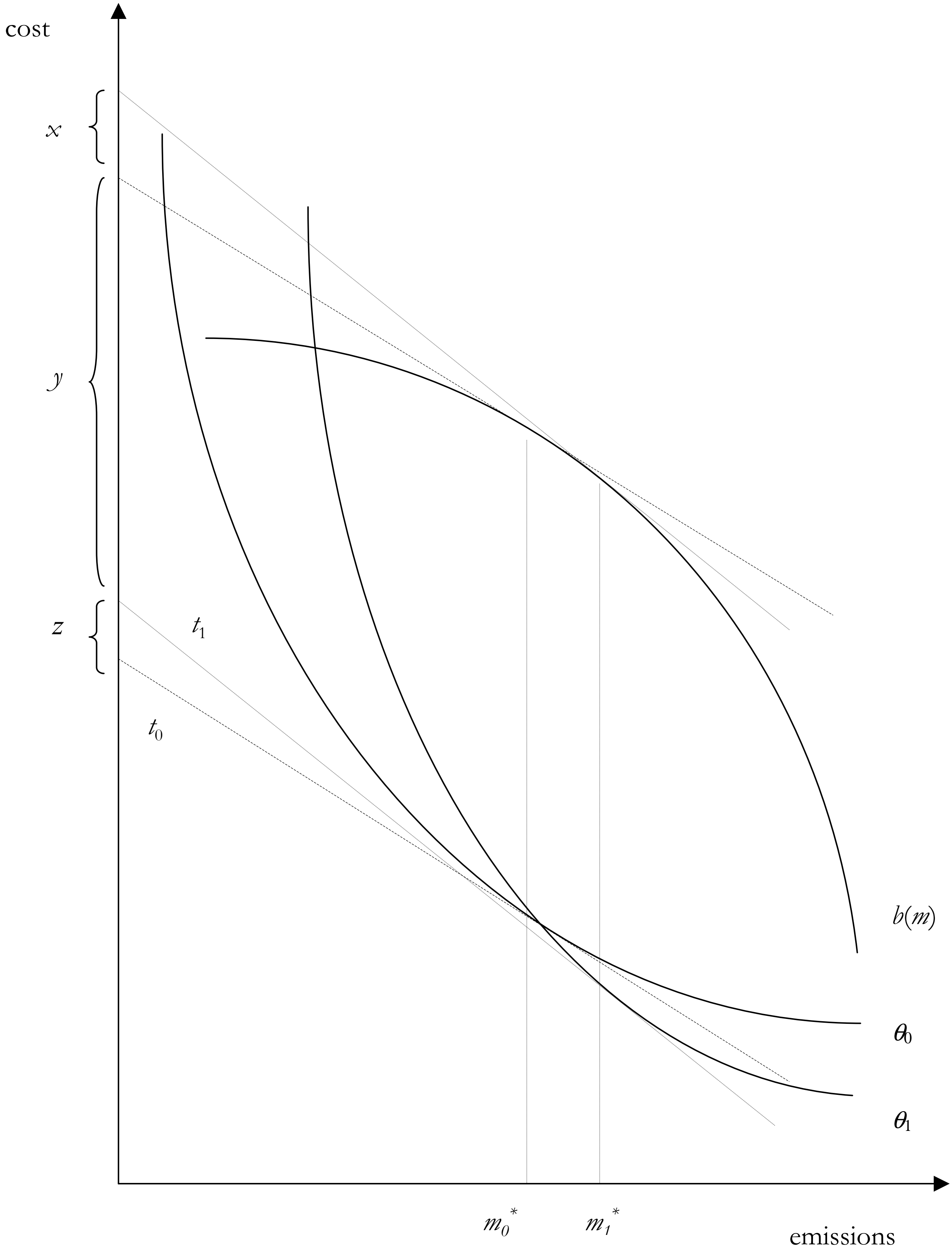

FIGURE 6 -- Optimal two-part tariff for a new technique with higher marginal costs.

θ_j. In the figure, the firm's *private* gain is given by distance z, the difference in its total compliance costs (including capital costs) under the two regimes. To align the firm's adoption incentive with the social interest, the regulator must charge a levy A_j so that the firm's private gain after paying the levy, $z - A_j$, equals the social benefit $z - x$. This levy is simply x. Note that the levy corresponds on the figure to the difference between the government's loss in tax revenue and its gain in gross abatement benefits – which is equivalent to the difference between the firm's tax savings and the increase in benefits to society, as given in equation (4).

The higher-marginal-cost case is illustrated by Figure 6. The net social benefit under the benchmark technique θ_0 is now $y + z$, while the net benefit under θ_j is $x + y$; hence the net social gain from the use of technique θ_j is $x - z$. The firm's compliance costs *increase*, however, so that its private gain is $-z$. With efficient taxes t_0 and t_j, the firm clearly would not adopt the new technique, even when it is in society's interest to do so. The regulator optimally offers a subsidy equal to x, which equalizes the social and private gains. Now, as the figure illustrates, the adoption subsidy x equals the *gain* in the government's revenue from the increase in the tax minus the loss in benefits due to increased abatement.

Note that the case of a higher-marginal-cost technique is naturally incorporated into the total cost and benefit approach used here.[38] For this technique ever to be attractive, however, the total fixed costs must be lower, so that $k_j < k_0$. Since the fixed cost k_j includes the cost of research and development, this case applies only when such research results in a sufficient savings in capital costs as to outweigh the costs of research. Nonetheless, even if this case will be rare, there is no reason to exclude it *ex ante*, as previous literature has done.

I now state my result formally, drawing on the discussion to this point.

Proposition 3 *Let Assumptions 1-6 hold, and consider the three-period model described above. Assume that if the polluting firm chooses technique $\theta_i \in \Theta$, it pays the ex post cost of producing and installing that technique, given its availability.*

Consider the following menu of two part-tariffs: For any technique i, including the benchmark technique 0, the regulator offers a combination of a tax $t_i = -b'(m_i^*)$ and an adoption levy $A_i^* \equiv (t_0 m_0^* - t_i m_i^*) - \int_{m_0^*}^{m_i^*} b'(m)dm$. (Note that the levy A_i^* will be positive for techniques with $\theta_i < \theta_0$ and negative (i.e., a subsidy) for techniques with $\theta_i > \theta_0$ (and zero for θ_0).)

Then the proposed menu of two-part tariffs achieves the efficient choice of technique and the efficient emissions rate, given the set of techniques Θ available to the polluting firm.

Proof For any technique i, the proposed system induces the efficient emissions rate m_i^* for that technique, since the firm chooses m_i to minimize $c(m;\theta_i) - b'(m_i^*)m + k + A_i^*$. I have already shown that A_i^* is positive iff $\theta_i < \theta_0$. I now show that the firm's choice of technique is optimal, given the set available to it. Substituting for A_j^* in equation (3) and rearranging, I get the polluter's net private gain from using technique j relative to technique 0 under the proposed policy, which is $NPB_j^* = (b(m_i^*;\theta_i) - c(m_i^*;\theta_i) - k_i) - (b(m_0^*;\theta_0) - c(m_0^*;\theta_0))$. This is identically equal to the net social benefits from using technique i rather than 0. Hence if more than one technique is available, the firm will choose the one with the highest net social benefits.■

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[38] A focus on marginal cost curves, on the other hand, tends to blind the analyst to the possibility that a higher-marginal-cost technique might be preferable.

Proposition 3 shows that by using a menu of two-part tariffs, the regulator can simultaneously induce efficiency in the choice of technique and the choice of abatement, despite her ignorance of the costs or probabilities of success of research and development. Under the proposed policy, the polluting firm's incentives are aligned with social welfare, so that the most valuable technique to the polluter is also the technique that maximizes net social benefits given the set of available techniques.[39]

While I have couched my discussion in terms of combining a price instrument and an adoption levy, it is straightforward to extend the concept of a two-part instrument to quantity instruments. The regulator could also maximize social welfare by offering a menu of quantity standards and adoption charges or subsidies. The argument follows precisely the same logic as in the example of taxes. Under such a policy, the social net benefits from the adoption of technique j rather than 0 are obviously unaffected, and are given by (2). The private net gains to the firm are simply $NPB_j = c(m_0^*; \theta_0) - c(m_i^*; \theta_i) - (k_j - k_0) - A_j$. Equating these terms for some arbitrary technique i and solving for A_i yields the optimal levy A_i^{**} to be paired with quantity standards $\{m_i^*\}$.

Corollary *Under the conditions of Proposition 5, the regulator could also achieve the efficient outcome by offering a menu of two-part instruments in which a firm choosing technique i must abate at rate m_i^* and is charged an adoption levy $A_i^{**} = b(m_0^*) - b(m_1^*)$.*

The optimal adoption levies under a menu of standards simply correspond to the benefits associated with the change in pollution due to the change in technique, and clearly internalize social benefits into the firm's adoption incentive.

So far, I have concentrated on stating the results in terms of a given set Θ of available techniques. Proposition 3, by itself, is a statement about adoption incentives, and is essentially independent of the assumptions made about innovative activity. It shows that for a given set of techniques resulting from innovation, the two-part instrument ensures both that the polluter chooses the technique with the greatest net social benefit, and that the firm emits at the socially optimal rate given that technique.

However, if in addition there was an R&D policy in place that induced the efficient level of research effort, then the proposed two-part instrument would also achieve efficient innovative activity. As an example, I suggested the particularly simple model of a "benign and well-informed government agency" model suggested in note __ above. Moreover, note that even an enlightened R&D policy would not on its own achieve optimal innovative effort, since a distortion of the firm's adoption incentives would also distort the incentives of innovators to do research.

If R&D policy is not optimal, I will necessarily end up in a "second-best" world, even apart from the limits on the regulator's knowledge of abatement cost functions. In general, one can defend my approach by arguing that an examination of optimal policies in one sector may reasonably assume optimal policies in other related areas of government. Of course, it might also be worthwhile to investigate second-best policies in the presence of inefficient policies in other realms of government; but it is also be desirable to know what policy instruments are optimal in an otherwise "first best"

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[39] Compare our approach with that of Biglaiser and Horowitz (1995), who conclude that the regulator's optimal policy is to require firms to adopt a certain "best available technology." To do so, however, the regulator must identify such a technology. Our proposed two-part instruments allow the regulator in effect to ensure that the firm adopts the best technique available to it, even when the regulator does not observe the costs of adopting different techniques (and therefore could not know the best available one).

world.[40]

Once seen, the optimality of a two-part tariff may appear obvious in this context, especially given the close resemblance between the regulator's problem here and its problem in other cases of public regulation, where screening models have been common. However, the application of two-part tariffs to environmental policy suggests some surprising consequences.

As an example, consider policies to promote the optimal use of energy-efficient methods of production. (Note that such policies would not necessarily be the same as policies to promote the use of *more* energy-efficient technologies, since it is conceivable that greater energy efficiency may come at too high a cost.) In discussions of the possible policies a regulator might use in this context, adoption subsidies – paying firms or consumers who purchase more energy-efficient technologies – are often proposed, both in analysis and in practice.[41]

More energy-efficient methods, by definition, entail a lower use of energy for a given output. I might also suppose that they entail a lower change in energy use to increase output on the margin.[42] If this is the case, then my model suggests that the regulator would optimally impose a *charge* on the adoption of more energy-efficient methods, and would subsidize the adoption of *less* energy-efficient techniques. Of course, in the former case the firm would be compensated by a reduction in the tax on energy. Moreover, one could argue that in the absence of such two-part standards, a stand-alone adoption subsidy remains a reasonable policy. Nonetheless, the contrast between the optimal policy and what is often advocated is somewhat surprising.

Of course, one might argue that what I care about is carbon dioxide emissions (say) rather than energy efficiency. Still, in this case, my model suggests that a regulator ought to charge a levy on adoption of new techniques with lower marginal costs of reducing CO_2 emissions, and a subsidy on the adoption of techniques with higher marginal costs of emissions reductions.

For another example, take the case of sulfur dioxide emissions from electric power plants. The basic message from my model is that an optimal policy, given technical change, would charge firms some amount for adopting a scrubber with a lower marginal cost, and pay firms to adopt a scrubber with a higher marginal cost. Again, these levies or subsidies would be offset by changes in the emissions tax (or required abatement rate).

5.3 Extension to multiple polluters

So far in my model with welfare, I have assumed the existence of one regulated firm – or equivalently a representative firm from some homogeneous industry. I now briefly sketch how my model of two-part tariffs with unit emissions taxes would generalize to the case of an industry with a number of heterogeneous firms.[43]

First, consider the case in which the firms are large and few enough that their actions affect the aggregate marginal cost curve for the industry. Suppose a given firm adopts a technique

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[40] In exactly the same fashion, there is utility both in traditional Pigouvian analyses of optimal taxes and in analyses of instrument choice in the presence of preexisting distortionary taxes (*e.g.,* Goulder *et al.* 1997).

[41] In two papers on the theory and empirical modeling of the diffusion of energy-efficient home insulation, for example, Jaffe and Stavins (1994, 1995) include adoption subsidies as one of the possible instruments for consideration. The point is not whether they advocate such policies (they do not), but rather that adoption subsidies are commonly accepted as conceivable parts of the optimal mix of policies.

[42] This assumption conforms to our model in which innovation does not simply reduce abatement cost by some fixed amount, but rather alters the marginal costs of abatement. This is a fairly standard way of modeling technological change.

[43] Because we are still considering the benefits of abatement, we continue to assume that each firm's output is fixed.

that lowers the aggregate marginal abatement cost. To ensure the optimal industry-wide level of abatement given the new marginal abatement cost curve, the regulator would need to reduce the emissions tax accordingly. However, this tax reduction would provide too large an incentive for the firm to adopt, as in the single-firm model above. The regulator could correct for this excess incentive by charging the adopting firm a levy equal to its total savings in tax payments, minus the social benefits from the increased abatement attributable to adoption, minus the real cost savings from reductions in abatement by other firms. Similarly, if the firm adopted a higher-marginal-cost technique, the regulator would raise the emissions tax and offer the adopting firm a subsidy equal to the difference between the firm's increase in tax payments and the loss of benefits and gain in other firm's abatement costs due to the adoption.

Thus the two-part tariff suggested above could also be applied when there is more than one firm, but each is large enough to affect aggregate marginal abatement cost. As in the model above, this two-part instrument would simultaneously create the optimal incentives for efficient adoption and for efficient abatement.

Although the two-part tariff would be conceptually similar in this case to that in the single-firm case, there are two interesting points to note. First, the emissions tax must rise or fall for the industry as a whole, not simply for the adopting firm; this is obviously necessary to ensure an efficient allocation of pollution control among the firms. As a result, each firm in the industry would reap a "windfall gain" if another firm adopted a lower marginal cost technique, and would bear a similar loss if another firm adopted a higher marginal cost technique. From the point of view of society, however, such gains or losses would simply be transfers between the firms and the government, with no welfare consequences of their own.

A second twist involves the size of the levy or subsidy. A firm that adopts a new technique would not get credit or blame from the government for the windfall gain or loss in tax payments that other firms enjoy or suffer, since those gains or losses are simply transfers. However, the change in the tax *will* affect the abatement decisions of other firms, which in turn will affect total abatement and hence total benefits and costs. Those "real" effects would be reflected in the adoption levy.

Suppose that a certain firm's adoption of a low-marginal-cost technique reduces the efficient tax from t_0 to t_1. Each non-adopting firm i would emit more than before, since it chooses m^i to equate marginal abatement cost with the tax, and $-c_m(m_0^i) = t_0 > t_1 = -c_m(m_1^i) \Rightarrow m_0^i < m_1^i$. These increased emissions would partially offset the adopting firm's own reduction in emissions, reducing the social benefits from adoption and hence increasing the adoption levy. At the same time, the abatement costs of the non-adopting firms would fall as those firms abated less; this fall in cost would rightly be credited to the adopting firm.[44]

Similarly, in the case of a higher-marginal-cost technology, the adopting firm's increase in emissions (and hence the resulting reduction in abatement benefits) would be dampened by decreases in the emissions of other firms; but the adopting firm's savings in abatement costs would also be partially offset by the increased costs incurred by the other firms.

Finally, consider the case in which firms are many and "small," so that the effect of any individual firm's choice of technique on aggregate abatement or marginal cost is negligible. In this case, the two-part tariff could not be applied to polluting firms. However, a modified version of it could be applied by assessing the adoption levy on the *innovating* firms, assuming that the innovations they produce are adopted widely enough to affect aggregate marginal abatement cost in the

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[44] In their model of an adopting firm and a responsive regulator, Downing and White (1986) make a similar point about the welfare effects of adoption by a "large" firm, although of course they do not consider two-part instruments.

regulated industry.

The two-part tariff would now work as follows. Suppose an innovating firm produces a new technique with lower marginal costs of reducing emissions, and the technique is adopted by a number of firms sufficient to drive the efficient emissions tax down to t_1 from t_0. Suppose further that the innovator is able to capture all of the gain to the firms resulting from their fall in tax payments. The regulator would, as before, adjust the emissions tax to its new efficient level, ensuring optimal abatement given the new aggregate marginal cost curve. Instead of charging the adoption levy to the individual firms, the regulator would collect it from the innovator. The size of this adoption levy would equal the change in total tax payments (now summed across adopting firms) minus the social benefits from increased abatement.

6 Conclusion

The model in Section 3, while simple, relates the discussion of endogenous techniques to the standard model of policy instrument choice under uncertainty, due to Weitzman. Its major contribution, relative to previous attempts in the literature to compare the welfare effects of policy instruments, is that it starts from the premise that a welfare-maximizing regulator will take into account the possibility of technical change, and choose an instrument accordingly. It therefore avoids the pitfall of the existing literature, in which the regulator is apparently not even aware of the possibility of technical change.

Even when the regulator takes the possibility of technical change into account in her choice of policy instrument, the Weitzman relative-costs prescription does not necessarily hold (although, notably, it does continue to hold in the important case in which the costs of developing new techniques are small relative to the social benefits). The model demonstrates that simply allowing the firm to choose a technique can make a significant difference in the optimal policy instrument *ex ante,* because the cost savings to the firm from adopting the new technique differ under a price and quantity. Although crude, the model hints at a possible bias in favor of quantity instruments, since the possibility of inefficient adoption is compounded by the greater flexibility created by the price instrument. In some cases, the price instrument makes the firm *too* responsive to the costs of abatement.

The second and major contribution of this paper is to demonstrate the attractiveness of a previously unexplored instrument for environmental policy: a two-part instrument, with a menu of unit emissions taxes and subsidies or levies on adoption. By implementing such a regime, the regulator is able to achieve both the efficient adoption decision and the efficient abatement level by the firm, given the set of techniques made available by research. This is true despite the fact that the regulator does not know the outcome of research in advance, nor the costs or success probabilities of research efforts. Moreover, in combination with an optimal R&D policy, this two-part instrument is also optimal, so that the regulator can achieve the first best outcome. Although this instrument has been overlooked, I have provided several reasons why it should be considered among the set of instruments available to the regulator.

As I point out, this instrument bears a strong resemblance to the two-part tariffs and cost-price menus suggested in the industrial organization literature. However, it yields an interesting twist when applied to environmental policy. The optimal policy involves levies on the adoption of lower-marginal-cost techniques, and subsidies on the adoption of higher-marginal-cost techniques. I suggest that in some contexts, this leads to much different policy prescriptions than usually advocated.

With the advent of global environmental policy issues with long time horizons, the costs of pollution abatement over the long run assume growing importance. Hence there is a corresponding need for a clearer understanding of the ways in which policy instruments affect technique choice, and of the policies that might promote optimal choices by firms. This paper hopes to achieve a small step in that direction.

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