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Learning about Environmental Damage: Implications for Emissions Trading

by

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ABSTRACT

`This paper examines the impact of adjusting the supply of permits in an emissions trading program, in response to new information about environmental damage, on incentives for cleaner technology adoption. Two policy rules for adjusting the supply of are examined: open market operations; and a proportional adjustment rule under which the regulator expropriates permits from individual firms in proportion to their existing permit holdings. Adjustment via open market operations is neutral with respect to cleaner technology investment decisions but may be politically difficult to implement. The proportional adjustment rule is also neutral with respect to investment decisions and at the same time allows more flexibility from a political perspective.

INTRODUCTION

One of the most important problems facing regulators when setting environmental policy is uncertainty about environmental damage. Thousands of substances are released into the environment every day and in many cases their impact on human health and environmental quality is entirely unknown. Even in cases where there is a clear link between a particular substance and an associated environmental impact, the nature and extent of that link are usually uncertain.

The problem of designing regulations in the face of this uncertainty is complicated further by the possibility of learning: beliefs about damage are generally revised over time as new information comes to light. This means that an emissions target for a particular substance set today on the basis of current knowledge may have to be revised in the future if new information reveals the substance to be significantly more or less damaging than originally believed. This in turn raises an important policy issue: how should firms who have made irreversible investment decisions based on current environmental targets be treated if those targets are revised in the future? This paper addresses that policy issue in the context of an emissions trading program.[1]

The supply of permits in an emissions trading program should ideally be set to balance the costs and benefits of pollution abatement. New information about damage can potentially shift that balance and require a change in the supply of permits. In particular, "bad news" about damage may mean that some permits have to be retired, while "good news" may call for the issue of additional permits. The manner in which such adjustments are made has important implications for the incentives firms have to invest in pollution abatement technology. The key point to recognize in this respect is that emission permits are tradeable assets: a permit confers on its holder the right to emit a stream of emissions over time. Any anticipated regulatory change that is expected to affect the future value of permits, such as a change in the supply of permits, will affect incentives to hold permits today. This in turn will generally influence the decision to adopt a cleaner technology because holding permits and switching to a cleaner technology are to some extent substitute investment strategies for a firm. My paper focuses on this link between permit supply adjustment and incentives for cleaner technology adoption.

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[1] I examine a trading program in which firms must hold permits to cover their emissions. A variation on this scheme is an "emissions reduction credit program" under which firms can buy and sell credits for emission reductions from a particular base. The analysis in this paper can be easily recast in terms of an emissions reduction credit program; the same basic insights emerge.

A number of other papers have examined technology adoption under emissions trading, though none have addressed the issue of supply adjustment in response to learning.[2] Malueg (1989) argues that emissions trading in general may not create the right incentives for new technology adoption, but his analysis is flawed by a failure to examine incentives *in equilibrium;* the firms in his paper do not base their investment decisions on a rational expectation of equilibrium prices. Downing and White (1986) and Milliman and Prince (1989) similarly neglect equilibrium considerations. Biglaiser et al. (1995) claim that technology adoption is distorted under emissions trading because of a time inconsistency problem for the regulator. However, this problem arises in their model only when the investment decisions of individual firms have a significant effect on aggregate emissions. This possibility is not consistent with their assumption of price-taking behavior on the permit market. If firms are small players in the permit market then there is no dynamic inconsistency problem and no associated distortion of technology investment decisions. Laffont and Tirole (1996) also claim that technology adoption is distorted under emissions trading. However, their result is due to a distortion associated with a non-unitary marginal cost of public funds: the regulator cannot commit not to distort future permit prices for the purpose of raising revenue. This is principally a standard capital taxation issue, and is not specific to emissions trading *per se*.

Contrary to these results in the existing literature, my paper demonstrates that emissions trading can induce efficient technology adoption, even when the regulatory problem is complicated by learning. I characterize the incentives for technology adoption under a general specification of the permit supply adjustment policy and then focus on two specific adjustment rules: “open market operations” and “proportional adjustment”. I show that adjustment via open market operations, whereby the regulator buys or sells permits at the market price, yields efficient investment decisions, but the policy may be politically difficult to implement because it rewards firms when emissions are found to be more damaging than expected. I then propose a proportional adjustment rule, under which the regulator expropriates a fixed share of permits from each firm if the supply of permits must be reduced, and grants additional permits on a proportional basis if the supply must be increased. The price paid for expropriated permits and the price charged for additional permits granted is set independently from the supply adjustment, and

[2] See Kemp (1997) for a partial survey of this literature.

this allows greater flexibility from a political perspective. The adjustment rule nonetheless implements efficiency with respect to cleaner technology adoption decisions.

The rest of the paper is organized as follows. Section 2 presents a simple model on which my analysis is based. Section 3 characterizes efficiency in the context of that model. Section 4 then examines implementation via emissions trading. Section 5 concludes.

THE MODEL

Time is divided into two periods. There are a large number of price-taking polluting firms in each period and environmental damage in each period is an increasing function of the flow of their aggregate emissions. Marginal damage is constant and denoted δ. The true value of δ is uncertain in period 1 and has expected value μ. At the beginning of period 2 it becomes known that either $\delta = \delta_H$ or $\delta = \delta_L < \delta_H$, where the "H" subscript denotes high damage and the "L" subscript denotes low damage. Prior beliefs about δ (common to all agents) are represented by $\{\pi_L, \pi_H\}$.

At the beginning of period 1 firms must choose between retaining their existing technology and adopting a new cleaner technology.[3] The existing technology has an associated abatement cost function $c_0(\bar{e}_0 - e)$, where e denotes emissions and $\bar{e}_0$ is the level of emissions corresponding to no abatement. Thus, $\bar{e}_0 - e$ represents abatement.[4] Abatement cost is increasing and strictly convex in abatement: $c_0' > 0$ and $c_0'' > 0$. The new technology has an associated abatement cost function $c_1(\bar{e}_1 - e)$ with $c_1' > 0$ and $c_1'' > 0$, where $\bar{e}_1 \le \bar{e}_0$ and $c_1' < c_0'$ for any $e \le \bar{e}_0$. Thus, any positive level of abatement can be achieved at lower cost with the new technology. Adopting the new technology involves a fixed sunk cost K.[5]

[3] The model is easily extended to allow firms to adopt the new technology in period 2 if they have not done so in period 1. However, this adds nothing of substance to the analysis because the choice in period 2 is made under certainty and it is *uncertainty* that creates the potential for distortion in the investment decision.
[4] Abatement may involve a variety of measures, including a reduction in output, a change in inputs or some end-of-pipe remedial action. The abatement cost function here measures the least cost mix of abatement measures.
[5] Note that firms are assumed to be identical *ex ante*. This assumption simplifies the analysis but it is not important for the main results. This point is discussed further in section 4.

EFFICIENCY

There are two parts to the characterization of efficiency: a static efficiency component and a dynamic efficiency component. Static efficiency requires that the supply of permits in each period be such that marginal damage and marginal abatement cost are equated given the technologies in place in that period. Dynamic efficiency requires that firms adopt the new technology if and only if the net social benefit from doing so is positive.[6] Each component is discussed in turn.

Static efficiency

Suppose all firms use technology i in period 1 (where $i = 0$ denotes the old technology and $i = 1$ denotes the new technology). Then static efficiency in period 1 requires that each firm sets emissions e_{1i}^* such that marginal abatement cost is equated to expected marginal damage. That is,

$$c_i'(\bar{e}_i - e_{1i}^*) = \mu \text{ for } i = 0,1 \qquad [1]$$

This familiar rule minimizes the expected social cost (abatement cost plus expected damage) in period 1, given the technology in place. The solution is illustrated for both the old and new technologies in Figure 1 as e_{10}^* and e_{11}^* respectively.[7]

Static efficiency in period 2 also requires the equality of marginal abatement cost and marginal damage, given the technologies in place:

$$c_i'(\bar{e}_i - e_{2i}^*) = \delta \text{ for } i = 0,1 \qquad [2]$$

The associated optimal level of emissions for a firm depends on the value of δ and whether or not the firm has adopted the new technology. Figure 2 illustrates the case where $\delta = \delta_H$. If the new technology is in place then emissions should be $e_{21}^*(H)$, while if the old technology has been retained then emissions should be $e_{20}^*(H)$. Figure 3 illustrates the case where

[6] The constancy of marginal damage in this model means that the expected social benefit from any single firm adopting the new technology is independent of how many other firms adopt. Thus, if it is efficient for one firm to adopt then it is efficient for all firms to adopt. If marginal damage is increasing then efficiency may call for adoption by only a subset of firms. (See Kennedy and Laplante (1995)). It can be shown that the qualitative results obtained in this paper extend to the case where marginal damage is increasing.

[7] For illustrative purposes only, the figure is drawn for the case where marginal abatement cost is linear and $\bar{e}_1 = \bar{e}_0 = \bar{e}$.

$\delta = \delta_L$, in which case the optimal level of emissions is $e^*_{21}(L)$ under the new technology and $e^*_{20}(L)$ under the old technology.

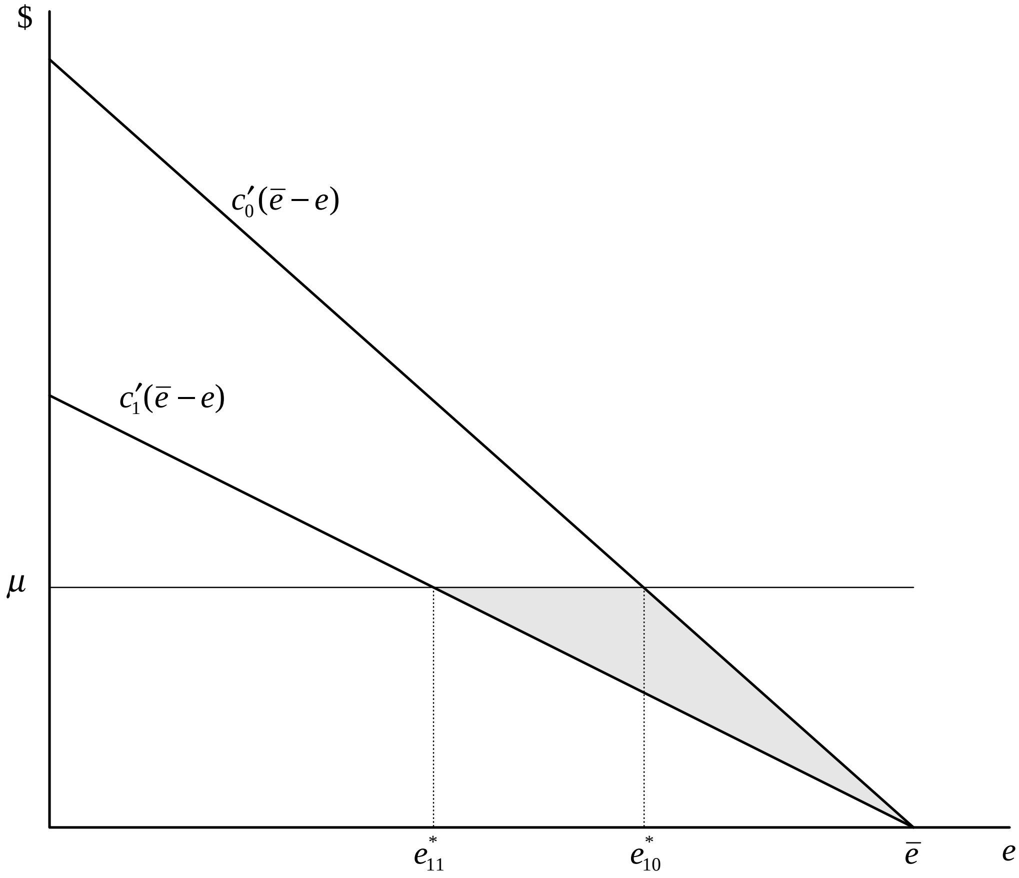

FIGURE 1

Figures 2 and 3 also show for comparison purposes the optimal levels of emissions in period 1 for the old and new technologies. Note that achieving static efficiency in period 2 requires an adjustment to emissions in response to the information about δ; an increase if $\delta = \delta_L$, a decrease if $\delta = \delta_H$. In the context of an emissions trading program this means that the aggregate supply of permits will either have to be increased or reduced depending on what is learned about damage. The policy problem is to make this adjustment in period 2 in a way that does not distort technology adoption decisions in period 1. That is, the problem is to achieve static efficiency in both periods and at the same time induce dynamic efficiency.

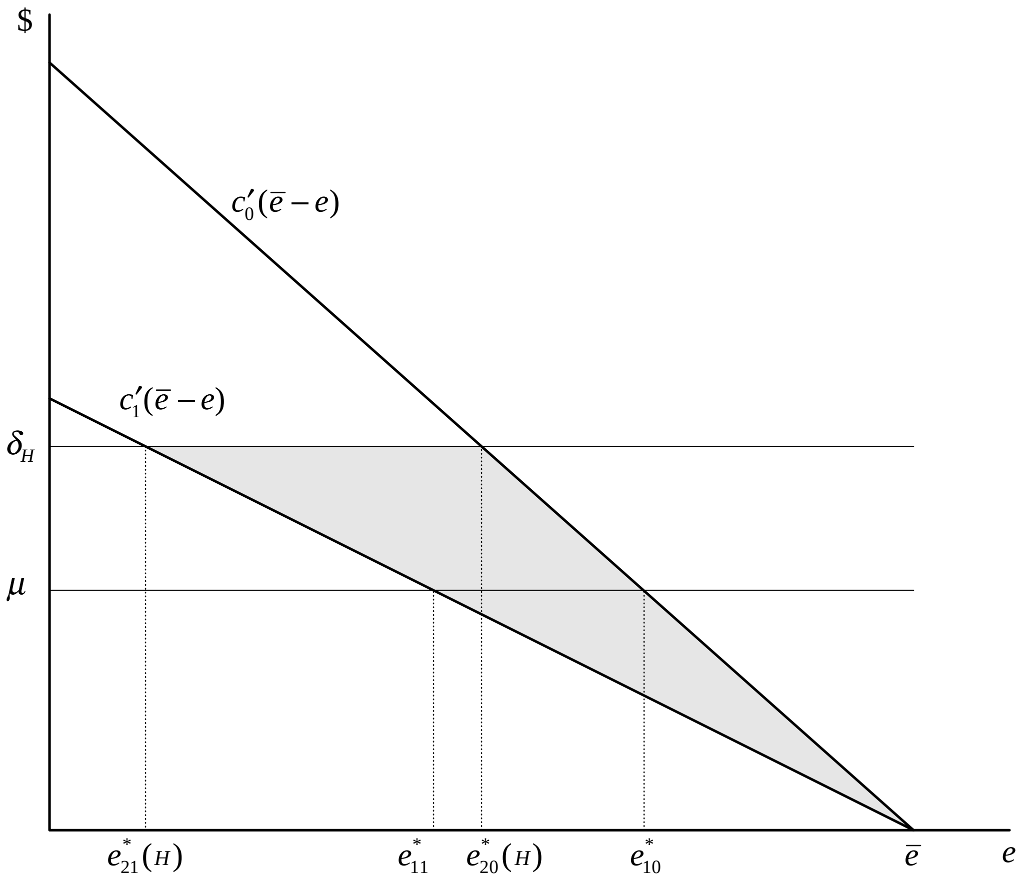

FIGURE 2

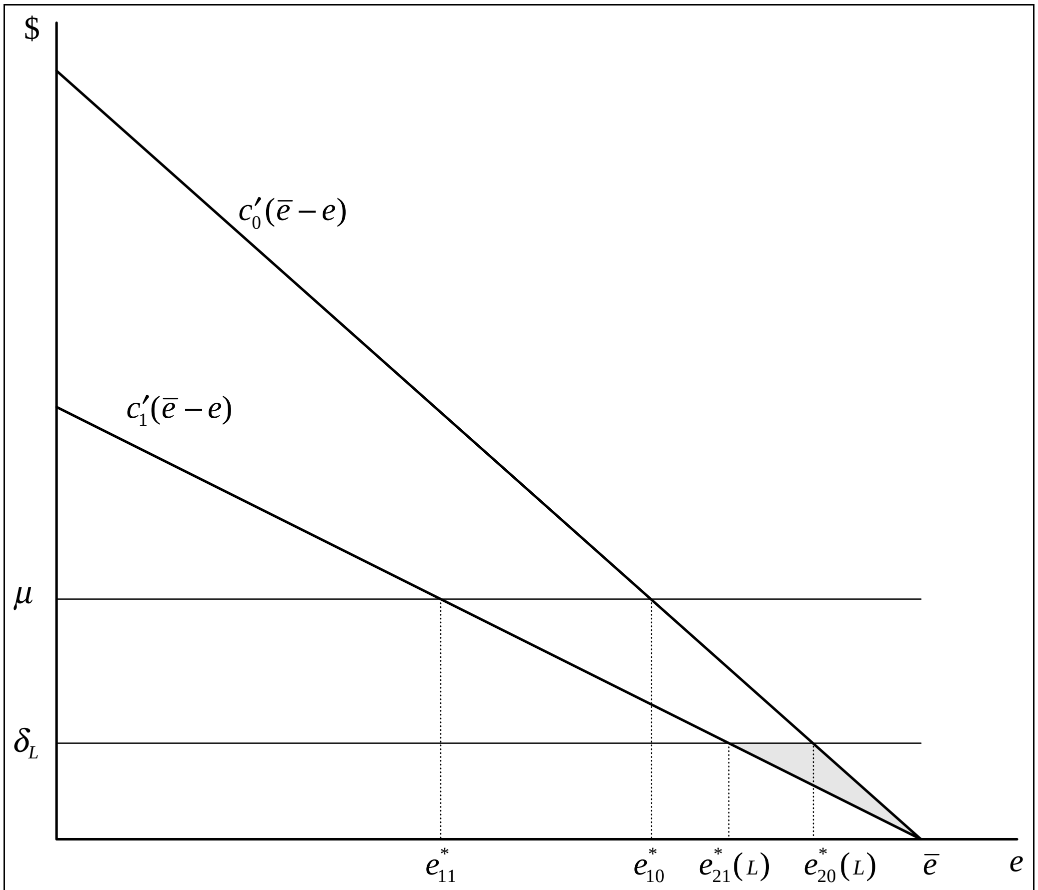

FIGURE 3

Dynamic efficiency

The social benefit from adopting the new technology depends on the damage associated with emissions. Since this is unknown at the time the adoption decision is made, the decision must be based on beliefs about damage. Let *SB* denote the discounted expected social benefit when a representative firm adopts the new technology in period 1:

$$SB = \left[\mu(e_{10}^* - e_{11}^*) + c_0(\bar{e}_0 - e_{10}^*) - c_1(\bar{e}_1 - e_{11}^*)\right] \qquad [3]$$
$$+ \beta \sum_{j=L,H} \pi_j \left[\delta_j\left(e_{20}^*(j) - e_{21}^*(j)\right) + c_0(\bar{e}_0 - e_{20}^*(j)) - c_1(\bar{e}_1 - e_{21}^*(j))\right]$$

where $\beta \in (0,1)$ is the discount factor. The first term (in square brackets) represents the expected social benefit from adoption that accrues in period 1, comprising the expected reduction in damage plus the reduction in abatement costs when emissions are chosen optimally for the technology in place. This term is illustrated as the shaded area in Figure 1. The second term represents the corresponding expected discounted social benefit that accrues in period 2, also calculated at the efficient emission levels. This term is represented by the probability-weighted sum of the shaded areas in Figures 2 and 3. Dynamic efficiency requires adoption of the new technology if and only if $SB \geq K$.

IMPLEMENTATION WITH TRADEABLE EMISSION PERMITS

Efficiency could be implemented by a variety of policy instruments in this setting. One possibility is an emissions fee set equal to expected marginal damage in period 1, and revised in period 2 when the true damage state is realized. In some respects this would be the simplest approach. However, there are a number of reasons why the regulator may prefer an emissions trading program even in this simple setting. Perhaps most importantly, emissions trading allows the regulator more flexibility with respect to the assignment of pollution rights. An emissions fee assigns the entire cost of pollution to the polluting firms, which may not be consistent with promoting the "international competitiveness" of domestic firms and the employment opportunities associated therewith; rightly or wrongly, such goals are of paramount importance to many policy makers. In contrast, emissions trading allows the implicit assignment of pollution rights to polluting firms, either through the free allocation of permits initially, or through an emissions reduction credit program.[8]

Another main advantage of an emissions trading program is that it allows the least-cost implementation of a specified emissions target. In reality, such a target may or may not be based on efficiency considerations. If not, there is little chance that the program will induce efficient technology adoption decisions. However, under ideal circumstances, an emissions target should be based on relative costs and benefits, and should be adjusted in response to new information about those costs and benefits. The purpose of this section is to show that this adjustment can be

[8] For example, there is little doubt that such concerns are at least partly behind the Canadian Government's current preference for emissions reduction credit trading over a carbon tax for the control of greenhouse gas emissions.

made in the context of an emissions trading program while still preserving the correct incentives for technology adoption. The setting is ideal in the sense that the regulator is assumed to possess enough information to assess expected costs and benefits, and so identify an efficient outcome. Thus, the emissions trading program is examined in the best possible light. This seems to be the most natural starting point for assessing how the program might perform in less ideal circumstances.

It should also be noted that the importance of emissions trading is not diminished in this model by the assumption of *ex ante* identical firms. Even though no net trade occurs between firms (assuming an equal initial allocation), the *possibility* of trade is crucial for creating the incentives that lead to implementation of efficiency as an equilibrium. Moreover, while firms are identical *ex ante*, heterogeneity across technologies *ex post* is a possible outcome in the model, and can even arise *in equilibrium* under some supply adjustment rules (although such an outcome is not efficient).[9] The main results derived in this section do not rely on the assumption of identical firms; the key property of the adjustment rules examined is that they specify the same policy parameters for each firm regardless of potential technology differences among firms.

The policy problem

The policy problem is to adjust the supply of permits between periods 1 and 2, in response to the new information about damage, so as to maintain static efficiency in each period and at the same time create the right incentives for technology adoption. That is, firms should have a strict incentive to adopt the new technology if $SB > K$ and a strict incentive not to adopt if $SB < K$. I examine this issue by assessing whether or not the social optimum (as defined by static and dynamic efficiency) is a rational expectations equilibrium in the permit market under a general specification of the supply adjustment rule. The first step is to derive the price path for permits at the optimum.

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[9] For example, an adjustment rule that expropriates a fixed number of permits from each firm in the event of bad news about damage will, under some circumstances, induce an (inefficient) equilibrium in which some firms adopt the new technology and others do not, even though all firms are identical *ex ante*. There is active inter-firm trading in this equilibrium. Moreover, in a more general setting with increasing marginal damage, the efficient equilibrium generally involves *ex post* heterogeneity and active trading even when firms are identical *ex ante*. (See footnote 6).

The permit price path at the social optimum

Suppose technology *i* is socially optimal and all firms use this technology. Then to achieve static efficiency in period 1 the regulator issues ne_{1i}^* permits in that period, where *n* is the number of firms. Each permit allows the holder to emit one unit of emissions in each period.[10] The permits may be issued free of charge (according to some type of "grandfathering" rule based on historical emission levels) or they may be auctioned; at this point it does not matter which approach is taken.

The aggregate supply of permits must be adjusted in period 2 once the true value of δ becomes known. The efficient level of emissions in period 2 is $ne_{2i}^*(H) < ne_{1i}^*$ if $\delta = \delta_H$ and $ne_{2i}^*(L) > ne_{1i}^*$ if $\delta = \delta_L$. Firms rationally expect the regulator to adjust the supply of permits in this way; no other policy will achieve static efficiency in period 2 and so no other policy is time consistent. Accordingly, the price path of permits is solved by backward induction beginning in period 2.

Each firm sets emissions in period 2 such that

$$c_i'(\bar{e}_i - e) = p_2 \qquad [4]$$

where p_2 is the price of permits in that period. That is, the marginal cost of abatement is just equated to the marginal cost of not abating. Since the supply of permits is set to ensure that $c_i'(\bar{e}_i - e) = \delta$, it follows that in equilibrium $p_2 = \delta$. Note that this equilibrium price in period 2 is independent of the manner in which the supply of permits is adjusted between periods 1 and 2 since the equilibrium price must clear the market after any adjustment has taken place regardless of how that adjustment is made.

Next consider period 1. The equilibrium price of a permit in period 1 must be such that the return from selling a permit is just equal to the expected return from holding it for that period. The return from selling a permit in period 1 is simply equal to its price in that period, p_1. The expected return from holding a permit for the period is the avoided cost of one unit of abatement (because holding a permit allows one unit of emissions) plus the discounted expected value of a

[10] It may appear that the supply adjustment problem can be solved easily by fixing the life of a permit at just one period. However, the problem in reality is that transaction costs undermine any trading program in which permits (or credits) are too short-lived. The model is constructed to capture the possibility that new information about

permit carried into period 2. Note that the expected value of a permit carried into period 2 is *not* necessarily equal to the selling price of a permit in period 2; the value of a permit carried forward will generally depend on the supply adjustment rule in place. For example, under a proportional adjustment rule, carrying a permit into period 2 may lead to an increase or decrease in permit holdings through supply adjustment, and this effect will be reflected in the expected value of carrying the permit forward.

To clarify this distinction between expected selling price and expected value, let v_j denote the value of a permit carried forward into period 2. Note that v_j is contingent on the realisation of the damage state (that is, $j = L$ or $j = H$) since the effect of any supply adjustment rule will generally depend on which state is realized. Thus, the equilibrium price of a permit in period 1 when all firms are using technology *i* must be

$$p_1 = c_i'(\bar{e}_i - e_{1i}^*) + \beta \sum_{j=L,H} \pi_j v_j \qquad [5]$$

Since the supply of permits in period 1 is set such that $c_i'(\bar{e}_i - e_{1i}^*) = \mu$, it follows that

$$p_1 = \mu + \beta \sum_{j=L,H} \pi_j v_j \qquad [6]$$

Thus, since v_j depends on the particular supply adjustment rule in place, so too does the equilibrium price of permits in period 1. This has important implications for investment decisions in that period.

Supply adjustment and dynamic efficiency

Consider the investment incentives for an individual firm when faced with the above permit price path. It is important to note that firms are price-takers on the permit market, which means that an individual firm does not expect the price of permits to depend on its own technology adoption decision. Thus, a firm that deviates unilaterally from the social optimum continues to face the permit prices associated with the social optimum. However, the firm's technology choice will affect the number of permits it carries forward from period 1 to period 2, and this in turn determines the magnitude of any capital gain or loss the firm may experience

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damage may arise within the lifespan of a permit even if that lifespan is relatively short. The decomposition of the permit lifespan into “two periods” is simply a modelling convenience.

under the supply adjustment policy. Different supply adjustment policies have different implications for expected capital gains or losses and therefore have different impacts on technology adoption incentives.

I begin by characterizing the incentives associated with a general specification of the adjustment policy. Let $x_i(j)$ denote the number of permits repurchased (possibly via expropriation) from a firm using technology *i* when $\delta = \delta_j$. (A negative value for $x_i(j)$ means that additional permits are sold or given to the firm). Let q_j denote the price at which permits are repurchased (or sold), contingent on the value of δ. Finally, let PB denote the discounted expected private benefit to a firm that adopts the new technology:

$$\begin{aligned} PB = & \left[p_1\left(e_{10} - e_{11}\right) + c_0(\bar{e}_0 - e_{10}) - c_1(\bar{e}_1 - e_{11}) \right] \\ & + \beta \sum_{j=L,H} \pi_j \big[p_2[e_{11} - e_{21}(j) - x_1(j)] - p_2[e_{10} - e_{20}(j) - x_0(j)] \\ & + q_j[x_1(j) - x_0(j)] + c_0(\bar{e}_0 - e_{20}(j)) - c_1(\bar{e}_1 - e_{21}(j)) \big] \end{aligned} \qquad [7]$$

The first term (in square brackets) represents the difference between the two technologies in the value of the permit holdings required in period 1, plus the difference between the two technologies in abatement costs in that period. The second term represents the discounted expected private benefit received in period 2. This has three components. The first component represents the difference between the two technologies in the value of net permit sales at the market price in period 2. The net permit sales for a given technology are equal to the difference between permits required for period 2 emissions and permit holdings carried forward from period 1, less any repurchases; that is, $[e_{1i} - e_{2i}(j) - x_i(j)]$. The second component is the difference between the two technologies in the value of repurchases at price q_j; that is, $q_j[x_1(j) - x_0(j)]$. The third component is simply the difference in abatement cost in period 2 between the two technologies.

Expressions [3] and [7], evaluated at the efficient emission levels and the associated permit prices, yield an expression for the wedge between the private and social benefit from adoption at the social optimum:

$$PB^* - SB = \beta \sum_{j=L,H} \pi_j \left[(\delta_j - q_j)[x_0(j) - x_1(j)] + (e_{10}^* - e_{11}^*)(v_j - \delta_j) \right] \qquad [8]$$

This expression has the following interpretation. The $(\delta_j - q_j)$ term represents the penalty incurred by the firm when a permit valued at δ_j in the market is repurchased by the regulator at price q_j (or conversely, the bonus enjoyed by the firm when a new permit is acquired at less than the market price). The $[x_0(j) - x_1(j)]$ term measures the extent to which the number of permits repurchased (or sold) by the regulator depends on the technology choice made by the firm in period 1. This difference would most obviously arise through a supply adjustment rule that discriminates directly across firms according to their technology. Less obviously, but more importantly, discrimination on the basis of technology may arise indirectly through an adjustment rule that ties repurchases (or the right to make new purchases) to individual permit holdings. Recall that holding permits and adopting a new technology are substitute investment strategies for the firm; thus, any policy that ties individual adjustment to existing permit holdings necessarily links that adjustment to the technology choice, and hence has the potential to distort that choice.

The second additive term in expression [8] captures a "price effect" of the supply adjustment policy on investment incentives. The particular rule used to adjust the supply of permits in period 2 must, in equilibrium, feed back into the expected value of all permits carried forward into period 2, whether or not they are repurchased. The second term in [8] reflects this effect. In particular, if the supply adjustment policy causes the value of a permit carried into period 2 to differ from its true social value in period 2 (that is, $v_j \neq \delta_j$), then the difference in the permit holdings carried forward under the two technologies (that is, $e_{10}^* - e_{11}^*$) will have a private value different from their true social value. The second term in [8] represents this difference between the private and social value of permit holdings carried forward. It arises through the effect of the anticipated supply adjustment rule on the equilibrium price of permits in period 1.[11]

If $PB^* \neq SB$ then each firm has an incentive to deviate unilaterally from the social optimum. In particular, if $PB^* > SB$ then private incentives are distorted in favour of the new technology. Conversely, if $PB^* < SB$ then the investment decision is biased towards retaining the old technology. If the wedge between PB^* and SB is sufficiently large, such that $PB^* > K > SB$

[11] I am grateful to an anonymous referee for pointing out this effect.

or $PB^* < K < SB$, then the social optimum is not supported as a rational expectations equilibrium.

Expression [8] can be used to examine the incentive effects of a variety of supply adjustment polices. I confine specific consideration to two alternative policies: open market operations; and a proportional adjustment rule.

Open market operations

Supply adjustment through open market operations simply involves buying or selling permits in period 2 at the prevailing market price. In particular, the regulator announces at the beginning of period 1 that in period 2 it will repurchase permits at price $q_H = \delta_H$ if $\delta = \delta_H$, and sell permits at price $q_L = \delta_L$ if $\delta = \delta_L$. Under this adjustment rule the value of a permit carried forward into period 2 is equal to its market price in that period; that is, $v_j = \delta_j \;\; \forall j$. It follows from expression [6] that

$$p_1 = (1+\beta)\mu \qquad [9]$$

This expression is the dynamic analogue of the standard Pigouvian pricing rule: the price of a permit at the social optimum is just equal to the present value of the expected damage associated with the stream of emissions it allows. Accordingly, I will refer to this price as the *Pigouvian price*.

The dynamic efficiency properties of the open market adjustment policy are described in the following proposition.

<u>Proposition 1</u>

Supply adjustment through open market operations implements the social optimum. Proof.

Substitute $q_L = v_L = \delta_L$ and $q_H = v_H = \delta_H$ in [8] to yield $PB^* = SB$.♣

The intuition behind this result is straightforward. A permit worth $p_1 = \mu(1+\beta)$ in period 1 is valued at $p_2 = \delta$ in period 2 since all repurchases or new issues are made at the market price. After adjusting for the rental value of holding the permit in period 1 (the abatement cost avoided in that period), a capital loss of $(\mu - \delta_L)$ is incurred if $\delta = \delta_L$ and a capital gain of $(\delta_H - \mu)$ is enjoyed if $\delta = \delta_H$. Thus, the *ex ante* expected gain or loss when viewed from period 1 is zero, so there is no associated distortion of the technology adoption decision.

While adjustment through open market operations yields an efficient outcome, there may exist political difficulties associated with its implementation. Suppose permits are initially sold (or auctioned) in period 1 at the market-clearing price $p_1 = \mu(1+\beta)$. If $\delta = \delta_H$ then the regulator will have to repurchase some of those permits in period 2 at a price $p_2 = \delta_H$; if β and π_H are relatively small then the repurchase price may be higher than the price paid initially. That is, firms may make a *windfall gain* if the damage caused by their emissions is more severe than expected. That windfall gain is even larger if permits are initially awarded to firms free of charge. Such an outcome is unlikely to sit well with environmental groups since it appears that firms are being rewarded for emitting substances that are more damaging than initially expected. However, from an efficiency perspective, this windfall gain when $\delta = \delta_H$ is needed to offset in expectation the capital loss when $\delta = \delta_L$ and thereby leave the permit holding decision and the associated technology adoption decision undistorted.

Proportional adjustment

An alternative to market operations that does not suffer from the same potential political problems is a *proportional adjustment rule*. Consider a supply adjustment policy that expropriates a fixed share of permits from each firm if the supply of permits must be reduced and grants additional permits on a proportional basis if the supply must be increased. The price paid for expropriated permits and the price charged for additional permits granted are then set independently of the supply adjustment to satisfy the distributional goals of the policy maker. The only restriction these prices must satisfy is $q_L \leq \delta_L$; otherwise no firm would be willing to buy the additional permits granted to it.

Under this proportional adjustment scheme $x_i(j) = \alpha(j)e_{1i}$, where

$$\alpha(j) = \left[\frac{e_{1i}^* - e_{2i}^*(j)}{e_{1i}^*}\right] \qquad [10]$$

is the proportion by which the aggregate supply of permits must be increased or decreased in period 2 to restore static efficiency. (Note that $\alpha(H) \in (0,1)$ and $\alpha(L) \in (-1,0)$, and recall that

$x_i(j)$ is defined as the number of permits expropriated from firm *i*; thus, $x_i(H) > 0$ and $x_i(L) < 0$).

Consider the implications of this proportional adjustment rule for the equilibrium price of permits. A permit carried forward into period 2 will be effectively transformed into $(1-\alpha(j))$ permits after the supply adjustment in period 2. That is, if $j = H$ then the firm will lose a fraction $\alpha(H)$ of each permit it holds; if $j = L$ then firm will be granted the option to purchase a fraction $\alpha(L)$ for each permit it holds. Each of these permits has a market price of δ_j in period 2. Thus, in state *j*, the value of a permit carried forward into period 2 is

$$v_j = (1-\alpha(j))\delta_j + \alpha(j)q_j \qquad [11]$$

Thus, from equation [6], the equilibrium price of a permit in period 1 under the announced proportional adjustment rule is

$$p_1 = (1+\beta)\mu - \beta \sum_{j=L,H} \pi_j \alpha(j)(\delta_j - q_j) \qquad [12]$$

Whether or not this price is higher or lower than the Pigouvian price depends on q_j, and on the properties of the abatement cost functions. That relationship is described in the following proposition.

Proposition 2

The equilibrium price of permits in period 1 under the proportional adjustment rule is

(a) decreasing in q_L and increasing in q_H ;

(b) equal to the Pigouvian price if $q_L = \delta_L$ and $q_H = \delta_H$; and

(c) at $q_L = q_H = 0$, is

(i) lower than the Pigouvian price if marginal abatement cost for the optimal technology is concave or mildly convex; and

(ii) higher than the Pigouvian price if marginal abatement cost for the optimal technology is strongly convex.

Proof. In the appendix.

The intuition behind parts (a) and (b) of this result is straightforward. A high value of q_L reduces the value of the option to buy more permits from the regulator in period 2 if the low damage state is realized, while a high value of q_H raises the compensation paid for permits expropriated if the high damage state is realized; these effects have a direct impact on the equilibrium price of permits in period 1. If $q_L = \delta_L$ and $q_H = \delta_H$ then the proportional adjustment policy is equivalent to market operations and so the Pigouvian price arises.

Part (c) of proposition 2 requires further explanation; first consider part (i). If $\delta = \delta_L$ then a firm will be granted, free of charge, additional permits whose unit market value is $p_2 = \delta_L$. Conversely, if $\delta = \delta_H$ then the firm will lose, without compensation, permits whose unit market value is $p_2 = \delta_H > \delta_L$. Thus, the loss from losing a permit exceeds the benefit from gaining a permit. This asymmetry is the key to the result. Under a proportional adjustment rule the *number* of permits lost or gained is proportional to the number of permits carried forward from period 1. Thus, holding fewer permits in period 1 can reduce the firm's exposure to the asymmetry between unit gains and losses in period 2. Given the fixed supply of permits in period 1, this reduced demand for permits must translate into a lower equilibrium price.

The point can be seen most clearly in a diagram. Consider Figure 4, which illustrates the case where $\pi_L = \pi_H = \frac{1}{2}$ and marginal abatement cost for the optimal technology (which might be $i = 0$ or $i = 1$) is linear. In this case, the fraction of permits expropriated from a firm when $\delta = \delta_H$ is just equal to the fraction by which its permit holdings are increased when $\delta = \delta_L$. That is, $\alpha(H) = |\alpha(L)|$. Moreover, each outcome is equally likely, so the asymmetry between unit gains and losses means that the firm expects to lose on average, and that loss is proportional to its permit holdings. (The expected loss is illustrated in Figure 4 as the probability-weighted difference between the shaded areas labelled "G", for gain, and "L", for loss). This reduces the demand for permits at any given price and so causes the equilibrium price in period 1 to fall.

Figure 5 illustrates the case where marginal abatement cost for the optimal technology is strictly concave (and $\pi_L = \pi_H = \frac{1}{2}$). In this case, the fraction of permits expropriated from a firm at the optimum when $\delta = \delta_H$ *exceeds* the fraction by which its permit holdings are increased when $\delta = \delta_L$. That is, $\alpha(H) > |\alpha(L)|$. This exacerbates the expected capital loss associated with holding permits and so amplifies the downward pressure on the equilibrium price.

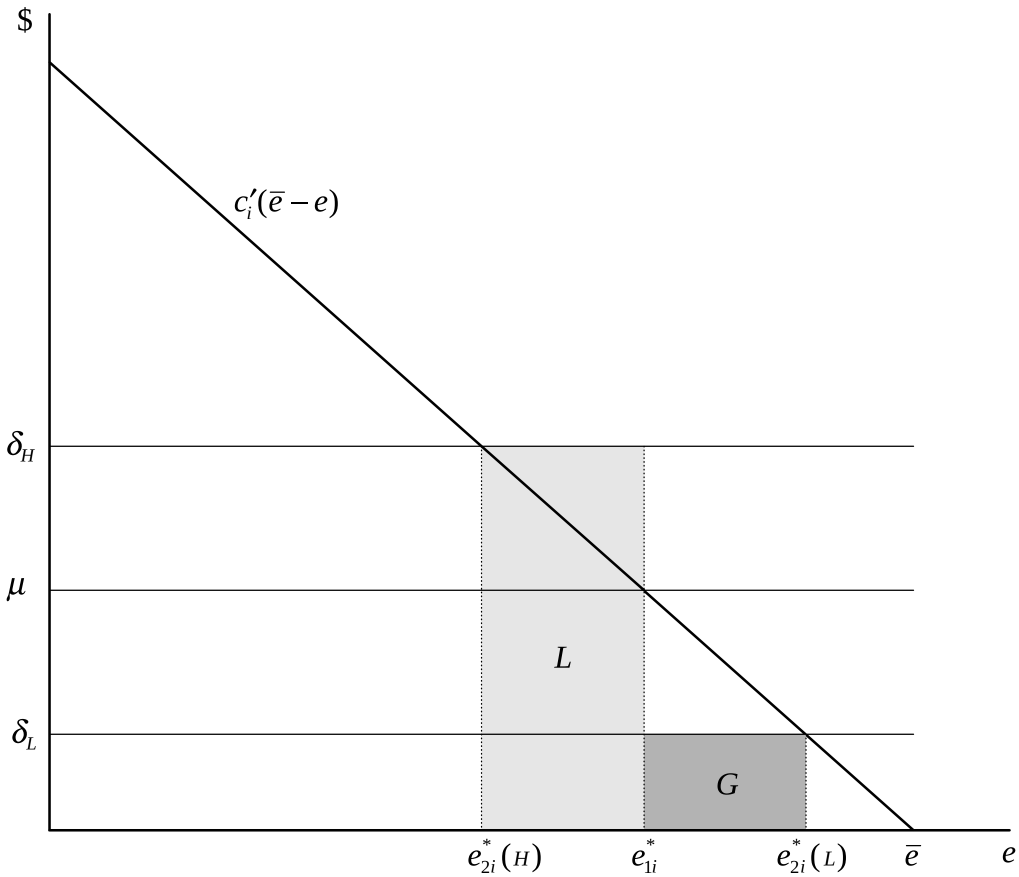

FIGURE 4

In contrast, Figure 6 illustrates the case where marginal abatement cost for the optimal technology is strongly convex (and $\pi_L = \pi_H = \frac{1}{2}$). In this case the fraction of permits expropriated from a firm when $\delta = \delta_H$ is *smaller* than the fraction by which its permit holdings are increased when $\delta = \delta_L$. That is, $\alpha(H) < |\alpha(L)|$. This effect can potentially offset the disincentive to hold permits associated with the asymmetry between unit gains and losses. In the case illustrated, $area(G) > area(L)$; thus, the firm will gain on average if it carries more permits into period 2. This possibility underlies part (c)(ii) of proposition 2.

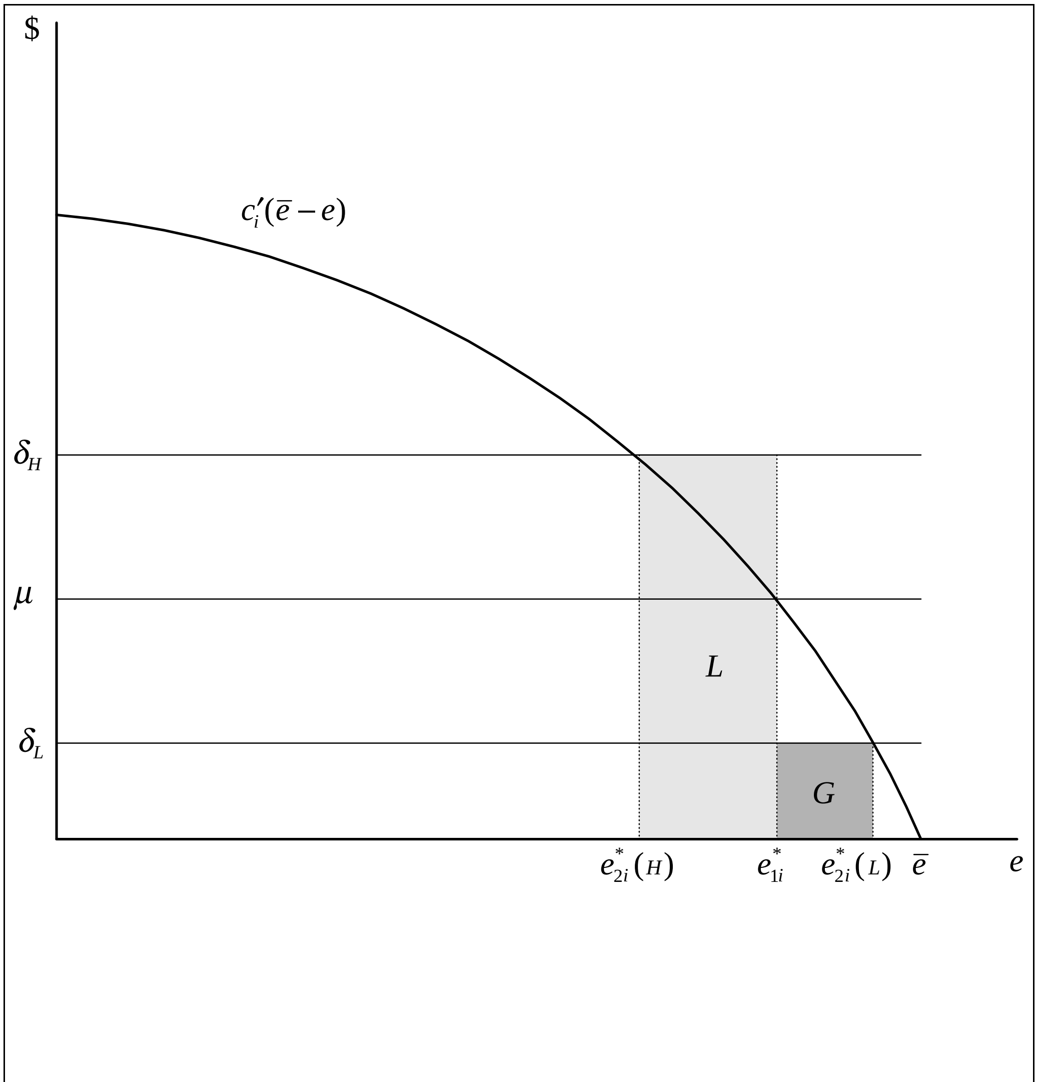

FIGURE 5

Whether marginal abatement costs are concave or convex is an empirical question, the answer to which will depend on the specific context. The more important policy question relates to the effect of the proportional adjustment rule on technology adoption decisions. This effect is described in the following proposition.

Proposition 3.

Proportional supply adjustment implements the social optimum.

Proof. Substitute [11] for v_j and $x_i(j)=\alpha(j)e_{1i}$ in equation [8] evaluated at the social optimum to yield $PB^* = SB$.♣

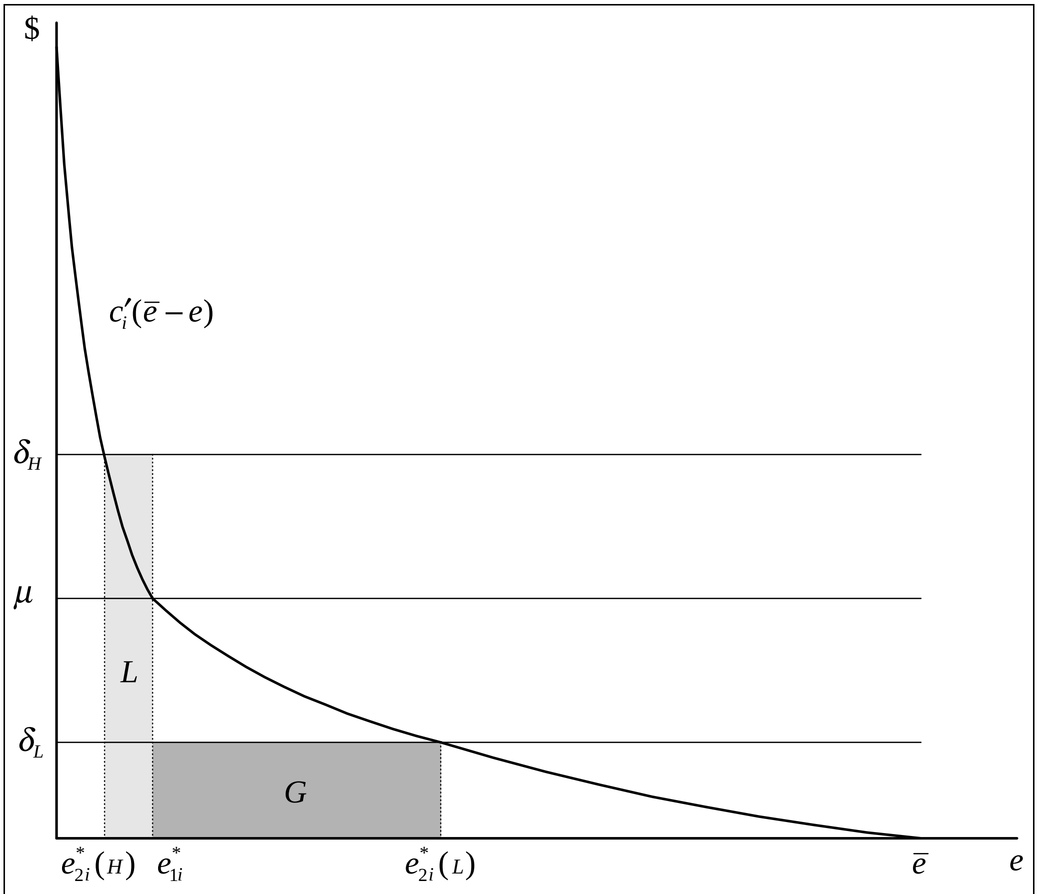

FIGURE 6

The intuition behind this result is the following. If the proportional supply adjustment policy is announced in period 1 then any associated incentive for firms to hold more or fewer permits than is socially optimal is translated fully into the equilibrium price of permits. That is, permit prices completely absorb any distorting effect that the adjustment policy might otherwise have. The key to the ameliorating role of prices under proportional adjustment is the fact that the adjustment fraction applied to a firm in period 2 is independent of which technology the firm is using; it is based purely on aggregate quantities evaluated at the optimum, given the realized damage state.[12]

[12] Note that the credibility of this adjustment rule relies on there being a large number of firms. Of course, this is also a precondition for a competitive permit market.

Note that the neutrality of the proportional adjustment rule with respect to technology adoption decisions is independent of how prices are set for permit expropriation or new issue. Thus, these prices can be set independently of the supply adjustment according to the distributional goals of the policy maker.

It is also worth stressing that the neutrality of proportional adjustment rule does not rely on the assumption of *ex ante* identical firms. In particular, the factor of proportionality, $\alpha(j)$, is based only on aggregate emission levels and is applied uniformly across firms, regardless of the technologies those firms bring into period 2. Moreover, note from equation [11] that the value of a permit carried forward into period 2 is independent of the technology used by the firm that holds the permit; this must be true in equilibrium or else trade would occur between firms until the value of a permit is equalized across firms.

CONCLUSION

This paper has examined the problem of adjusting the supply of permits in an emissions trading program in response to new information about environmental damage. The key issue of interest is whether or not such an adjustment can be made without distorting investment decisions with respect to the adoption of cleaner technologies.

I have shown that open market operations, whereby the regulator buys or sells permits as needed at the market price, implements an efficient solution with respect to the choice of emissions in each period and with respect to cleaner technology adoption decisions. However, this supply adjustment policy is unlikely to be politically acceptable because it rewards firms with a windfall gain if the damage caused by their emissions turns out to be worse than expected.

I have proposed an alternative adjustment rule under which the regulator expropriates a fixed share of permits from each firm if the supply of permits must be reduced, and grants additional permits on a proportional basis if the supply must be increased. The price paid for expropriated permits and the price charged for additional permits granted can be set independently from the supply adjustment to satisfy the distributional goals of the policy maker. Such an adjustment policy causes the equilibrium price of permits to differ from its Pigouvian level (unless the adjustment prices are set equal to market prices), in a direction that depends on the properties of abatement cost functions. The key property of this proportional adjustment rule is that it implements efficiency, both in terms of emission levels and in terms of technology choices. Thus, the proportional adjustment rule delivers the same efficiency advantages of adjustment through market operations but at the same time provides much greater flexibility from a political perspective.

In closing, it is important to stress that both the market operations policy and the proportional adjustment policy work because they are announced in advance, as part of the emissions trading program design. A failure to specify how the supply of permits will be adjusted, if necessary, will create considerable uncertainty over the value of permits in any emissions trading program, and could seriously undermine the functioning of that program.

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APPENDIX

Proof of Proposition 2. Parts (a) and (b) follow directly from equation [12]. For part (c), note from equation [1]:

$$c_i'(\bar{e}_i - e_{1i}^*) = \sum_{j=L,H} \pi_j \delta_j$$

Therefore, using [2]:

$$c_i'(\bar{e}_i - e_{1i}^*) = \sum_{j=L,H} \pi_j c'(\bar{e}_i - e_{2i}^*(j))$$

If $c_i'(\bar{e}_i - e_{1i}^*)$ is concave then

$$\sum_{j=L,H} \pi_j c'(\bar{e}_i - e_{2i}^*(j)) \le c_i'\left(\sum_{j=L,H} \pi_j [\bar{e}_i - e_{2i}^*(j)]\right)$$

and so

$$c_i'(\bar{e}_i - e_{1i}^*) \le c_i'\left(\sum_{j=L,H} \pi_j [\bar{e}_i - e_{2i}^*(j)]\right)$$

Then since by assumption $c_i''(\bar{e}_i - e_{1i}^*) > 0$, it follows that

$$(\bar{e}_i - e_{1i}^*) \le \sum_{j=L,H} \pi_j [\bar{e}_i - e_{2i}^*(j)]$$

and so

$$e_{1i}^* \ge \sum_{j=L,H} \pi_j e_{2i}^*(j) \qquad \text{[A1]}$$

Therefore, deducting $e_{2i}^*(j)$ from both sides,

$$e_{1i}^* - e_{2i}^*(H) \ge \pi_L [e_{2i}^*(L) - e_{2i}^*(H)] \qquad \text{[A2]}$$

and

$$e_{1i}^* - e_{2i}^*(L) \ge \pi_H [e_{2i}^*(H) - e_{2i}^*(L)] \qquad \text{[A3]}$$

Then using [10], together with [A2] and [A3], we have

$$\sum_{j=L,H} \pi_j \alpha(j) \delta_j > \left[\frac{e_{10}^* - e_{11}^*}{e_{1i}^*}\right] \pi_L \pi_H (\delta_H - \delta_L)(e_{2i}^*(L) - e_{2i}^*(H)) \qquad \text{[A4]}$$

The RHS of [A4] is strictly positive. Part (c)(i) of proposition 2 then follows directly from [12]. If $c_i'(\bar{e}_i - e_{1i}^*)$ is strictly convex then the inequality in [A1], and hence in [A4], is reversed; this proves part (c)(ii) of the proposition.♣