ENVIRONMENTAL POLICY AND TIME CONSISTENCY: EMISSION TAXES VS. EMISSIONS TRADING

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ABSTRACT

We examine the time consistency properties of a Pigouvian emissions tax and emissions trading when firms can adopt a cleaner technology. If damage is linear in emissions then efficiency requires either universal adoption of the new technology or universal retention of the old technology depending on the cost of adoption. The first-best tax policy and the first-best permit supply policy are both time consistent under these conditions, and the induced equilibrium is efficient. If damage is strictly convex then efficiency may require strictly partial adoption of the new technology. In this case the first-best tax policy is not time consistent and tax ratcheting must be used. Ratcheting will nonetheless induce an efficient equilibrium if there is a continuum of firms. If there are relatively few firms then ratcheting creates excessive incentives for adoption of the new technology. Thus, the resulting equilibrium may involve too much adoption. The first-best permit supply policy is also time consistent if there is a continuum of firms and induces the efficient solution. If there are relatively few firms then the first-best policy may not be time consistent, and the regulator must use permit supply ratcheting. This policy creates an under-incentive for firms to adopt the new technology. Thus, the resulting equilibrium may involve too little adoption.

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1. INTRODUCTION

A key consideration in the choice of pollution control instruments is the incentive for regulated firms to adopt cleaner technologies. The adoption of less polluting production techniques holds the key to long term consumption growth with limited accompanying environmental damage. More immediately, it allows firms to achieve pollution reduction targets at lower cost and with potentially smaller impact on their international competitiveness. These issues are of particular importance to many developing countries where high growth rates mean that a large number of key industrial technology choices are being made on a daily basis. It is essential that those choices are the right ones if the net benefits of growth are to be maximized.

Of course, the right technology is not necessarily the cleanest technology available. This is especially true when an existing production technology is already employed and the associated investment has been sunk. Retooling with a less polluting production method or the retrofitting of abatement equipment can be very costly; that cost must be carefully weighed against the benefits of reduced pollution from technological change. Thus, it is not enough that policy instruments create incentives for technological change; they must create the *right* incentives, in the sense that they induce technology adoption decisions which correctly balance the benefits and costs of alternative technologies.

There is a wide array of pollution control policies available to regulators and each of them have different properties with respect to incentives for technological change. In this paper we focus on emission taxes and emissions trading. These market-based instruments are becoming increasingly popular in practice due in part to their dynamic incentives. By attaching an explicit price to emissions, these policy instruments create an ongoing incentive for firms to continually reduce their emission volumes. In contrast, command-and-control type emission standards create incentives to adopt cleaner technologies only up to the point where the standards are no longer binding (at which point the shadow price on emissions falls to zero). However, the ongoing incentives created by market-based instruments are not necessarily the right incentives. In particular, time consistency constraints on the setting of these instruments can potentially limit the ability of the regulator to set polices that implement efficiency as rational expectations equilibria with respect to technology adoption choices. This paper explores these time consistency issues for Pigouvian emission taxes and emissions trading.

We examine the policy problem under a range of conditions relating to the structure of the "pollution market" and the nature of the environmental damage. We show that time consistency constraints do not limit the ability of the regulator to achieve a first-best outcome if there is a continuum of regulated firms or if environmental damage is linear in aggregate emissions. However, if there are relatively few regulated firms, such that there is strategic interaction between firms and the regulator, and environmental damage is strictly convex in aggregate emissions, then time consistency problems do arise. In particular, the rational expectations equilibrium under emission taxes exhibits excessive incentives for the adoption of a new technology while the equilibrium under emissions trading exhibits incentives for adoption that are too weak.

Our paper contributes to a broad existing literature on incentives for technological change under environmental regulation.[1] Downing and White (1986) examine the incentive effects of an emissions tax but they do not take account of time consistency issues and whether or not the outcomes examined can in fact be rational expectations equilibria. Malueg (1989) argues that emissions trading may not create the right incentives for new technology adoption but his analysis is also 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. Milliman and Prince (1989) similarly neglect equilibrium considerations in their comparative analysis of emission taxes and emissions trading.

Biglaiser, Horowitz and Quiggin (1995) examine incentives in a rational expectations environment and claim that an emissions tax does *not* suffer from a time consistency problem. Their result is correct in the context of their model but they restrict attention to the case of linear damage. They also claim that technology adoption is distorted under emissions trading because of a time consistency 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 time inconsistency problem in their model (which assumes damage is linear) and no associated distortion of technology investment decisions.

Laffont and Tirole (1996a) and (1996b) also examine technological change under emissions trading. A primary focus of their work is the time consistency problems arising from a non-unitary cost of public funds. They show that incentives for innovation are weakened if the regulator cannot commit to distort future permit prices for the purpose of raising revenue.

Jung, Krutilla and Boyd (1996) compare the incentive effects of emission taxes and emissions trading but they fail to account for time consistency issues. In particular, they assume that firms expect the tax rate to remain unchanged after adoption of a cleaner technology even though this tax rate is sub-optimal *ex post*. Similarly, they assume that firms expect the supply of permits to remain unchanged even though that supply is sub-optimal *ex post*. In their model these expectations are fulfilled in equilibrium but only because the regulator fails to make the optimal adjustments. Thus, the regulator is assumed to be able to commit to a policy that is not time consistent. This also raises a problem with their comparative analysis of taxes and permits because the implicit objective of their regulator varies with the instrument used to implement it. The implicit objective under a tax policy is to maintain the tax rate constant while the implicit objective under permits is to achieve a given level of emissions. These objectives are not consistent.

Our analysis focuses on the time consistency of policy and its implications for the importance of examining incentives in equilibrium. Our rational expectations framework allows a direct and consistent comparison of emission taxes and emissions trading. The rest of the paper is organized as follows. Section 2 describes the model on which our analysis is based. Section 3 characterizes efficiency with respect to technology adoption in the context of that model. Sections 4 and 5 then examine the circumstances under which efficient technology choices can and cannot be implemented through a Pigouvian emissions tax and emissions trading respectively. Section 6 concludes.

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

2. THE MODEL

Time is divided into two periods. In period 1 each of *n* firms uses a production technology with 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. 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 measures the least cost mix of abatement measures. Abatement cost has the following important properties: $c_0' > 0$ and $c_0'' > 0$.

A cleaner technology becomes available at the beginning of period 2. It can be adopted by any firm at some fixed installation cost *K*. This technology has an associated abatement cost function $c_1(\bar{e}_1 - e)$ with $c_1' > 0$ and $c_1'' > 0$, where $\bar{e}_1 \leq \bar{e}_0$ and $c_1' < c_0'$ for any $e \leq \bar{e}_0$. Thus, any positive level of abatement can be achieved at lower cost with the new technology.

Polluting firms are assumed to be price-takers on the product market. This means that private and social marginal abatement cost coincide. It is important to note that this assumption can hold even if the number of polluting firms in the regulated region is small since the regulated firms do not necessarily constitute the whole industry. Such is the case, for example, when polluting firms take world prices as given.

Environmental damage *D(E)* in any period is an increasing function of aggregate emissions *E* in that period. That is, attention is restricted to the case of a dissipative pollutant that is uniformly mixed relative to the regulated region. Two cases are considered with respect to the damage function: $D''(E) > 0$ (strictly convex damage) and $D''(E) = 0$ (linear damage).[2]

3. EFFICIENCY

We begin with an analysis of a single firm since this helps to illuminate the key issues with respect to efficiency in technology adoption. We then examine the case with many firms.

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[2] Some environmental problems are possibly characterized by concave damage at very high pollution levels but we have not examined that case here.

3.1 A Single Firm

Figure 1 illustrates the marginal damage schedule drawn for the case of linear damage. Marginal damage is denoted by δ. Also illustrated are the marginal abatement cost schedules associated with the old and new technologies, labeled $c_0'(\bar{e}-e)$ and $c_1'(\bar{e}-e)$ respectively. The efficient level of emissions if the firm uses technology *i* is e_i^* such that $c_i'(\bar{e}_i - e_i^*) = \delta$.[3]

The shaded area in Figure 1 represents the social benefit obtained if the firm adopts the cleaner technology. This social benefit comprises the reduction in damage associated with the fall in emissions from e_0^* to e_1^*, represented by area (A+C) plus any reduction in abatement cost associated with switching to the cleaner technology, represented by area (B-C) in the Figure. Note that abatement cost could be *higher* under the cleaner technology since efficiency requires that more abatement is undertaken for that technology. However, the overall social benefit is necessarily positive. Let *G* denote that social benefit.

Figure 2 illustrates an increasing marginal damage schedule, labeled $D'(E)$. The efficient level of emissions for the firm if it uses technology *i* is e_i^* such that $c_i'(\bar{e}_i - e_i^*) = D'(e_i^*)$. The shaded area in Figure 2 represents the social benefit obtained if the firm adopts the cleaner technology. It has the same interpretation as in the constant marginal damage case.

Whether or not adoption of the cleaner technology yields a positive *net* social benefit depends on the size of the adoption cost *K*. Adoption is worthwhile if and only if $G > K$. It is clear from Figures 1 and 2 that adoption of the cleaner technology is most likely to be worthwhile if marginal damage is high and the difference between marginal abatement costs is significant.

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[3] For clarity, all graphs are drawn for the case where $\bar{e}_0 = \bar{e}_1 = \bar{e}$.

3.2 Many Firms

Now suppose there are $n > 1$ regulated firms. Let *m* denote the number of firms to adopt the cleaner technology. Efficient emission levels for a given value of *m* are given by $e_0(m)$ and $e_1(m)$ such that

(1) $c_0'(\bar{e}_0 - e_0(m)) = c_1'(\bar{e}_1 - e_1(m)) = D'(E(m))$

where

(2) $E(m) = me_1(m) + (n - m)e_0(m)$

Note that if damage is linear then the efficient emission levels are independent of *m*. In contrast, if damage is strictly convex then $e_0'(m) > 0$, $e_1'(m) > 0$ and $E'(m) < 0$. These important properties reflect the fact that if more firms use the cleaner technology then marginal damage is lower (when $D'' > 0$), and so the balance between marginal damage and marginal abatement cost calls for a higher level of emissions from any individual firm using a given technology.

Next consider efficiency with respect to technology adoption. Figure 3 illustrates the case of $n = 2$ and linear damage. The shaded area represents the social benefit from adoption of the new technology by one of the firms. (Net social benefit is this shaded area less the cost of adoption). Efficiency requires that emissions for the adopting firm fall from e_0^* to e_1^*; emissions for the non-adopting firm are unchanged at e_0^*, while aggregate emissions fall from $E(0)$ to $E(1)$. The social benefit from adoption comprises the reduction in damage associated with the fall in aggregate emissions plus any reduction in abatement cost for the adopting firm.

The picture is somewhat more complicated when damage is strictly convex. Figures 4(a) and 4(b) illustrate the adoption of the new technology by one of the two firms. Efficiency requires that emissions for the adopting firm fall from $e_0(0)$ to $e_1(1)$, and that emissions for the non-adopting firm rise from $e_0(0)$ to $e_0(1)$. The efficient level of aggregate emissions falls from $E(0)$ to $E(1)$. The shaded areas in figure 4(a) reflect the reduction in abatement cost for the adopting firm: area (B-A). The shaded areas in figure 4(b) represent the other components of the social benefit from adoption: area D is the reduction in damage associated with the fall in aggregate emissions; area C is the reduction in abatement cost for the *non-adopting firm* associated with the rise in its emissions. Note that this latter component of social benefit does not arise in the linear damage case. Figure 4(c) combines the areas in figures 4(a) and 4(b) to illustrate the overall social benefit from adoption by one firm.

Now consider the social benefit from adoption by the second firm. This is illustrated in figure 5. Efficiency requires that emissions for the adopting firm fall from $e_0(1)$ to $e_1(2)$, and that emissions for the existing new technology firm rise from $e_1(1)$ to $e_1(2)$. The efficient level of aggregate emissions falls from $E(1)$ to $E(2)$. A comparison of figures 5 and 4c reveals that the social benefit from the second firm adopting the new technology is less than the social benefit from the first firm adopting. This is due to the fact that marginal damage falls when the first firm adopts, so the social benefit from the second firm adopting is smaller. Since the cost of adoption is constant, this means that efficiency may require strictly partial adoption: some firms should adopt the cleaner technology and some firms should retain the old technology, even though all firms are identical *ex ante*.

In contrast, strictly partial adoption is never efficient when damage is linear since marginal damage is constant in that case, and so the social benefit from adoption by one firm is independent of how many firms adopt. Efficiency in that case requires adoption of the cleaner technology either by all firms (if *K* is relatively small) or by no firms (if *K* is relatively large). Of course, a corner solution can also be efficient in the strictly convex damage case if *K* is large enough or small enough.

4. IMPLEMENTATION WITH AN EMISSIONS TAX

The timing of the game between the firms and the regulator is as follows. In period 1 the tax is set according to the Pigouvian rule for the prevailing technology. The new technology arrives at the beginning of period 2 and the regulator announces a tax rate for that period. Firms then decide whether or not to adopt the cleaner technology, taking as given the simultaneous technology adoption decisions of other firms. The regulator cannot commit to a tax rate that is time inconsistent. That is, the tax rate announced for period 2 must be consistent with the technology choices that the tax induces.

4.1 A Single Firm

The equilibrium to the game between the firm and the regulator depends importantly on whether damage is linear or strictly convex. We examine each case in turn.

(a) Linear Damage

The unit tax rate on emissions is set equal to marginal damage: $t^* = \delta$. This is illustrated in Figure 1. Note that this optimal tax rate is independent of which technology is in place because marginal damage is constant. The firm responds to the tax by setting its emissions level to equate its marginal abatement cost with the tax rate: $c_i'(\bar{e}_i - e_i) = t^*$. Thus, the firm chooses e_0^* if it uses the old technology, and e_1^* if it uses the new technology. That is, the emissions tax implements static efficiency for any given technology.

The private benefit to the firm from adopting the cleaner technology comprises the reduction in tax payments, $t^*(e_0^* - e_1^*)$, plus any reduction in abatement cost. Note that the reduced tax payments correspond exactly to the reduced environmental damage since $t^* = \delta$. It follows that the private benefit to the firm from adopting the new technology is identical to the social benefit. Thus, the emissions tax also implements efficiency with respect to technology adoption.

(b) Strictly Convex Damage

The regulatory problem is somewhat more complicated when marginal damage is increasing. For an emissions tax to implement the efficient level of emissions for any given technology *i*, the tax rate must be set equal to marginal damage evaluated at the efficient level of emissions; that is, $t_i^* = D'(e_i^*)$. Thus, the tax rate required depends on which technology is in use. This creates a potential time consistency problem for the regulator. If adoption of the new technology is efficient then the regulator would like to announce a tax rate t_1^* for period 2. Conversely, if adoption of the new technology is not efficient then the regulator would like to announce a tax rate t_0^* for period 2. The problem is that a tax rate of t_0^* may actually induce the firm to adopt the *new* technology, while a tax rate of t_1^* may induce the firm to retain the *old* technology. In both cases the announced tax rate would not be optimal *ex post* and hence could not be committed to *ex ante*.

Under what conditions will this time consistency problem arise? Suppose adoption of the new technology is not efficient; that is, $G \le K$. Then the first-best tax rate for period 2 is t_0^*. Figure 6 illustrates the private benefit to the firm from adoption of the new technology at this fixed tax rate. If the firm retains the old technology then it sets emissions equal to e_0^*. Conversely, if it adopts the new technology then it sets emissions equal to $e_1(t_0^*)$. Let $B(t_0^*)$ denote the private benefit from adoption at t_0^*. Comparing Figures 2 and 6 reveals that $B(t_0^*) > G$. That is, the private benefit from adoption at t_0^* exceeds the social benefit from adoption. This does *not* necessarily create a time consistency problem. In particular, if $B(t_0^*) \le K$ then adoption of the new technology is not privately worthwhile for the firm, and so t_0^* is optimal *ex post*. In this case the announced t_0^* tax rate is credible, and the Pigouvian tax policy implements efficiency with respect to technology adoption.

However, if $B(t_0^*) > K$ then t_0^* will induce adoption of the new technology, and so t_0^* will not be optimal *ex post*. In this case the regulator cannot commit to the first-best tax rate. The best the regulator can do in this case is to announce that it will set the tax at t_0^* if the firm does not adopt the new technology, and set the tax at t_1^* if the firm does adopt the new technology; no other Pigouvian tax strategy is time consistent. Milliman and Prince (1989) refer to this policy as *tax ratcheting*.

Figure 7 illustrates the private benefit to the firm from adoption of the new technology under the tax ratcheting policy. If the firm retains the old technology then it faces a tax rate of t_0^* and sets emissions at e_0^*. Conversely, if it adopts the new technology it faces a tax rate of t_1^* and sets emissions at e_1^*. Let $B(t_0^*, t_1^*)$ denote the private benefit from adoption in this case. Comparing Figures 3 and 7 reveals that $B(t_0^*, t_1^*) > B(t_0^*)$. It follows that if $B(t_0^*) > K \ge G$ then $B(t_0^*, t_1^*) > K \ge G$. Thus, if efficiency calls for retention of the old technology but t_0^* is not time consistent, then the only time consistent policy is ratcheting, and this policy induces the *inefficient* adoption of the new technology.

There is no corresponding problem if efficiency calls for adoption of the new technology (that is, if $G > K$). In this case the first-best tax rate for period 2 is t_1^*. Figure 8 illustrates the private benefit to the firm from adoption of the new technology at this tax rate. If the firm retains the old technology then it sets emissions equal to $e_0(t_1^*)$. Conversely, if it adopts the new technology then it sets emissions equal to e_1^*. Let $B(t_1^*)$ denote the private benefit from adoption at t_1^*. Comparing Figures 2 and 8 reveals that $B(t_1^*) < G$. That is, the private benefit from adoption at t_1^* is less than the social benefit. This does not create a time consistency problem if $B(t_1^*) > K$ since in that case the firm will adopt the cleaner technology at t_1^* even though $B(t_1^*) < G$. Conversely, if $B(t_1^*) < K$ then t_1^* is not time consistent and the only time consistent policy is tax ratcheting. However, if $G > K$ then $B(t_0^*, t_1^*) > K$ since $B(t_0^*, t_1^*) > G$. Thus, if efficiency calls for adoption of the new technology then ratcheting will always implement that outcome.

These results indicate that the emissions tax cannot induce too little technological change but it can induce too much technological change. This problem with the emissions tax stems from the fact that it does not discriminate across units of emissions according to the damage they cause. The tax rate is set equal to the damage caused by the *marginal* unit of emissions and this tax rate is applied to every unit of emissions. This means that when marginal damage is increasing the total tax payment exceeds the total damage done. In assessing the private benefit to adopting a cleaner technology, the firm thinks in terms of reduced tax payments but what matters from a social perspective is reduced damage. Since the reduction in tax payments under ratcheting exceeds the reduction in damage, the firm’s incentive is distorted in favour of cleaner technology adoption. This generates the wrong technology choice if efficiency calls for retention of the old technology.

It is important to note that the dynamic incentive problem associated with the emissions tax is *not* due to the assumed timing of the game between the regulator and the firm. We have assumed that the regulator moves first by announcing a tax rate to which the firm responds with a technology choice. An alternative timing of the game would have the firm leading with a technology adoption decision and the regulator responding with the announcement of a tax rate. Under this timing the only time consistent strategy the regulator can ever play is ratcheting. The outcome to this differently timed game corresponds to the outcome of the game we have examined where the regulator moves first but the time consistency constraint is binding.

4.2 Many Firms

We now turn to the case of many firms. For any given *m*, where *m* is the number of firms that adopt the new technology, the optimal tax rate is equal to marginal damage evaluated at the efficient level of aggregate emissions:

(3) $t(m) = D'(E(m))$

Thus, if $D'' = 0$ then $t'(m) = 0$, and if $D'' > 0$ then $t'(m) < 0$. This tax induces the efficient emission levels for *given* technologies; that is, a firm with technology *i* chooses its emissions $e_i(t(m))$ such that

(4) $c_i'(\bar{e}_i - e_i(t(m))) = t(m)$

This implements equation (1); that is, $e_i(t(m)) = e_i(m) \quad \forall i$.

Whether or not the tax implements efficiency with respect to cleaner technology adoption depends again on whether damage is linear or strictly convex. We consider each case in turn.

(a) Strictly Convex Damage

Recall from the single firm case that the first-best tax rate may not be time consistent when damage is strictly convex. The same potential problem arises in the case of many firms and is in fact more acute. In particular, if efficiency requires strictly partial adoption of the new technology ($0 < m^* < n$) then the corresponding first-best tax rate is never time consistent. Why? If an announced fixed tax rate of $t(m^*)$ induces adoption of the new technology by *any* firm then it will induce adoption by *all* firms; it cannot induce strictly partial adoption among *ex ante* identical firms. Thus, if efficiency calls for strictly partial adoption then the associated first-best tax rate, $t(m^*)$, cannot be time consistent.

If the first-best tax rate is not time consistent then the only time consistent tax policy is ratcheting. Ratcheting in the context of many firms simply means announcing that the *ex post* tax rate will be set according to equation (3), based on the number of firms that adopt the new technology. The equilibrium induced by ratcheting exhibits excessive incentives for the adoption of the new technology. This is illustrated in figure 9 for the case of $n = 2$ and $m^* = 1$. The shaded area in figure 9 represents the private benefit to the second firm from adopting the new technology. This private benefit comprises the reduction in tax payments plus any reduction in abatement cost. Comparing figures 9 and 5 reveals that the private benefit exceeds the social benefit. Thus, there is an excessive incentive for the second firm to adopt. The basic intuition behind this result is the same as for the case of a single firm: the total tax payments made under the Pigouvian emissions tax exceed the true external cost of emissions when damage is strictly convex.

(b) Linear Damage

When damage is linear the optimal tax rate is independent of the technologies used and so there is no potential time consistency problem for the regulator. Thus, the Pigouvian emissions tax policy implements efficiency with respect to technology adoption. The intuition behind the result is straightforward. When damage is linear the tax payments by a firm are exactly equal to the damage caused by its emissions. It follows that the private and social benefit from cleaner technology adoption coincide.

4.3 A Continuum of Firms

It is worth noting that when there is a continuum of firms, the Pigouvian emissions tax policy implements efficiency with respect to technology adoption even if damage is strictly convex. The reason is straightforward. If there is a continuum of firms then each firm is insignificant relative to the aggregate, and so each firm perceives that its own technology adoption choice has no impact on the tax rate chosen by the regulator.

5. IMPLEMENTATION WITH EMISSIONS TRADING

We now turn to the potential time consistency problems associated with emissions trading. It is important to note at the outset that we assume the regulator is committed to adjusting the aggregate supply of permits to maintain an efficient balance between marginal damage and marginal abatement costs. Thus, we assume that the regulator has the same objective whether the policy instrument of choice is an emissions tax or an emissions trading program. This ensures a consistent comparison between the two instruments.

We examine a tradeable permit program that operates in the following way. At the beginning of period 1 the regulator issues an aggregate number of permits corresponding to the efficient level of emissions based on the existing technology (used by all firms in period 1). It is not important for the problem at hand whether permits are issued by auction or through some sort of grandfathering scheme provided that the initial distribution does not create asymmetric market power. Each permit allows one unit of emissions during period 1. We assume that no banking is allowed (which means that permits unused in period 1 cannot be carried forward to period 2).[4] The new technology arrives at the beginning of period 2 and the regulator then issues permits for use in period 2. The regulator may or may not then have to re-adjust that supply of permits in response to the technology adoption that actually occurs in equilibrium, depending on whether or not the first-best permit supply is time consistent.

Recall that the first-best tax rate under an emissions tax is the tax rate that induces efficiency with respect to technology adoption and at the same time generates the efficient level of aggregate emissions given the technologies in place. If this tax rate is not time consistent then the regulator must use tax ratcheting. Similarly, the first-best supply of permits (and associated equilibrium permit price) is that which induces efficient technology adoption choices and at the same time corresponds to the efficient aggregate level of emissions, given those technology choices. If this first-best permit supply is not time consistent then the regulator must use a responsive policy, akin to tax

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[4] Allowing banking makes no difference at all since the arrival of a new technology in period 2 with lower abatement costs means that the option to bank would never be exercised.

ratcheting, whereby the supply of permits is set at the beginning of period 2 and then adjusted *ex post* in response to equilibrium technology choices. As in the case of an emissions tax, the time consistency of the first-best solution depends on the nature of the damage function and on the number of regulated firms. We begin with a situation in which there is a continuum of firms and then consider a situation where the number of firms is small enough that each firm has some market power in the permit market. In both cases we examine a situation with linear damage and a situation with strictly convex damage.

5.1 A Continuum of Firms

(a) Linear Damage

Recall from section 4 that when damage is linear the regulator does not need to respond to technological change if an emissions tax is used. The tax rate is simply set equal to marginal damage and no adjustment is required. Moreover, this tax rate creates the correct incentives for technological change to occur. Thus, the regulator does not need to respond to the advent of a cleaner technology.

In contrast, the advent of a new technology requires a reassessment of the permit supply under an emissions trading program even when damage is linear. In particular, the aggregate supply of permits that is efficient for an existing technology will generally *not* be efficient if a new technology is adopted; the first-best permit supply depends on the technologies in use. Recall from section 3 that when damage is linear, efficiency requires either adoption of the new technology by all firms or retention of the old technology by all firms, depending on the magnitude of the adoption cost. If efficiency calls for universal adoption then the first-best aggregate permit supply is $E_1^* = ne_1^*$ such that $c_1'(\bar{e}_1 - e_1^*) = \delta$. In contrast, if efficiency calls for universal retention of the old technology then the first-best permit supply is $E_0^* = ne_0^* > E_1^*$ such that $c_0'(\bar{e}_0 - e_0^*) = \delta$.

Consider first the case where efficiency calls for universal adoption. If the regulator issues the corresponding first-best number of permits then adoption by all firms is the equilibrium response and the permit supply is efficient *ex post*. The key to this result is the fact that the *ex post* equilibrium price of permits is equal to marginal damage; thus, the private benefit from adoption to any individual firm is, in equilibrium, exactly equal to the social benefit.

Similarly, if efficiency calls for retention of the old technology and the permit supply is left unchanged from period 1, then the *ex post* price of permits in an equilibrium with no adoption is equal to marginal damage, and so the private benefit to adoption in that equilibrium is equal to the social benefit. Thus, leaving the supply of permits unchanged between periods is time consistent and induces efficiency.

It is important to emphasize that leaving the supply of permits unchanged in response to the advent of a new technology ensures efficiency with respect to the adoption of that technology only if efficiency calls for no adoption. If the regulator does not adjust the supply of permits *ex ante* then the permit price in a candidate equilibrium in which all firms adopt the new technology would be lower than marginal damage and so the private benefit to adoption in that candidate equilibrium would be less than the social benefit. The private benefit to adoption in the candidate equilibrium could therefore be less than the cost of adoption, in which case adoption by all firms could not in fact be an equilibrium even though adoption by all firms is efficient. Thus, ensuring efficiency when efficiency calls for the adoption of the new technology generally requires an adjustment to the supply of permits in response to the advent of that new technology even when damage is linear.

(b) Strictly Convex Damage

Recall from section 4 that when damage is strictly convex the regulator faces a time consistency problem with an emissions tax when there is a relatively small number of firms but that problem vanishes when there are a continuum of firms because each firm is insignificant relative to the aggregate and so perceives an independence between its own choices and the policies implemented by the regulator. The same is true in the case of emissions trading with a continuum of firms: there are no time consistency problems associated with implementation of the first-best policy even when damage is strictly convex.

The policy problem for the regulator in this case is in fact somewhat simpler under emissions trading than under an emissions tax. Recall that strictly convex damage means that efficiency may require strictly partial adoption of the new technology. In that case the regulator must use tax ratcheting since committing to the first-best tax rate *ex ante* cannot induce asymmetric technology choices by *ex ante* symmetric firms, as required for an efficient equilibrium. In contrast, under emissions trading the regulator can set the first-best permit supply at the beginning of period 2, without the need for *ex post* adjustment, and nonetheless induce an asymmetric and time consistent equilibrium.

The key to this result is the flexibility of the permit price to respond to technology adoption choices in equilibrium. The equilibrium price of permits is decreasing in the number of firms that adopt the new technology since the demand for permits is lower when more firms use the new technology. This equilibrating role of the permit price means that the private benefit to any firm from adopting the new technology is decreasing in the number firms using that technology, and this in turn allows an equilibrium to exist in which some firms adopt but additional potential adopters find it unprofitable to do so. No comparable automatic adjustment to the price of emissions occurs under a fixed tax rate policy; hence the need for explicit tax ratcheting.

The equilibrium induced by the first-best supply adjustment is efficient. Each firm takes the permit price as independent of its own action, and since each firm is insignificant relative to the aggregate, marginal damage is effectively constant with respect to the emissions of each individual firm. Thus, the saving to the firm from having to hold fewer permits at the first-best equilibrium price fully reflects the reduction in damage.

5.2 A Small Number of Firms

The conditions required for a "perfectly competitive" permit market breakdown when there are only a "small" number of firms. However, emissions trading can still yield valuable efficiency gains under such circumstances and can still be an effective regulatory instrument if potentially destructive collusive and predatory practices can be controlled. Our approach here is to abstract from these potential "anti-competitive" problems and focus on the implications of strategic interaction between firms, and between individual firms and the regulator, for the time consistency of permit supply adjustment policy. We begin with the case of linear damage.

(i) Linear Damage

The key issue of interest is the same as in the case with a continuum of firms: is it a time consistent policy for the regulator to issue the first-best number of permits at the beginning of period 2 without the need for *ex post* adjustment?

Consider first the case where efficiency calls for retention of the old technology by all firms. (Recall that efficiency requires "all or nothing" when damage is linear). Suppose the regulator issues permits corresponding to the associated first-best level of aggregate emissions: $E(0) = ne_0(0)$. Retention of the old technology by all firms will be an equilibrium response to this policy if no firm has an incentive to deviate from that equilibrium by adopting the new technology.

Consider the incentives for a potentially deviating firm. This firm is not a price-taker since the permit market is not characterized by perfect competition. The firm must instead sell permits through individual bargaining with other firms. The specific trading schedule the potential deviant faces depends on the number of firms in the market and the nature of the bargaining game between firms. However, that schedule must have two general properties. First, the trading schedule cannot lie above δ since no firm will be willing to purchase a permit if the asking price is higher than its marginal abatement cost. Since $c_0'(\bar{e}_0 - e_0(0)) = \delta$ at the candidate equilibrium, and since $c_0'' > 0$, it follows that the potential deviant cannot sell a permit for a price higher than δ. Second, the trading schedule cannot be downward sloping (since $c_0'' > 0$). An example schedule satisfying these two properties is illustrated as SS is figure 10. Faced with this trading schedule the deviating firm sets emissions at $\tilde{e}_1$ and the private benefit from its new technology adoption is the shaded area in figure 10. A comparison with figure 1 reveals that the private benefit to the deviating firm cannot be greater than the social benefit from that deviation (and will generally be less). Since the social benefit is less than the cost of adoption (by nature of the fact that efficiency here by construction involves no adoption), it follows that the private benefit is also less than the cost of adoption, and so the deviation is not privately optimal. Thus, universal retention of the old technology is a time consistent equilibrium response to the first-best permit supply policy when universal retention of the old technology is efficient.

The first-best policy is also time-consistent when efficiency calls for universal adoption of the new technology. The argument is exactly analogous to one just made. Figure 11 illustrates the private benefit to a deviating firm that retains the old technology when all other firms adopt the new technology. The deviating firm cannot purchase permits for less than the lowest marginal abatement cost of the other firms, and so the deviating firm's trading schedule cannot lie below δ for permit purchases. Thus, the private cost (or foregone benefit) of retaining the old technology for the deviating firm (the shaded area in figure 11) must exceed the social benefit from adoption, which in turn exceeds the cost of adoption. Thus, the avoided cost of adoption for the deviating firm is less than the cost of the deviation, and so the deviation is not worthwhile. Thus, universal adoption of the new technology is a time consistent equilibrium response to the first-best permit supply policy when universal adoption is efficient.

(ii) Strictly Convex Damage

In section 4 we argued that strictly convex damage combined with relatively few firms means that a Pigouvian emissions tax is generally not able to implement efficiency with respect to technology adoption. In particular, unless efficiency involves a corner solution, the only time consistent tax policy is ratcheting, and this policy creates excessive incentives for technology adoption. A similar problem arises under emissions trading but with the opposite implication for incentives.

Figures 9 and 12 illustrate the comparison between the tax policy and the emissions trading policy for the case of two firms and where $m^* = 1$. Recall that the shaded area in figure 9 represents the private benefit (under ratcheting) to the remaining old technology firm if it deviates from the first-best solution. In comparison, the shaded area in figure 12 illustrates the maximum private benefit to the remaining old technology firm if it deviates from the first-best solution under emissions trading, where the supply of permits has been fixed at its first-best level. This area can be explained as follows. The maximum price the deviating firm can obtain for permits sold to the new technology firm is the latter firm's marginal abatement cost. The schedule labeled *SS* in figure 12 plots that maximum price. Faced with this trading schedule, the deviating firm will set emissions at $\tilde{e}_1$ and so derives a private benefit from the deviation equal to the shaded area. A less favorable bargaining solution for the deviating firm will mean a smaller benefit than the shaded area. Comparing figures 9 and 12 shows that the private benefit to the deviating firm is strictly less under emissions trading than under an emissions tax. Thus, the private benefit to deviation under emissions trading is less likely to exceed the cost of adoption than under the emissions tax. This means that under some conditions the first-best permit supply policy will be time consistent (and so implement efficiency) while the emissions tax policy leads to excessive technology adoption.

When the private benefit to deviation from the first-best solution does exceed the cost of adoption, the first-best permit supply policy will not be time consistent: the permit supply corresponding to the first-best technology choices will not implement those choices and so will not be optimal *ex post*. In such cases the only time consistent permit supply policy is a type of ratcheting, whereby the regulator initially issues the same number of permits in period 2 as in period 1 but then buys back permits to adjust the supply in response to technology adoption choices. Suppose the regulator cannot expropriate permits but must repurchase permits from willing sellers. Then the only time consistent policy is to announce that permits will be repurchased at a price equal to marginal damage evaluated at the optimum, given the technologies in place.

This is illustrated in figure 13. At the beginning of period 2 both firms are using the old technology and the regulator issues $E(0)$ permits accordingly. Suppose one of the firms then adopts the new technology, in which case the efficient level of aggregate emissions falls to $E(1)$. The regulator then offers to buy permits at price $p(1) = MD(E(1))$. At that price the adopting firm is willing to sell $e_0(0) - e_1(1)$ permits. The non-adopting firm is willing to pay a price higher than $p(1)$ for $e_0(1) - e_0(0)$ permits and so the adopting firm sells this many permits to the non-adopting firm. The remaining $E(0) - E(1)$ permits are sold back to the regulator. The resulting equilibrium is efficient, given the technologies in use. No other repurchase price will induce an efficient supply adjustment and so no other policy is time consistent.

The shaded area in figure 13 represents the maximum private benefit to the single adopting firm under the permit supply ratcheting policy. This benefit comprises the payment received from the regulator for repurchased permits, plus the maximum possible payment from the adopting firm for traded permits, plus any reduction in its own abatement costs. In comparison, recall from figure 4(c) the social benefit from adoption by one firm. It is clear that the private benefit under-represents the social benefit. Thus, the permit supply ratcheting policy tends to create an under-incentive for the adoption of the new technology. Recall that the opposite result obtains for an emissions tax but the underlying reason is of the same nature. The ratcheting policy under emissions trading creates an under-incentive for adoption because the payment received from the regulator for the repurchased permits under-states the social value of the reduced damage.

6. CONCLUSION

We have examined the time consistency properties of a Pigouvian emissions tax and emissions trading. Our main results can be summarized as follows. If damage is linear then efficiency with respect to technology adoption involves either universal adoption of the new technology or universal retention of the old technology depending on the cost of adoption. The first-best tax policy and the first-best permit supply policy are both time consistent under these conditions, and the induced equilibrium is efficient.

If damage is strictly convex then efficiency may require strictly partial adoption of the new technology. In this case the first-best tax policy is not time consistent and tax ratcheting must be used. Ratcheting will nonetheless induce an efficient equilibrium if there is a continuum of firms. If there are relatively few firms then ratcheting creates excessive incentives for adoption of the new technology. Thus, the resulting equilibrium may involve too much adoption.

The first-best permit supply policy is time consistent if there is a continuum of firms and induces the efficient solution. If there are relatively few firms then the first-best policy may not be time consistent, and the regulator must use permit supply ratcheting. This policy creates an under-incentive for firms to adopt the new technology. Thus, the resulting equilibrium may involve too little adoption.

Since both the Pigouvian emission tax and emissions trading both potentially fail to induce efficiency when damage is strictly convex and there are relatively few firms, our results do not speak strongly in favour of one instrument over the other. However, it should be noted that if an emissions trading program is intended to implement technological efficiency then it is necessary to continually adjust the supply of permits in response to technological change, even when damage is linear. This continual adjustment is not needed for an emissions tax when damage is linear, a distinction that gives the emissions tax a possible advantage over emissions trading.

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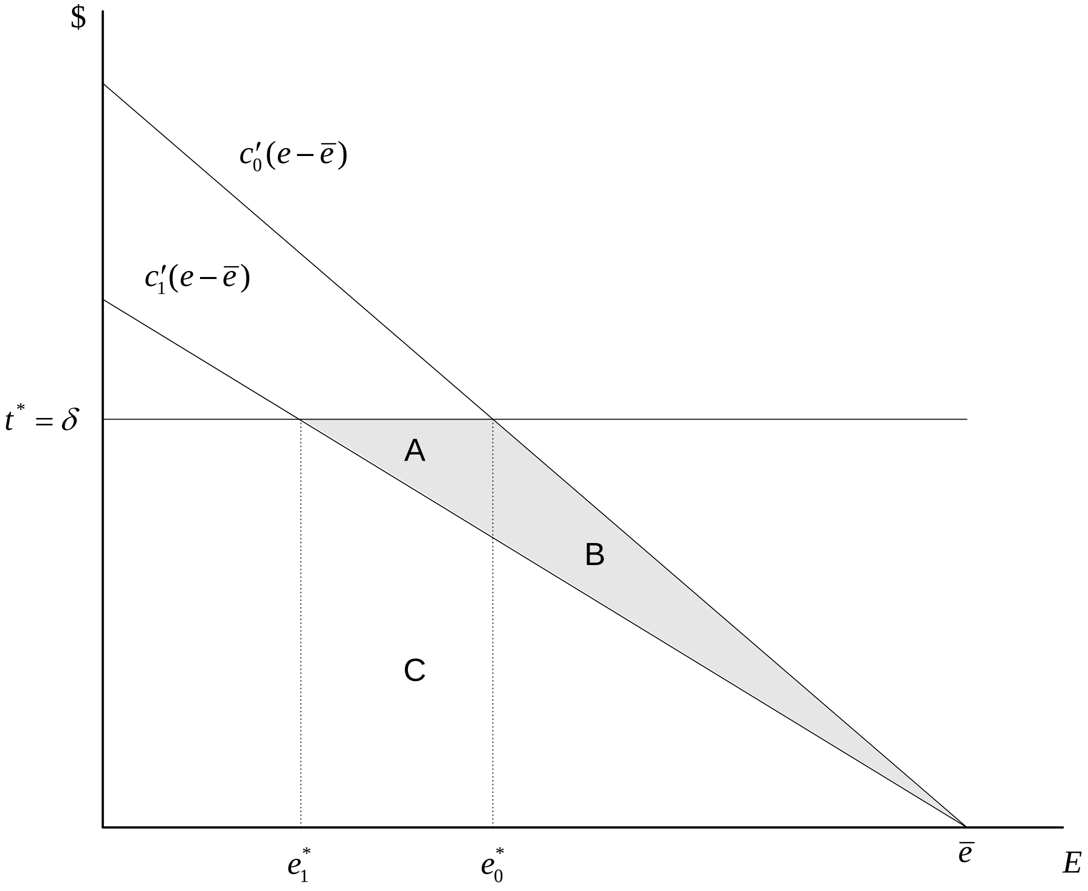

FIGURE 1
Social benefit from technology adoption
(linear damage)

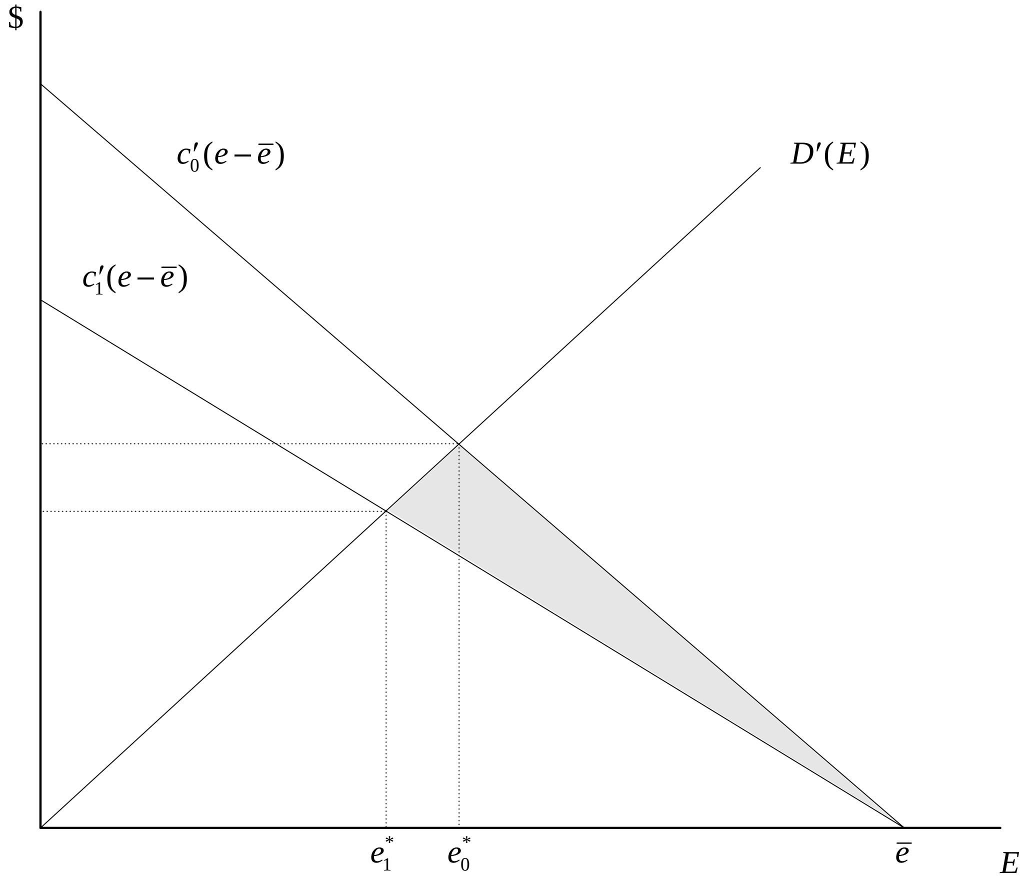

FIGURE 2
Social benefit from technology adoption
(strictly convex damage)

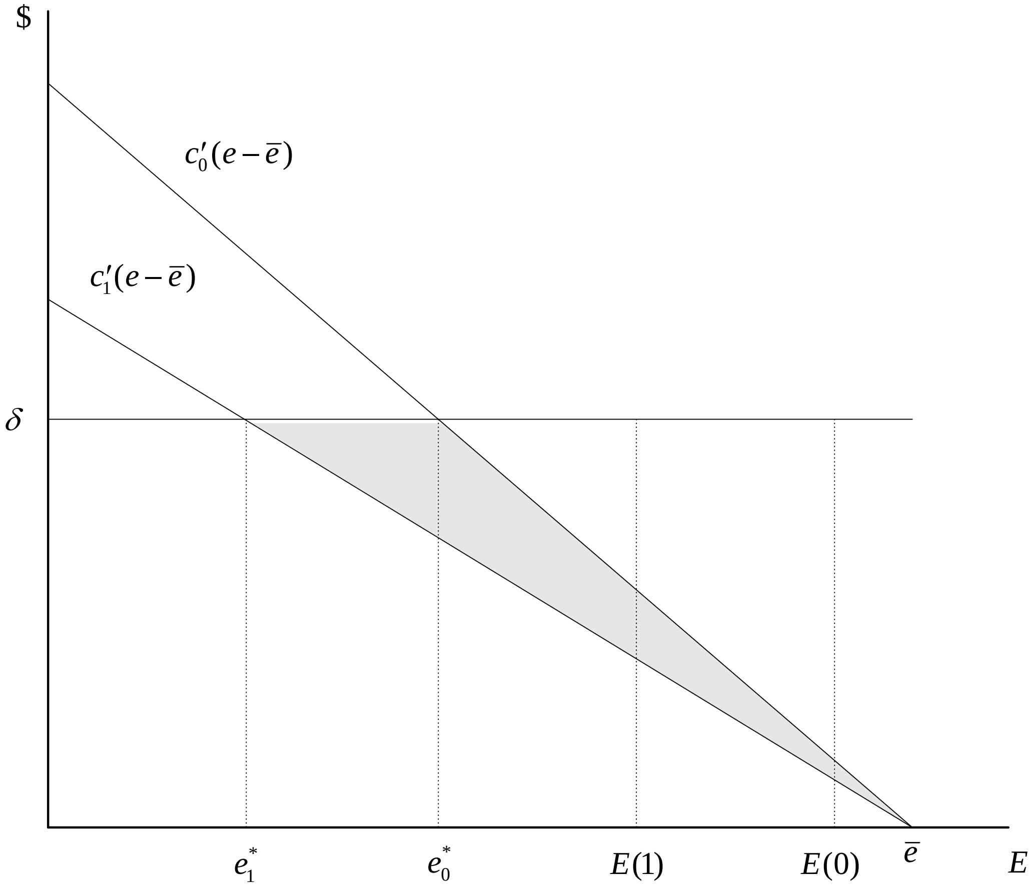

FIGURE 3
Social benefit from technology
adoption by one firm
(linear damage)

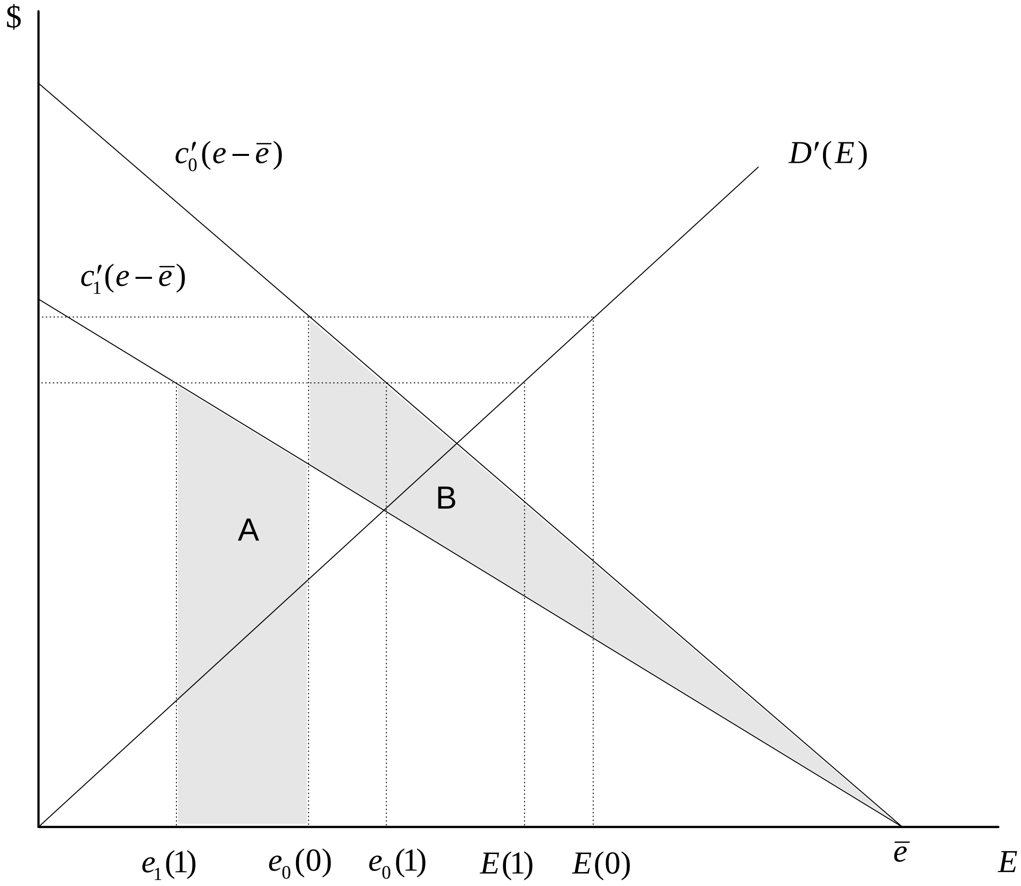

FIGURE 4a
Adoption by one firm: reduction in abatement cost for the adopting firm (strictly convex damage)

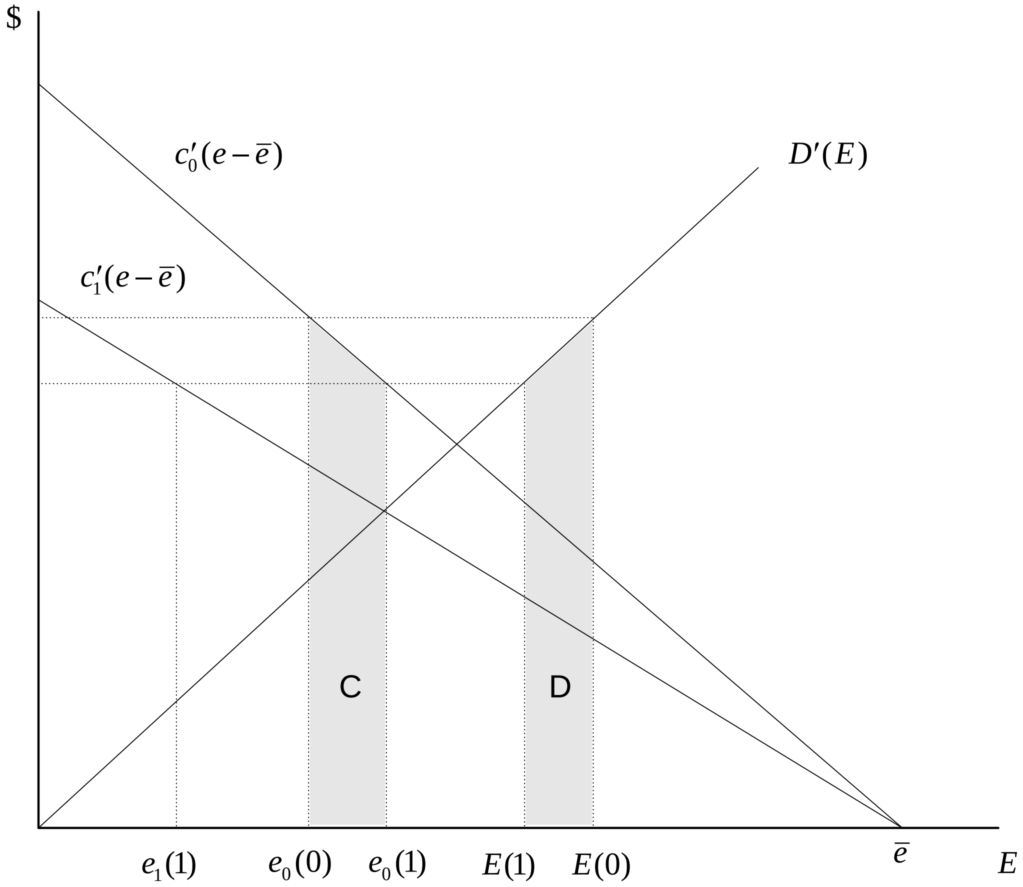

FIGURE 4b
Adoption by one firm: reduction in damage and reduction in abatement cost for the non-adopting firm (strictly convex damage)

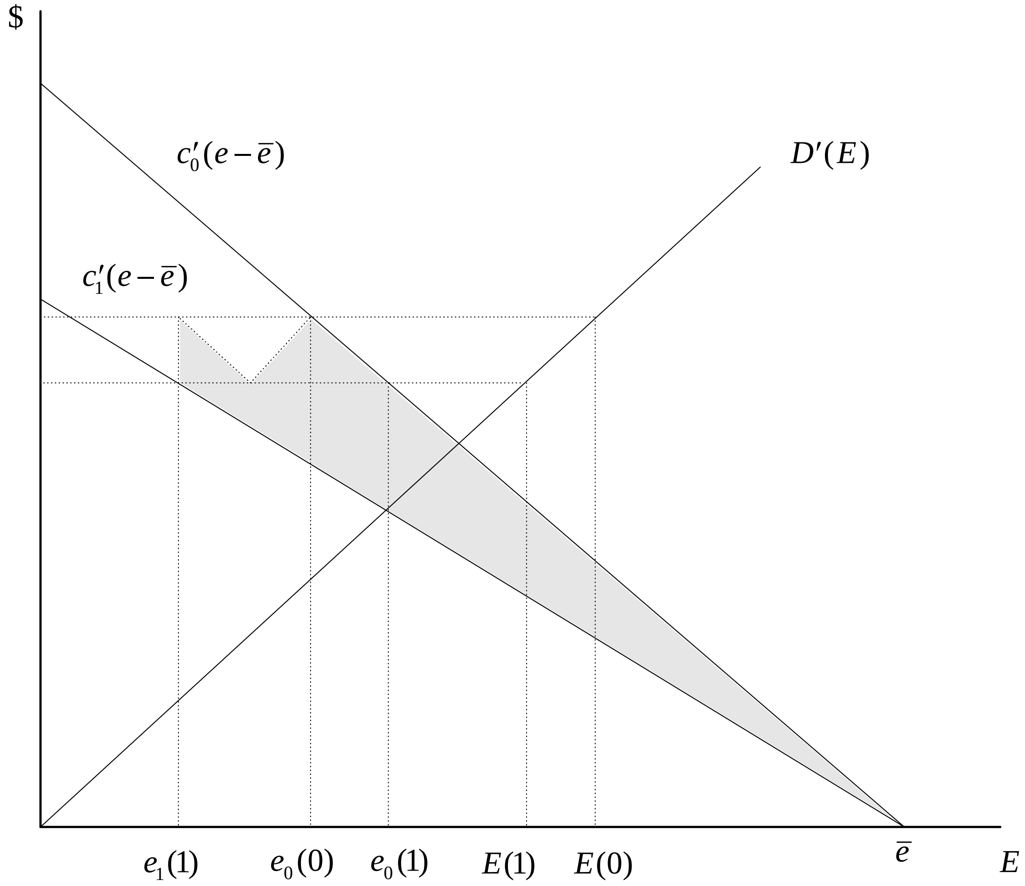

FIGURE 4c

Social benefit from adoption by one firm
(strictly convex damage)

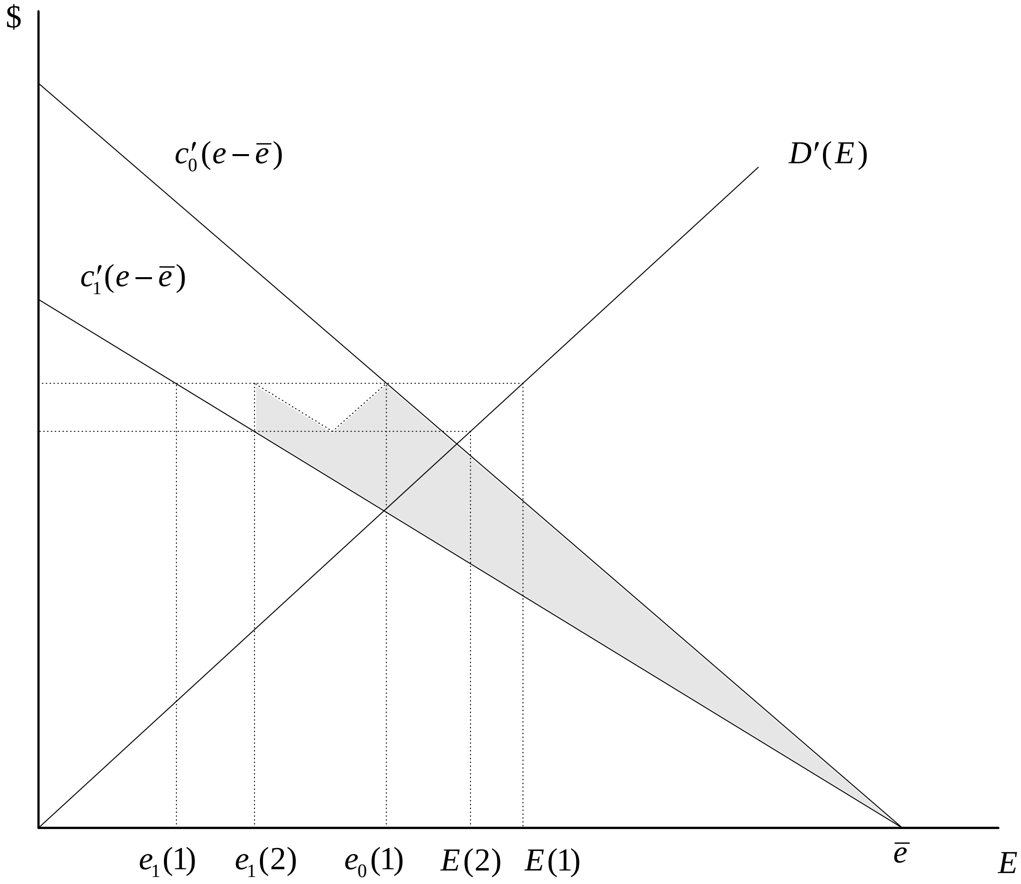

FIGURE 5
Social benefit from adoption
by the second firm
(strictly convex damage)

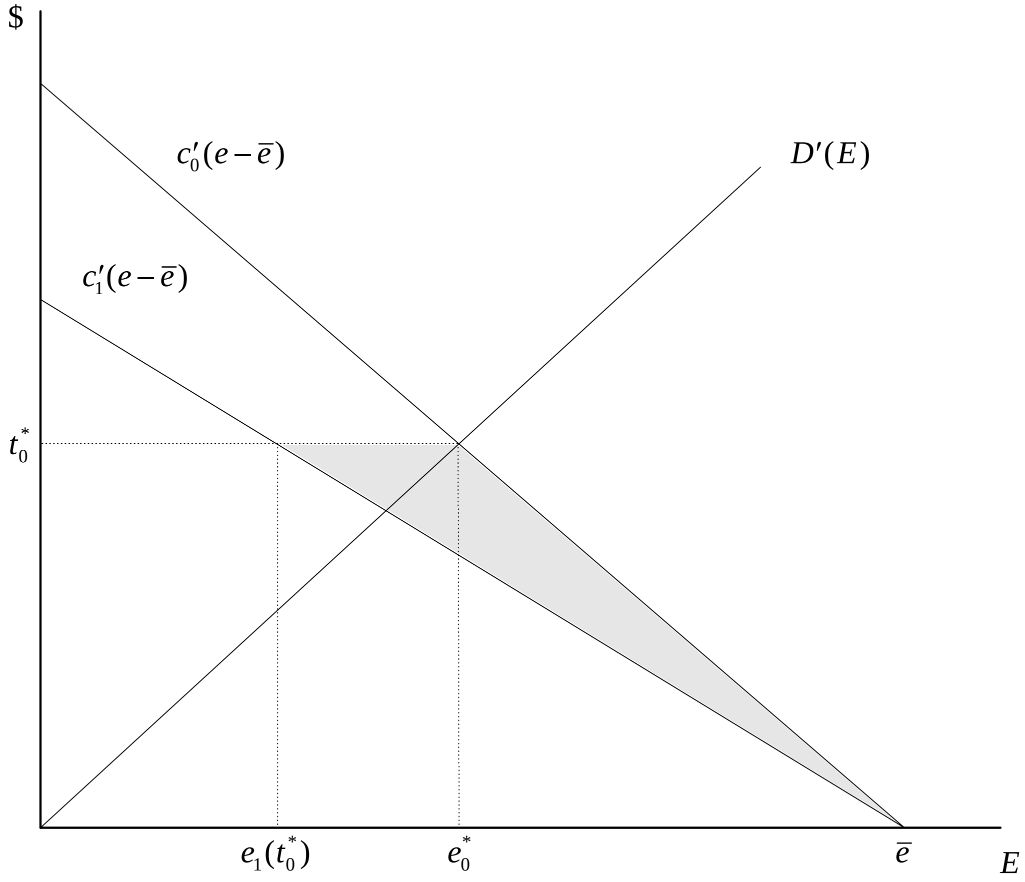

FIGURE 6
Private benefit from technology adoption
$(at\ t_0^*)$

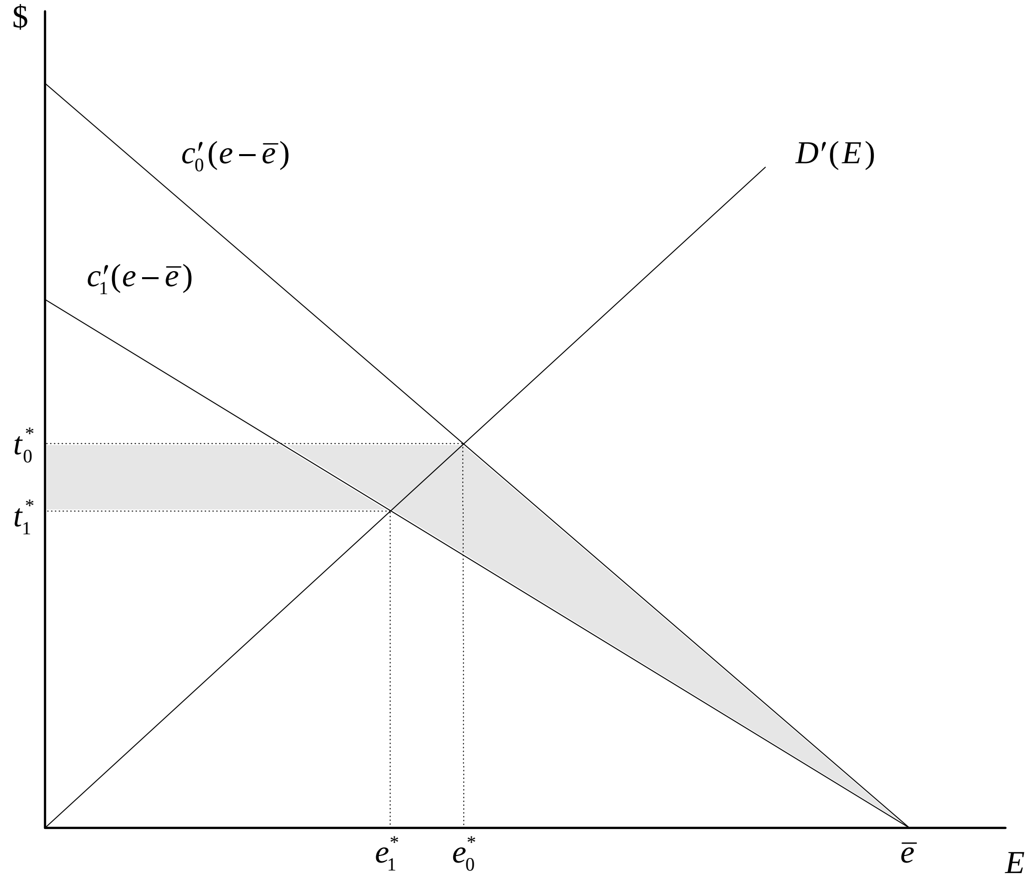

FIGURE 7
Private benefit from technology adoption under ratcheting

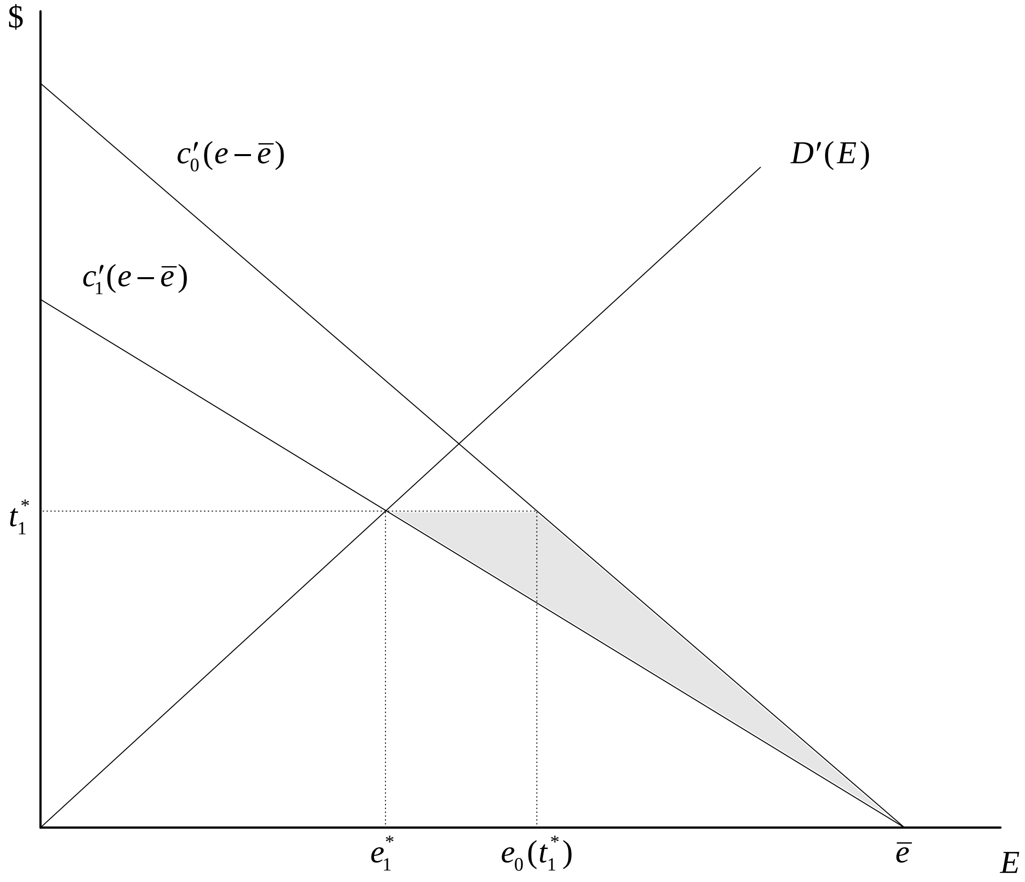

FIGURE 8
Private benefit from technology adoption
$(at\ t_1^*)$

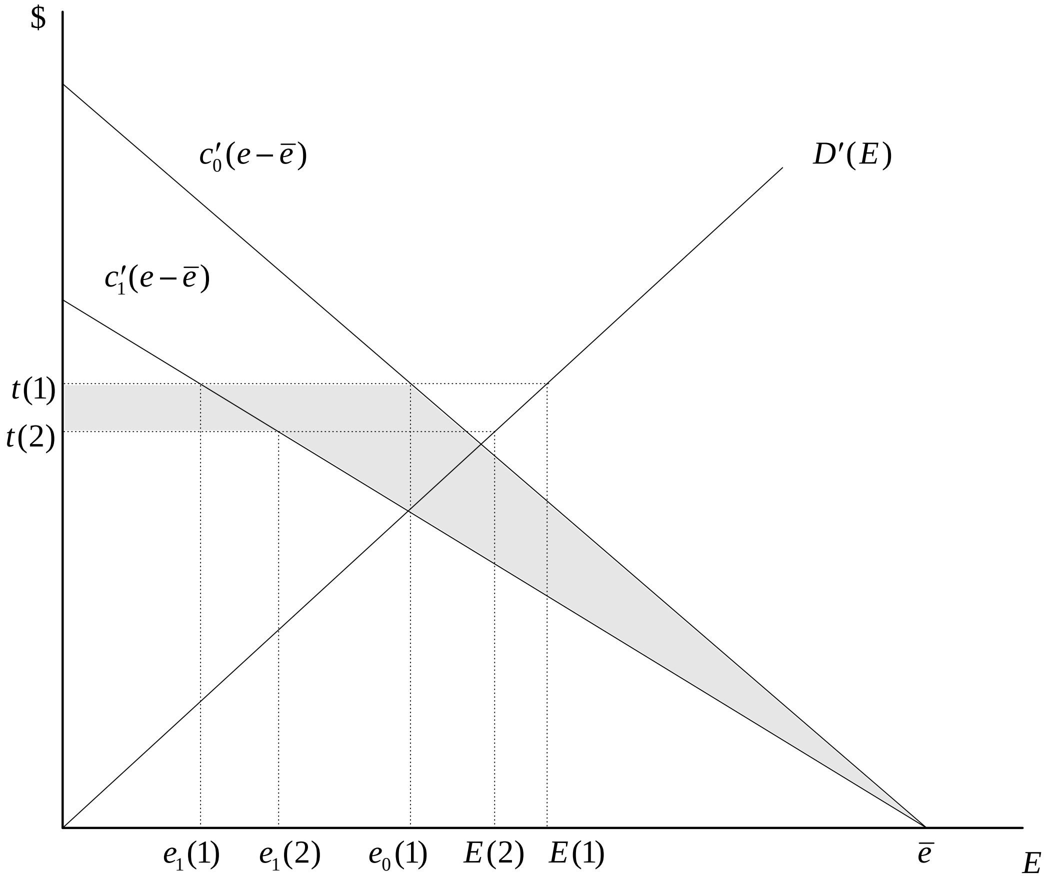

FIGURE 9
Private benefit to the
second adopting firm
(strictly convex damage)

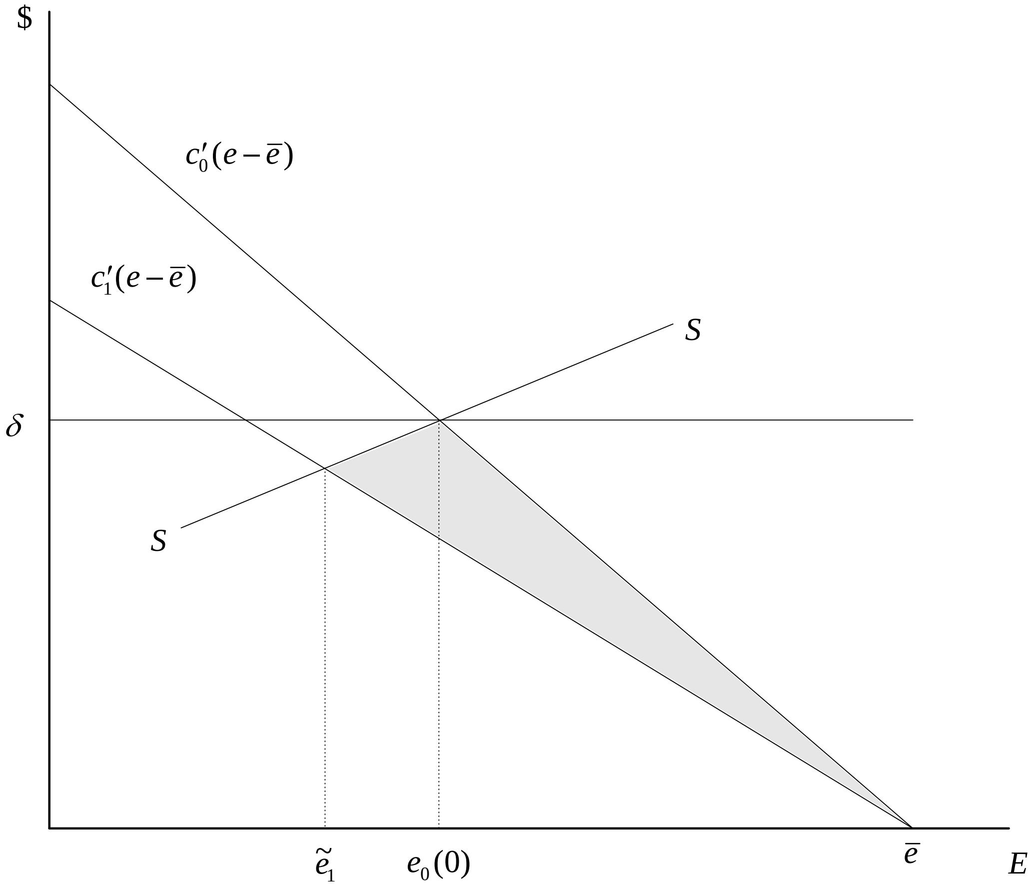

FIGURE 10
Private benefit to a deviating firm
that adopts the new technology
(linear damage)

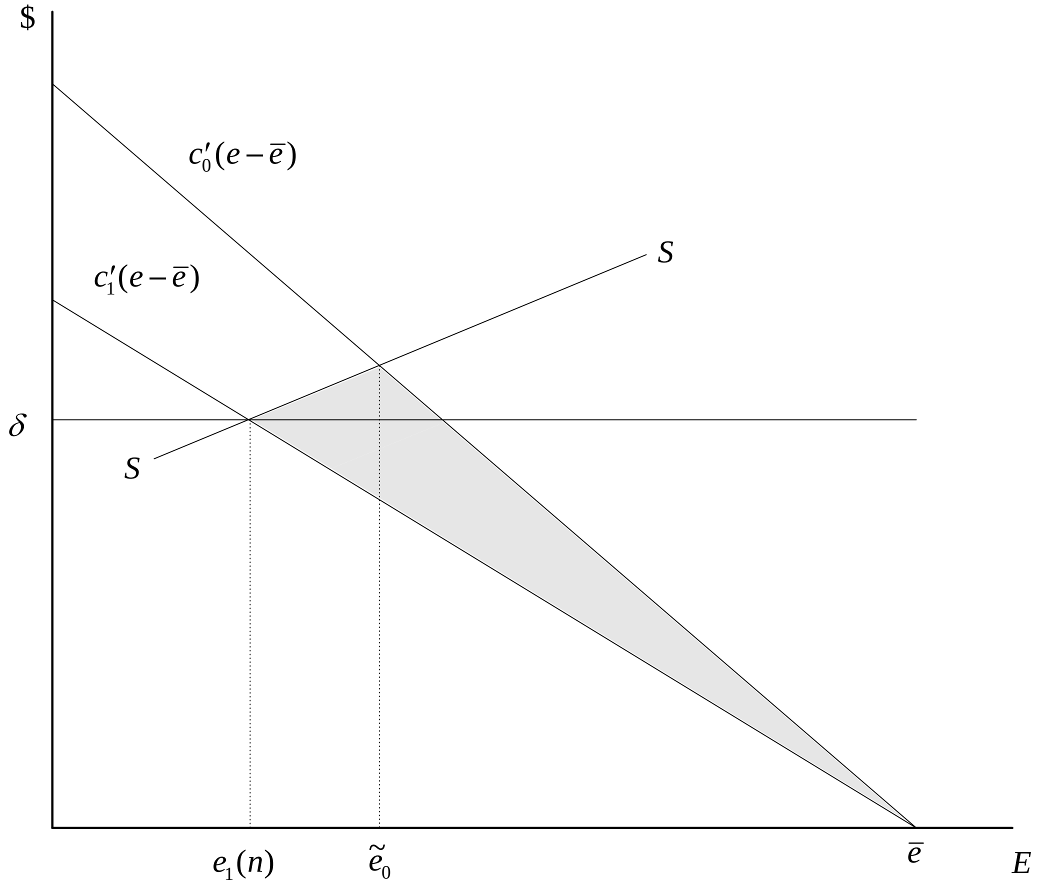

FIGURE 11
Private benefit to a deviating firm
that retains the old technology
(linear damage)

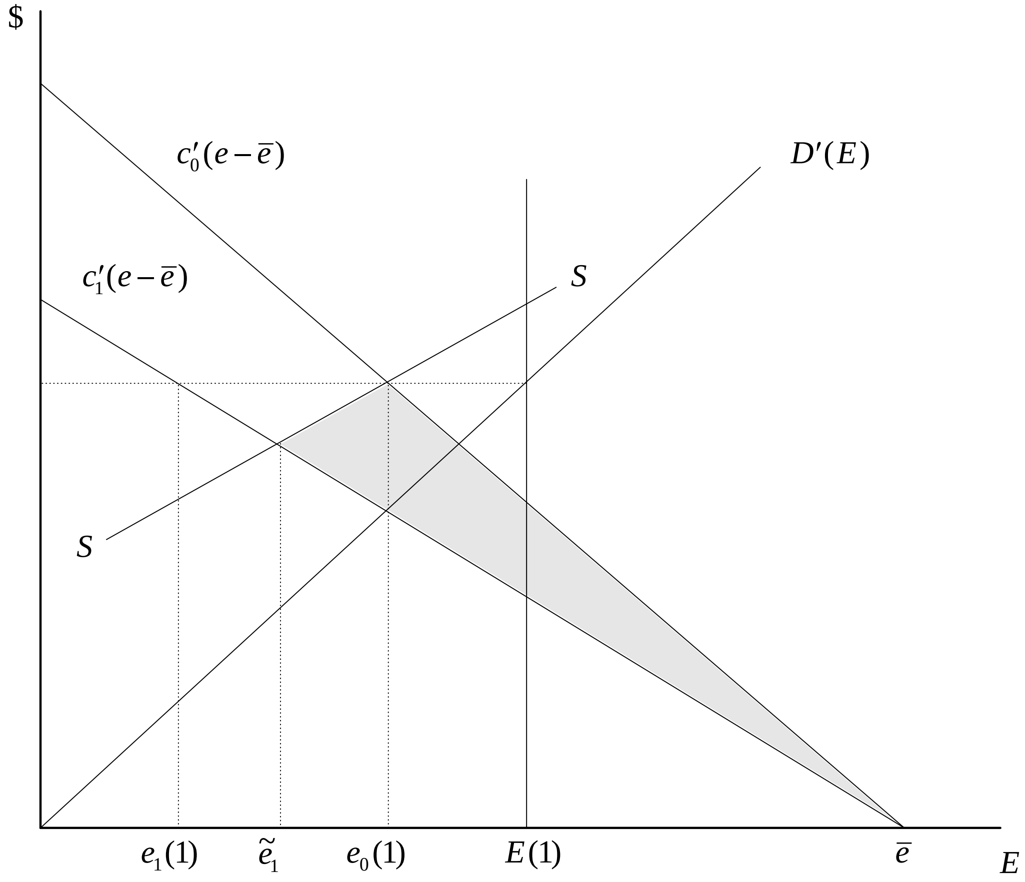

FIGURE 12
Private benefit to the
second adopting firm
at the first-best permit supply
(strictly convex damage)

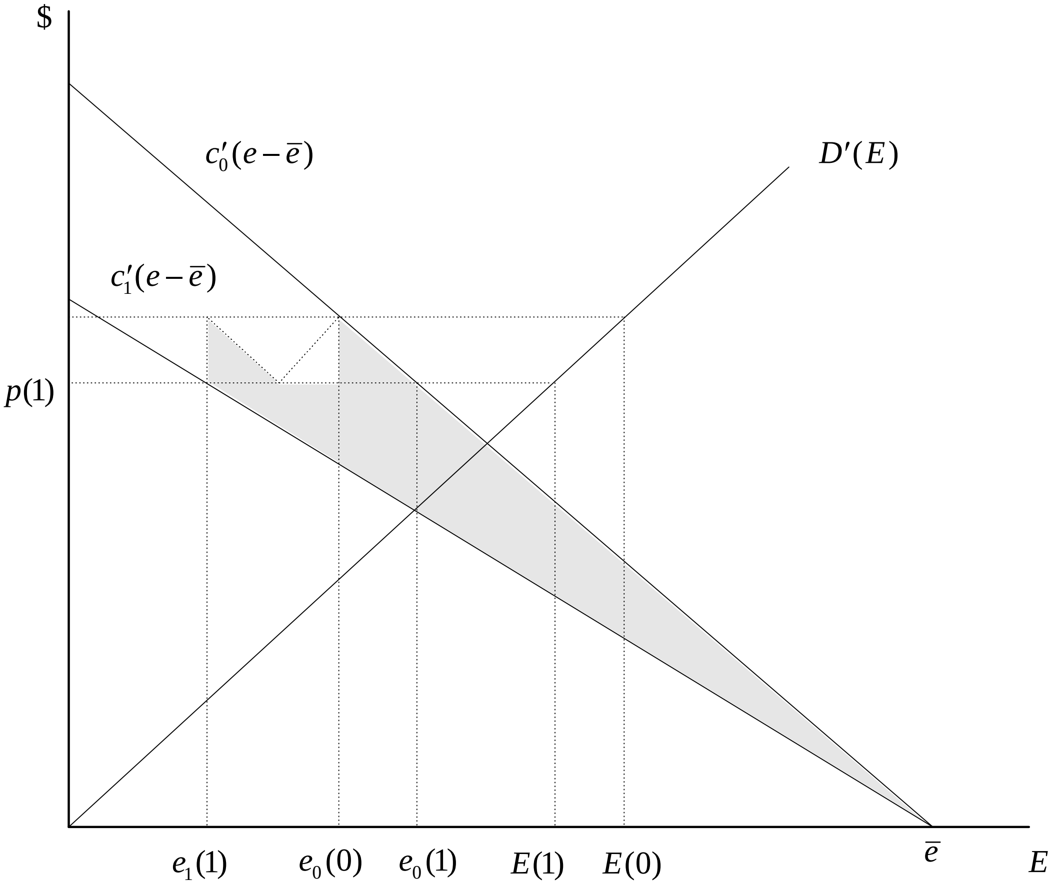

FIGURE 13
Private benefit from adoption by one firm under permit supply ratcheting (strictly convex damage)