WPS-1491

POLICY RESEARCH WORKING PAPER 1491

Equilibrium Incentives for Adopting Cleaner Technology Under Emissions Pricing

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Under certain circumstances, Pigouvian pricing does not induce an efficient (social welfare-maximizing) level of innovation of cleaner technology. Pigouvian pricing must be examined in equilibrium—adopting a less polluting technology does not necessarily improve welfare.

The World Bank
Policy Research Department
Environment, Infrastructure, and Evnironment Division
August 1995

Summary findings

Policymakers sometimes presume that adopting a less polluting technology necessarily improves welfare. This view is generally mistaken. Adopting a cleaner technology is costly, and this cost must be weighed against the technology's benefits in reduced pollution and reduced abatement costs.

The literature to date has not satisfactorily examined whether emissions pricing properly internalizes this tradeoff between costs and benefits. And if the trend toward greater use of economic instruments in environmental policy continues, as is likely, the properties of those instruments must be understood, especially for dynamic efficiency.

Kennedy and Laplante examine incentives for adopting cleaner technologies in response to Pigouvian emissions pricing *in equilibrium* (unlike earlier analyses, which they contend, have been generally incomplete and at times misleading).

Their results indicate that emissions pricing under the standard Pigouvian rule leads to efficient equilibrium adoption of technology only under certain circumstances. They show that the equilibrium level of adopting a public innovation is efficient under Pigouvian pricing only if there are enough firms that each firm has a negligible effect on aggregate emissions. When those circumstances are not satisfied, Pigouvian pricing does not induce an efficient (social welfare-maximizing) level of innovation.

The potential for inefficiency stems from two problems with the Pigouvian rule. First, the Pigouvian price does not discriminate against each unit of emissions according to its marginal damage. Second, full ratcheting of the emissions price in response to declining marginal damage as firms adopt the cleaner technology is correct *ex post* but distorts incentives for adopting technology *ex ante*.

The next natural step for research is to examine second-best pricing policies or multiple instrument policies. The challenge is to design regulatory policies that go some way toward resolving problems yet are geared to implementation in real regulatory settings.

Clearly, such policies must use more instruments than emissions pricing alone. Direct taxes or subsidies for technological change, together with emissions pricing, should give regulators more scope for creating appropriate dynamic incentives. Such instruments are already widely used: investment tax credits (for environmental research and development), accelerated depreciation (for pollution control equipment), and environmental funds (to subsidize the adoption of pollution control equipment).

Such direct incentives could be excessive, however, if emissions pricing is already in place. All incentives should be coordinated.

This paper — a product of the Environment, Infrastructure, and Agriculture Division, Policy Research Department — is part of a larger effort in the department to promote clearer understanding of important environmental policy issues. Copies of the paper are available free from the World Bank, 1818 H Street NW, Washington, DC 20433. Please contact Elizabeth Schaper, room N10-021, telephone 202-473-3457, fax 202-522-3230, Internet address eschaper@worldbank.org (40 pages). August 1995.

Produced by the Policy Research Dissemination Center

Equilibrium Incentives for Adopting Cleaner Technology Under Emissions Pricing

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EXECUTIVE SUMMMARY

This paper examines incentives for cleaner technology adoption in response to Pigouvian emissions pricing. There is sometimes a presumption among policy-makers that the adoption of a less polluting technology necessarily improves social welfare. This view is generally mistaken. The innovation and adoption of a cleaner technology is costly, and this cost must be weighed against the benefits of the new technology, in the form of reduced pollution and reduced abatement costs. Whether or not emissions pricing properly internalizes this tradeoff between the costs and benefits of technological change is a question that has not been addressed satisfactorily in the literature to date. We believe it is important to fill that gap. If the current trend towards greater use of economic instruments in environmental policy continues (and there is every reason to believe that it will), then it is crucial that the properties of those instruments be understood fully, especially as they pertain to the question of dynamic efficiency. Our attention to incentives *in equilibrium* distinguishes our analysis from existing work in this area, which has generally been incomplete and at times misleading.

Our results indicate that emissions pricing according to the standard Pigouvian rule leads to efficient equilibrium technology adoption only under some specific circumstances. We characterize those circumstances in terms of the number of polluting firms and whether or not marginal damage is increasing in aggregate emissions. In particular, we show that if the number of firms is sufficiently large that each firm has negligible effect on aggregate emissions, then the equilibrium level of adoption of a public innovation is efficient under Pigouvian pricing. When those circumstances are not satisfied, Pigouvian pricing does not induce the efficient (social welfare maximising) level of innovation. The potential for inefficiency stems from two distinct problems associated with the Pigouvian rule. The first relates to the fact that the Pigouvian price does not discriminate across each unit of emissions according to its marginal damage. The second problem relates to the ratcheting of the emissions price in response to declining marginal damage as firms adopt the cleaner technology. Full ratcheting according to the Pigouvian rule ensures that he emissions price is correct *ex post* but distorts incentives for technology adoption *ex ante*.

We have not examined second-best pricing policies or multiple instrument policies in this paper. To do so is the natural next step in this avenue of research. The challenge is to design regulatory policies that go some way towards resolving the problems we have highlighted but at the same time are geared towards implementation in real regulatory settings. It seems clear that such policies will need to use more instruments than emissions pricing alone. In particular, direct taxes or subsidies applied to technological change, used in concert with emissions pricing, are likely to give regulators greater scope in creating appropriate dynamic incentives. Such instruments are already in widespread use, usually in the form of investment tax credits (for environmental R&D), accelerated depreciation provisions (for pollution control equipment), and the creation of environmental funds (for subsidizing the adoption of pollution control equipment). Our results suggest that these direct incentives for

technological change should be used with caution if emissions pricing is already in place; the incentives so created could in fact be excessive. It is crucial that all instruments in place be properly coordinated in recognition of their inter-related incentive effects. Further research that provides a clearer understanding of those effects can contribute usefully to the design of real policy.

1. Introduction

One of the most important contributions of economic analysis to environmental policy has been to demonstrate the potential advantages of incentive-based regulation over "command and control". It is now well recognized that economic instruments that attach a price to emissions, such as emission charges and tradeable emission permits, can in many circumstances out-perform traditional command and control policies that simply dictate what individual firms can and cannot do. Economic instruments have the potential to implement environmental quality targets at lower cost and with fewer informational requirements than command and control policies.[1] Perhaps most important of all, economic instruments create dynamic incentives for technological change. Command and control policies that simply penalize a firm for non-compliance with a specified standard provide no incentive for that firm to employ cleaner production techniques beyond the point at which the regulatory constraint no longer binds. In contrast, policy instruments that attach a price to every unit of emissions provide firms with an ongoing incentive to reduce their emissions through the adoption of new technology if this can be achieved at a cost lower than the price they are paying to emit.

However, dynamic efficiency requires that emissions pricing do more than simply create ongoing incentives for technological change. It must create the *right* incentives. There is sometimes a presumption among policy-makers that the adoption of a less

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[1] See Bohm and Russell (1985), Cropper and Oates (1992), and Tietenberg (1991) for further discussion on the advantages of incentive-based instruments.

polluting technology necessarily improves social welfare. This view is generally mistaken. The innovation and adoption of a cleaner technology is costly, and this cost must be weighed against the benefits of the new technology, in the form of reduced pollution and reduced abatement costs. Whether or not emissions pricing properly internalizes this tradeoff between the costs and benefits of technological change is a question that has not been addressed satisfactorily in the literature to date. We believe it is important to fill that gap. If the current trend towards greater use of economic instruments in environmental policy continues (and there is every reason to believe that it will), then it is crucial that the properties of those instruments be understood fully, especially as they pertain to the question of dynamic efficiency. The purpose of this paper is to provide a systematic analysis of the circumstances under which emissions pricing does and does not create efficient incentives for technological change.

There already exists an extensive literature on incentives for technological change under environmental regulation, but an analysis of the type we provide in this paper is surprisingly absent from that literature.[2] The papers most closely related to our own are those by Downing and White (1986), and Milliman and Prince (1989). Both of these papers examine the incentives for technological change under emissions pricing. We devote section 5 of our paper to relating our work to these papers. At this point we wish to note only that the main shortcoming of these papers is that they fail to consider

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[2] See Milliman and Prince (1989) for a survey of literature previous to their paper. More recent work includes Biglaiser and Horowitz (1994), Laffont and Tirole (1994), Requate (1994) and Xepapadeas and Katsoulacos (1994).

incentives *in equilibrium*. This turns out to be very significant. Our paper stresses the importance of equilibrium considerations. We focus on a rational expectations equilibrium in which firms correctly anticipate the behavior of other firms and the optimal response of the regulator.[3]

Our paper has a sharp focus in two respects. First, we do not examine incentives for *innovation*. Our focus is on technology *adoption*. We believe it is most important to gain an understanding of the adoption stage first because the incentives for innovation are derived from the equilibrium incentives for adoption. Second, we focus on the standard Pigouvian rule for emissions pricing. This rule relates the price of emissions to marginal environmental damage. If the price of emissions is not tied to damage then there is no reason to expect that the dynamic incentives induced by emissions pricing will properly balance the full costs and benefits associated with technology adoption. Only a pricing rule based on damage can hope to achieve that goal. We confine our attention to the Pigouvian rule since it is the theoretical ideal in setting emission prices to induce static efficiency. Our paper asks whether, and under what conditions, the Pigouvian rule also induces dynamic efficiency.

The rest of the paper is organized as follows. In section 2 we construct a simple model that provides the basis for our analysis. In section 3 we examine the adoption of a public innovation (for which no license fee is payable). We consider this case to highlight

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[3] We comment on the appropriateness of this particular equilibrium concept in section 6.

some important results that become less transparent when complicated by the introduction of a patent holder. We consider the patented innovation case in section 4. In section 5 we relate our results to the existing literature. We provide a brief summary of our results and some thoughts on directions for future research in section 6.

2. The Model

Time is divided into two periods. In period 0 all firms use a production technology with associated abatement cost $MAC_0(e)$ defined over their emissions e.[4] This schedule is illustrated in Figure 1. In the absence of emissions pricing, a firm will undertake no abatement and will produce emissions $\bar{e}$ where $MAC_0(\bar{e}) = 0$. We assume that marginal abatement cost is increasing in abatement. Equivalently, $MAC_0'(e) < 0$. In period 1 a cleaner technology becomes available with associated marginal abatement cost $MAC_1(e)$. This is also illustrated in Figure 1. We assume that $MAC_1(e)$ is strictly lower than $MAC_0(e)$ for all positive levels of abatement.[5] The new technology can be *adopted* by any firm at some fixed cost A. This represents the real cost of manufacturing and installing the new equipment. We assume constant returns to scale in both of these processes. In addition, adopting firms may also have to pay a license fee F to the innovator. We assume that the innovator is a firm outside the polluting industry. This is consistent with real economies in which new technologies are to an ever increasing

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[4] The assumption that firms are initially homogeneous is deliberate. The reason will soon become clear.

[5] We have chosen to focus on this case because it allows us to present our main insights in the clearest way possible and because it ensures that our analytical structure is directly comparable to those used in the existing literature.

degree developed by specialist technology firms and then licensed to polluting firms. There are n polluting firms in each period.[6]

We assume that private and social marginal abatement costs coincide. This implies that polluting firms are price-takers on the product market. It is important to note that this assumption can hold even if the number of polluting firms in the regulated region is small. The regulated firms do not necessarily constitute the whole industry. Such is the case, for example, when polluting domestic firms take world market prices as given. While it may be interesting to consider the case where firms have some price-setting power, we do not do so here. Our purpose is to examine technology adoption equilibria in response to emissions pricing in the most transparent setting possible. This requires that we abstract from distortions induced by market failures elsewhere.[7]

Marginal environmental damage is a function of aggregate emissions E and is denoted MD(E). We make the standard assumption that $MD'(E) \geq 0$. The regulator sets the price of emissions (either directly through a charge or indirectly through the supply of tradeable permits) according to the standard Pigouvian rule. This means that in period zero the price of emissions is set equal to $p_0^* \equiv MD(E_0^*)$, where E_0^* is the optimal level of

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[6] We abstract from the possibility of entry in the post-innovation period to ensure, once again, that our analysis is directly comparable to the existing literature.

[7] It is well-known that imperfect competition in the product market calls for the distortion of the standard Pigouvian pricing rule [Buchanan (1969), Lee (1975), Barnett (1980)]. Such a distortion will in turn distort technology adoption decisions induced by emissions pricing.

aggregate emissions in period 0 given by the standard condition equating marginal damage with marginal abatement cost for each firm:[8]

$$\text{(1)} \qquad \mathrm{MD}(E_0^*) = \mathrm{MAC}_0(E_0^* / n)$$

We assume that the regulator continues to apply the Pigouvian pricing rule in period 1. This means that the price of emissions is adjusted to take account of the reduced marginal abatement costs for firms that adopt the new technology. This policy adjustment is called *ratcheting*. The adjusted price is set as follows. Let α denote the fraction of firms that adopt the new technology, and let e_{11} and e_{10} denote, respectively, the emissions in period 1 for a firm that adopts the new technology and a firm that retains the old technology. Then the Pigouvian rule requires that the price of emissions in period 1, p_1^*, be set equal to $\mathrm{MD}(E_1^*)$, where E_1^* is the optimal level of emissions in period 1 *given* that a fraction α of the firms have adopted the new technology. This optimal level of emissions is determined by the equality of marginal damage and marginal abatement cost equalized across firms:

$$\text{(2)} \qquad \mathrm{MD}(E_1^*) = \mathrm{MAC}_1(e_{11}^*) = \mathrm{MAC}_0(e_{10}^*)$$

where

$$\text{(3)} \qquad E_1^* = n\alpha e_{11}^* + n(1-\alpha)e_{10}^*$$

It is clear that $p_1^* < p_0^*$ when $\alpha > 0$ since $\mathrm{MAC}_1(e) < \mathrm{MAC}_0(e)$ at any given level of emissions below $\bar{e}$. Firms will rationally expect the regulator to ratchet the emissions

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[8] The planning problem is to choose e_i to min $D(E) + \sum_{i=1}^{n} AC_0(e_i)$ s.t. $\sum_{i=1}^{n} e_i = E$, where D(E) is damage and $AC_0(e_i)$ is abatement cost. If $\mathrm{MD}'(E) \geq 0$ and $\mathrm{MAC}'(e) > 0$, then the solution is equation (1).

price in this way unless the regulator can commit to an announced alternative rule. In section 4 we explain why the regulator might like to be able to commit to an alternative rule despite the fact that the Pigouvian rule is efficient *ex post*.

3. A Public Innovation

We begin our analysis by supposing that the innovation is public and so can be adopted without the payment of a license fee. We present this case mainly for pedagogical reasons. It is well known that knowledge, once created, is a public good and efficiency *ex post* requires that all agents have access to it regardless of their willingness to pay. But in order to create *ex ante* incentives for the creation of the new knowledge, it is necessary to price it *ex post*, and this will generally exclude some potential beneficiaries. Limited patents and copyrights are designed to trade-off these conflicting objectives. We wish to abstract initially from this standard problem in order to focus on the elements of the issue that are peculiar to the environmental setting. In section 4 we examine the case where the innovation is patented.

In this section, we consider first the case where the number of firms is sufficiently large that each firm has negligible impact on aggregate emissions. We then turn to the case where the number of firms is small and firms act strategically in their technology adoption decisions.

3.1 When the number of firms is large

We begin by deriving the efficient level of adoption as the solution to a planning problem. We then compare this efficient solution to the rational expectations equilibrium outcome.

Efficiency

It is important to note at the outset that the efficient solution may not involve universal adoption of the cleaner technology. This point has generally not been recognized in the literature to date. The intuition behind this point can be explained most easily with the aid of Figure 2 which illustrates the marginal abatement cost and marginal damage schedules for an individual firm. The md(e) schedule represents the marginal damage of the emissions from an individual firm drawn for a *given* level of emissions from other firms. The md(e) schedule has zero slope even if $MD'(E) > 0$ because the individual firm has a negligible impact on aggregate emissions. If a firm adopts the new technology, then society derives a gain indicated by the shaded region. This social gain comprises the cost reduction on existing abatement $(\bar{e} - e_{10}^{*})$ plus the net benefit from additional abatement $(e_{10}^{*} - e_{11}^{*})$ undertaken once the new technology is installed. This gain from adoption must be weighed against the cost of adoption when assessing whether or not the firm should adopt the new technology. Recall that the cost of adoption for any firm is independent of the number of firms that adopt (by the constant returns to scale assumption). However, when $MD'(E) > 0$, the *gain from adoption* is decreasing in the number of firms that adopt. This is because the damage done by the emissions from any one firm falls as more firms adopt the new technology and cut their emissions, thereby reducing MD(E). This means that md(e) schedule for any individual firm ***shifts down*** as more firms adopt the new technology. The shaded area in Figure 2 therefore shrinks as the number of adopting firms rises. If $A > 0$, then the gain from one firm adopting the cleaner technology may fall below A for a value of α strictly less than one. Thus, strictly partial adoption may be optimal when $A > 0$ and $MD'(E) > 0$.

If $A = 0$, then universal adoption is clearly the optimal solution regardless of whether or not $MD'(E) > 0$. Similarly, if $MD'(E) = 0$, then partial adoption will never be optimal. In this second case, the md(e) schedule in Figure 2 will *not* shift down as the aggregate level of emissions falls. The optimal solution will then involve either $\alpha = 1$ or $\alpha = 0$ according to whether or not the gain from adoption by any firm is greater than or less than A. Thus, $MD'(E) > 0$ is a necessary (but not sufficient) condition for optimal partial adoption.

To gain further insights, we need to be somewhat more formal. Let $C(\alpha)$ be the sum of abatement cost, damage and adoption costs when a fraction α of firms adopt the new technology, and emissions from adopting and non-adopting firms are set optimally using the Pigouvian pricing rule. That is,

$$C(\alpha) = n\alpha \int_{e_{11}^{*}}^{\bar{e}} MAC_1(e)de + n(1-\alpha) \int_{e_{10}^{*}}^{\bar{e}} MAC_0(e)de + \int_{0}^{E^{*}} MD(E)dE + \alpha nA \tag{4}$$

where e^*_{11}, e^*_{10} and E^*_1 are given by equations (2) and (3). The planning problem is to choose α to minimize this cost. The first-order condition for an interior integer solution is[9]

$$(5) \qquad \left. \int_{e^*_{10}}^{\bar{e}} MAC_0(e)de - \int_{e^*_{11}}^{\bar{e}} MAC_1(e)de \right] + MD(E^*_1)(e^*_{10} - e^*_{11}) = A$$

This condition can be interpreted in terms of Figure 2. The LHS represents the social gain when one more firm adopts the new technology. This is the shaded area in Figure 2. The first (bracketed) term represents the abatement cost reduction associated with the new technology. The second term represents the reduced damage associated with additional abatement under the new technology. The RHS represents the cost of adoption for the marginal firm. Condition (5) therefore implies that the benefit and cost of adoption by the marginal firm are just equated at the optimum.[10]

To complete our characterization of the efficient solution, we must also consider the possible corner solutions. If $\partial C(\alpha) / \partial \alpha \geq 0$ at $\alpha = 0$, then efficiency requires that no firms adopt the new technology. This situation arises when A is very large relative to the magnitude of the shift in the MAC schedule. Conversely, if $\partial C(\alpha) / \partial \alpha \leq 0$ at $\alpha = 1$, then efficiency requires universal adoption. This occurs when A is small relative to the

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[9] Allowing for the possibility that the first-best value of αn is not an integer complicates the analysis but does not provide any additional insights. We therefore maintain the integer assumption throughout.

[10] The second-order conditions for a minimum are satisfied by our assumptions that $MAC'(e) > 0$ and $MD'(E) \geq 0$.

magnitude of the innovation. As noted earlier, if A = 0, universal adoption is always optimal.

Equilibrium

We now turn to the equilibrium level of adoption. We confine consideration to a rational expectations equilibrium in which each firm correctly anticipates that the price of emissions in period 1 will be set according to the Pigouvian rule based on the fraction α of firms that adopt the new technology. In the case where n is large, each firm takes that fraction as given and independent of its own adoption decision. This means that each firm views the price of emissions in period 1 as independent of its own adoption decision. If a fraction α of firms adopt the new technology, and the price of emissions is set according to the Pigouvian rule, then the price in period 1 will be

$$p_1(\alpha) = MD(n\alpha e^*_{11} + n(1-\alpha)e^*_{10}) \tag{6}$$

Faced with this anticipated price of emissions, each firm decides whether or not to adopt the new technology according to whether or not the net private benefit from doing so is positive. The net private benefit from adoption is

$$B(\alpha) = \left[\int_{e^*_{10}}^{\bar{e}} MAC_0(e)de + p_1(\alpha)e^*_{10}\right] - \left[\int_{e^*_{11}}^{\bar{e}} MAC_1(e)de + p_1(\alpha)e^*_{11}\right] - A \tag{7}$$

This net benefit represents the difference between the sum of abatement cost and tax payments under the two technologies, less the cost of adoption. Note that the firm bases its decision on the levels of emissions it expects to produce under the two alternatives, which by design, are the efficient levels induced by the Pigouvian pricing rule.

It is straightforward to show that $B(\alpha)$ is declining in α when $MD'(E) > 0$. The reason is that aggregate emissions decline as more firms adopt the new technology, and this reduces marginal damage when $MD'(E) > 0$. This means that the price of emissions falls as more firms adopt, and this in turn reduces the private gain to the firm from adopting the new technology. This relationship between $B(\alpha)$ and α is illustrated in Figure 3.

We can now characterize the equilibrium level of adoption and examine its efficiency properties. The interior rational expectations equilibrium occurs at $\hat{\alpha}$ where $B(\hat{\alpha}) = 0$. At levels of adoption below $\hat{\alpha}$, the net private benefit to a firm from adoption is positive and further adoption is thereby induced. Once the level of adoption reaches $\hat{\alpha}$, adoption by one more firm would yield a negative net benefit to that firm and so it will choose not to adopt. Of course, there may not exist an interior equilibrium if A is very large or very small. If $B(\alpha) \leq 0$ at $\alpha = 0$, as might be the case if A is very large, then no firms adopt in equilibrium. Conversely, if $B(\alpha) \geq 0$ at $\alpha = 1$, as might be the case if A is very small, then all firms adopt in equilibrium. Note that if $MD'(E) = 0$, then $B'(\alpha) = 0$, and so partial adoption is never an equilibrium in that special case.

Is the rational expectations equilibrium efficient? A comparison of equations (5) and (7) reveals that it is. Recall that $p_1(\alpha) = MD(E_1^*)$ when the price of emissions is set according to the Pigouvian rule. Making this substitution for $p_1(\alpha)$ in equation (7) reveals that $B(\alpha)$ and $\partial C(\alpha) / \partial \alpha$ are exactly equivalent. It follows immediately that the equilibrium level of adoption is efficient (for both the interior and corner cases). This result is summarized in the following proposition.

Proposition 1. If the number of firms is sufficiently large that each firm has negligible effect on aggregate emissions, and the price of emissions is set according to the Pigouvian rule, then the equilibrium level of adoption of a public innovation is efficient.

The key to this result is the Pigouvian pricing rule. Setting the price of emissions equal to marginal damage not only induces static efficiency but dynamic efficiency as well. Ratcheting the emissions price according to the Pigouvian rule ensures that the effect of any decline in marginal damage is fully internalized in technology adoption decisions. The anticipated price of emissions correctly tracks the declining marginal damage as more firms adopt the technology, and this creates the correct adoption incentives.

The central policy implication of proposition 1 is that ratcheting the price of emissions in response to new technology adoption according to the Pigouvian rule (and announcing this rule to firms), is necessary and sufficient to ensure dynamic efficiency, if the number of firms is large and the innovation is public. But what if these qualifying conditions are not met? We examine the implications of a patent on the innovation in section 4. In the next sub-section, we look at the case where the number of firms is small.

3.2 When the number of firms is small

Suppose the number of firms is sufficiently small that each firm has a significant effect on aggregate emissions. This has substantive implications for technology adoption only in the case where marginal damage is increasing. If $MD'(E) = 0$, then marginal damage is independent of the adoption decision of any individual firm and the analysis of the previous sub-section continues to apply. But if $MD'(E) > 0$ and each firm has a significant effect on E, then marginal damage is not independent of individual technology adoption decisions. For the remainder of this sub-section, we therefore restrict attention to the case where $MD'(E) > 0$.

We begin our analysis with Figure 4 which is the analogue of Figure 2 for the case where n is small. The marginal damage schedule md(e) reflects marginal damage associated with the emissions of a single firm drawn for a given level of emissions by other firms. This schedule has positive slope in this case because each firm has a significant effect on aggregate emissions, and marginal damage is increasing in aggregate emissions.[11] The shaded area represents the social gain from adoption by an individual firm. The md(e) schedule shifts down when other firms adopt the technology - just as it does in the case where n is large - and so the social gain to adoption shrinks. The efficient (interior) level of adoption is determined by the point where the shaded area for the marginal firm is just equal to the cost of adoption. The mathematics defining this efficient

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[11] Note that if $MD'(E) = 0$, then Figure 2 and Figure 4 are identical.

point is identical to that for the case where n is large; the condition for efficiency is equation (5).

Now consider the private incentive to adopt the new technology. The private gain from adoption is represented by the shaded area in Figure 5. This shaded area can be interpreted as follows. If the firm retains the old technology, then it correctly anticipates an emissions price equal to p_{10} (set according to the Pigouvian rule, given that this firm does not adopt the new technology). It would then abate up to e^*_{10} and so incur an abatement cost equal to the area beneath MAC_0 between e^*_{10} and $\bar{e}$. It also incurs the cost of paying a price p_{10} on its remaining emissions, equal to the area $p_{10}e^*_{10}$. If instead the firm adopts the new technology (taking the adoption decisions of other firms as given), then marginal damage will fall (along the md(e) schedule) because the firm is "large", and so the firm will correctly anticipate a price of emissions equal to $p_{11} < p_{10}$. That is, the firm recognizes that its own adoption decision will affect the price of emissions as determined by the Pigouvian rule. The total cost to the firm under the new technology is therefore equal to the area beneath MAC_1 between e^*_{11} and $\bar{e}$, plus the area $p_{11}e^*_{11}$. The difference between these total costs for the two technologies is the shaded area in Figure 5.

It is clear from figures 4 and 5 that the private gain to technology adoption exceeds the social gain. Downing and White (1986) derive an analogous result for the case of a single polluting firm. They explain their result correctly as follows. The

Pigouvian pricing rule levies a price equal to the damage on the marginal unit of emissions of *all* units of emissions. This means that the total payment for a given level of emissions exceeds the total damage associated with those emissions if marginal damage is increasing. Because the private gain from adopting a new technology stems in part from the reduced emission fees payable after adoption, and because this reduction in fees payable exceeds the reduced damage done, the private gain from adoption exceeds the social gain.

It is important to understand that this excessive incentive to adopt the cleaner technology is *not* due solely to the strategic interaction between the regulator and individual firms. Figure 6 illustrates the perceived private gain from adoption for a *myopic* firm that anticipates no ratcheting of the emissions price in response to its own adoption decision. It takes the emissions price as given in the same way as the "small" firms of the previous sub-section. The perceived private gain in this myopic case is smaller than when the firm anticipates ratcheting but it is nonetheless greater than the true social gain. The source of the problem is *not* the ratcheting *per se*. The problem stems from the fact that the Pigouvian pricing rule does not price each unit of emissions at its marginal damage when marginal damage is increasing. There is no associated distortion of the adoption decision when firms are small because marginal damage is effectively constant with respect to their emissions even if marginal damage is increasing in aggregate emissions. This is not true when firms are large. A reduction in their emissions does reduce marginal damage and so the reduced tax payments overstates the social gain. The strategic interaction induced by ratcheting merely exacerbates this distortion.

We now characterize the adoption equilibrium more formally and show that it will generally involve excessive adoption of the new technology. Consider a firm which takes as given the adoption decisions of the other n - 1 firms. Suppose that m of those firms adopt the new technology. If the firm in question adopts the new technology then it will face an emissions price in period 1 equal to

$$(8) \qquad p_{11}(m) = MD((m+1)e_{11}(p_{11}) + (n-m-1)e_{10}(p_{11}))$$

where $e_{11}(p_{11})$ and $e_{10}(p_{11})$ solve $p_{11}(m) = MAC_0(e_{10}) = MAC_1(e_{11})$. If, instead, the firm chooses to retain the old technology, it will face an emissions price in period 1 equal to

$$(9) \qquad p_{10}(m) = MD(me_{11}(p_{10}) + (n-m)e_{10}(p_{10}))$$

where $e_{11}(p_{10})$ and $e_{10}(p_{10})$ solve $p_{10}(m) = MAC_0(e_{10}) = MAC_1(e_{11})$. The private net benefit to adoption by the $(m+1)^{th}$ adopting firm is therefore given by

$$(10) \qquad B(m) = \left[\int_{e_{10}(p_{10})}^{\bar{e}} MAC_0(e)de + p_{10}(m)e_{10}(p_{10})\right] - \left[\int_{e_{11}(p_{11})}^{\bar{e}} MAC_1(e)de + p_{11}(m)e_{11}(p_{11})\right] - A$$

It is straightforward to show that $B'(m) < 0$ when $MD'(E) > 0$, for precisely the same reason that $B'(\alpha) < 0$ in the case where n is large: the Pigouvian pricing rule dictates that the emissions price fall with marginal damage as more firms adopt the cleaner technology and cut their emissions. The interior rational expectations equilibrium is therefore characterized by adoption by $\hat{m}$ firms such that $B(\hat{m}) = 0$.[12]

We now compare this equilibrium with the interior social optimum m^*. Our approach is to examine the sigh of $B(m^*)$. From this we can determine the direction of any distortion in equilibrium. We know that $e_{10}(p_{10}(m^*)) = e^*_{10}$ because m^* is the social optimum (and so a decision by the $(m^* + 1)^{th}$ firm *not* to adopt when facing an anticipated emissions price $p_{10}(m^*)$ must be efficient). Making this substitution in (10) yields

$$(11) \qquad B(m^*) = \left[\int_{e^*_{10}}^{\bar{e}_r} MAC_0(e)de + p_{10}(m^*)e^*_{10} \right] - \left[\int_{e_{11}(p_{11})}^{\bar{e}_r} MAC_1(e)de + p_{11}(m^*)e_{11}(p_{11}) \right] - A$$

Noting that $p_{10}(m^*) = MD(E^*_1)$, by definition of m^* as the social optimum, and assuming that m^* is an integer, we can use equation (5) to subtract $\partial C / \partial \alpha = 0$ from the RHS of (11) to obtain

$$(12) \qquad B(m^*) = \left[\int_{e^*_{11}}^{\bar{e}} MAC_1(e)de + p_{10}(m^*)e^*_{11} \right] - \left[\int_{e_{11}(p_{11})}^{\bar{e}_r} MAC_1(e)de + p_{11}(m^*)e_{11}(p_{11}) \right]$$

This difference is illustrated as the shaded area in Figure 7. We know that $p_{11}(m^*) < p_{10}(m^*)$ when $MD'(E) > 0$ because adoption of the cleaner technology by one more firm reduces marginal damage, and we know that $e^*_{10} < e_{11}(p_{11})$ because $MAC_1'(e) < 0$. It follows that $B(m^*) > 0$. That is, there is a strictly positive private net

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[12] We continue to assume an integer solution.

benefit from adoption for at least one more firm beyond the efficient level of adoption. This means that equilibrium will involve excessive adoption relative to the interior social optimum. We summarize this result in the following proposition.

Proposition 2. If each firm has a significant effect on aggregate emissions and marginal damage is increasing, and the price of emissions is set according to the Pigouvian rule, and the social optimum is an interior and integer one, then too many firms will adopt a public innovation in equilibrium.

We have already noted that the source of this inefficiency is the fact that the savings in emissions fees for the firm exceeds the reduction in damage when the price of emissions is set according to the Pigouvian rule and marginal damage is increasing. This distortion disappears when n is sufficiently large because marginal damage is effectively constant with respect to the emissions of any individual firm.[13] There may also be no distortion if the social optimum is a corner solution. In particular, if $m^* = n$ then $\hat{m} = n$, and there is no inefficiency. That is, if the innovation is so significant relative to its adoption cost that it should be adopted by all firms, then it will be adopted by all firms in equilibrium. Conversely, if efficiency requires that no firms adopt the new technology, then this may also be supported as an equilibrium if the difference between the private gain and the social gain is not too large (which requires that marginal damage for each firm not be too

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[13] This can be seen clearly in expression (12): $p_{11}(m^*) \rightarrow p_{10}(m^*)$ as $n \rightarrow \infty$ because small firms correctly perceive that their adoption decision will have no effect on the price of emissions, and so $e_{11}(p_{11}) \rightarrow e_{11}^*$. It follows that $B(m^*) \rightarrow 0$.

strongly increasing). In all other cases, there will be excessive adoption of the new technology.

The solution to this problem is in principle straightforward: emissions should be priced according to a discriminating pricing rule that sets the price of each unit of emissions equal to the marginal damage of that unit. This will eliminate the wedge between the private and social gain to technology adoption while at the same time preserving the static efficiency condition that marginal abatement cost and marginal damage be equated at the optimum in each period. However, implementing this ideal solution is likely to be difficult in practice due to the informational requirements involved. We comment further on this problem in section 6.

4. Equilibrium adoption of a patented innovation

We now suppose that adopting firms must pay a license fee to the patent holder. The problem for the patent holder is[14]

$$\max_{F} m(F)F \tag{13}$$

where F is the license fee, and m(F) is the anticipated number of firms that will choose to adopt the innovation. The patent holder calculates m(F) correctly as the rational expectations equilibrium level of adoption given the license fee. It turns out that the

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[14] We assume that the patent holder cannot price discriminate across firms when setting the license fee.

welfare implications of the license fee depend importantly on whether marginal damage is constant or increasing in aggregate emissions. We consider each case in turn.

4.1 Constant marginal damage

When marginal damage is constant, there is no ratcheting of the emissions price in response to technology adoption. This means the private benefit to adoption (B) does not depend on the number of firms that adopt. Hence, the m(F) schedule faced by the patent holder is perfectly elastic. The patent holder will induce universal adoption if it sets $F < B$, and no adoption if it sets $F > B$. If $B \geq 0$, then the profit-maximizing solution is to set $F = B - \varepsilon$ where ε is arbitrarily small. This will induce universal adoption and this is efficient because B reflects the true social gain to adoption when $MD'(E) = 0$. If instead $B < 0$, then the privately optimal solution is to set $F = 0$. This will induce no adoption and this too is efficient. There is therefore no distortion of the adoption equilibrium when a license fee is introduced if marginal damage in aggregate emissions is constant. Note that this result holds regardless of whether n is large or small because there is no effective difference between these cases when $MD'(E) = 0$. We summarize the result as follows.

Proposition 3. If marginal damage in aggregate emissions is constant, and the price of emissions is set according to the Pigouvian rule, then the patent holder sets a license fee that induces the efficient level of technology adoption.

It should be noted that this result relies on the assumption that all firms are identical. If firms are heterogeneous in their willingness to pay for the innovation then the m(F) schedule will be negatively sloped and the adoption equilibrium will generally be distorted. Such a distortion would reflect the usual *ex ante - ex post* tradeoff associated with awarding a patent.[15] We have focused deliberately on the homogeneous case so as to highlight the issues that are peculiar to the environmental setting. In particular, in the next sub-section we show that the ex-ante - ex post efficiency tradeoff arises even when firms are homogeneous if marginal damage is increasing in aggregate emissions.

4.2 Increasing marginal damage

Recall from section 3.2 that increasing marginal damage means that $B'(m) < 0$ when the price of emissions is ratcheted according to the Pigouvian rule. This means that the m(F) schedule is negatively sloped since the gain to adoption for any firm (and hence their willingness to pay for a license) falls as more firms adopt. An interior solution to the patent holder's problem is characterized by the familiar monopoly condition

$$m(F) + m'(F)F = 0 \tag{14}$$

This condition states that the license fee should be raised to the point where marginal revenue is zero. We know that the m(F) schedule is characterized by the adoption equilibrium condition $B(m) = F$ if the equilibrium is interior and integer. Making this substitution in (14) and rearranging yields an expression for the equilibrium level of adoption of the patented innovation:

$$B(m) / m = -B'(m) \tag{15}$$

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[15] See Biglaiser and Horowitz (1995) for an analysis of this problem in an environmental setting. They assume $MD'(E) = 0$ and heterogeneous firms.

The solution to this condition is depicted as $\tilde{m}$ in Figure 8. The LHS of (15) represents the slope of the dashed ray. The RHS of (15) represents the slope of the B(m) schedule. The dashed ray is orthogonal to the B(m) schedule at the equilibrium. For comparison, the (interior) equilibrium level of adoption for a *public* innovation is depicted in Figure 8 as $\hat{m}$. It is clear that $\tilde{m} < \hat{m}$. This is as expected: the license fee reduces the net benefit to adoption and leads to less adoption in equilibrium. The only possible exceptions are at the corner solutions. If $B(0) \leq 0$, then $\tilde{m} = \hat{m} = 0$. The patent holder will choose not to induce any adoption when $B(0) \leq 0$ because to do so would require setting a negative license fee. At the other extreme, if B(m) is sufficiently steep at m = n, then $\tilde{m} = n$. It follows that $\tilde{m} = \hat{m} = 0$ in that case.

The key question of interest is whether $\tilde{m}$ is smaller or larger than the first-best level of adoption m^*. The answer is clear in the case where n is large. Recall from proposition 1 that if n is sufficiently large then $\hat{m} = m^*$. Since $\tilde{m} < \hat{m}$, it follows that $\tilde{m} < m^*$ in that case, except when $m^* = 0$ (in which case $\tilde{m} = m^*$). We can summarize this result as follows.

Proposition 4. If the number of firms is sufficiently large that each firm has a negligible effect on aggregate emissions and marginal damage is increasing, and the price of emissions is set according to the Pigouvian rule, and at least some adoption of the new technology is efficient, then the patent holder sets a license fee that induces too little adoption.

This result reflects the familiar ex post inefficiency associated with the monopoly pricing of a patented innovation. However, it is important to understand that in this environmental setting this result is linked directly to the ratcheting of the emissions price. The private gain to a firm from adopting the new technology falls as more firms adopt it, because the regulator ratchets down the price of emissions in line with declining marginal damage. This causes the demand curve faced by the patent holder to be negatively sloped even though firms are homogeneous ex ante. The standard monopoly welfare result then applies directly.

Note that if the emissions price is not ratcheted then the B(m) schedule is not declining in m and the m(F) schedule is perfectly elastic. The patent holder would then set F to induce either no adoption or universal adoption (just as in the $MD'(E) = 0$ case). Of course this will generally not be an efficient outcome either. The level of technology adoption will generally be wrong, and the emissions price will be too high *ex post* (unless no adoption happens to be efficient). However, there is no reason to expect that the inefficiency associated with not ratcheting will necessarily be greater than the inefficiency induced by ratcheting. The key problem is that the regulator is faced with the conflicting goals of inducing the right level of technology adoption and setting the correct emissions price *ex post*. The second-best solution to this dilemma is unlikely to be full ratcheting according to the standard Pigouvian rule, since this puts exclusive emphasis on achieving the correct ex post emissions price. The second-best pricing policy will likely involve partial ratcheting which trades off the competing ex ante and ex post goals in an optimal way. Of course, this requires that the regulator be able to pre-commit to a tax rate that is sub-optimal ex post.

We complete our analysis in this section by examining the case where the number of firms is small. The efficiency properties of the equilibrium induced by full ratcheting in this case are ambiguous. Recall from section 3.2 that the non-discriminating nature of the standard Pigouvian pricing rule tends to induce excessive technology adoption when marginal damage is increasing and the number of firms is small. This effect can potentially offset the tendency towards under-adoption induced by full ratcheting when the technology is patented. The net effect is therefore ambiguous except in the special case where $n = 1$. In that case, there can never be under-adoption. We have seen from section 3.2 that a single firm will never choose non-adoption of a public innovation if adoption is efficient. The same must be true of a patented adoption. If adoption is efficient, then the firm would choose to adopt if $F = 0$. The patent holder would then never set a license fee that induces non-adoption since doing so is always less profitable than setting a lower (but still positive) fee that induces adoption.

5. Relation to existing literature

One purpose of our paper is to clarify and place in context some existing results in the literature. Our discussion here will focus on papers by Downing and White (1986) and Milliman and Prince (1989).

Downing and White (1986) provide a graphical analysis for the case of a single firm and examine its incentive to adopt a public innovation. They assume that marginal damage is increasing and distinguish between marginal and non-marginal innovations according to whether or not marginal damage changes. We have instead focused on a discrete innovation and distinguished cases on the basis of whether or not marginal damage is constant or increasing. The two approaches are technically equivalent for the single firm case (although our approach allows a clearer interpretation of results in more general cases). We have already noted in section 3 what we believe to be the key result in the Downing and White paper: the standard non-discriminating Pigouvian pricing rule creates excessive incentives for cleaner technology adoption when marginal damage is increasing because the reduction in emissions fees associated with technology adoption exceeds the reduction in damage.

Downing and White also consider briefly the case where there is a large number of firms. They assert that the results for the single firm case can simply be re-interpreted as applying to a large number of firms.[16] We have shown that this is not correct. The confusion in Downing and White seems to stem from their failure to consider incentives *in equilibrium*. They assume implicitly that each small firm expects every other firm to make the same decision it makes (as if it were making decisions on behalf of all firms). This expectation is not fulfilled in equilibrium.

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[16] Downing and White (1986, p. 24).

Milliman and Prince (1989) focus on incentives for innovation. They model an industry with many polluting firms in which a single firm innovates a new technology. They then examine how emission pricing affects the "diffusion" (adoption) of that technology and how this in turn affects incentives to innovate. Their analysis differs from ours most notably in that it is not an *equilibrium* analysis. Adoption decisions are not modeled explicitly and there is no consideration given to whether or not the adoption outcomes that are presupposed can in fact be equilibria. It turns out that they can be equilibria only under certain conditions. In particular, Milliman and Prince assume that adoption of the new technology is universal, regardless of whether the innovation is public or patented. We have shown that his is an assured equilibrium under Pigouvian ratcheting only if adoption is free. The problem in Milliman and Prince stems from their assumption that firms anticipate no ratcheting of the emissions price in response to technology adoption even when ratcheting does occur. This assumption is not consistent with rational, forward-looking behavior.[17]

6. Conclusion

In this paper, we have examined incentives for cleaner technology adoption in response to Pigouvian emissions pricing. Our attention to equilibrium considerations distinguishes our analysis from existing work in this area. Our principal results are

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[17] Malueg (1989) and Requate (1994) also examine technology adoption under emissions pricing. They too abstract from equilibrium considerations and their results should be interpreted cautiously. Requate (1994) examines properly the equilibrium between firms for a given policy, but still assumes that firms anticipate no policy adjustment in response to technology adoption, even when such adjustment does occur ex post.

summarized as propositions 1 to 4. The main thrust of these results is that emissions pricing according to the standard Pigouvian rule leads to efficient technology adoption only under some circumstances. We have characterized those circumstances in terms of the number of polluting firms and whether or not marginal damage is increasing in aggregate emissions.

The potential for inefficiency stems from two distinct problems associated with the Pigouvian rule. The first relates to the fact that Pigouvian pricing does not discriminate across each unit of emissions according to its marginal damage. This means that when marginal damage is increasing, the total emission fees paid by "large" firms exceed the damage caused by their emissions. This in turn tends to induce excessive adoption of cleaner technology. The second problem arises when the technology is patented, and relates to the ratcheting of the emission price in response to declining marginal damage as more firms adopt the cleaner technology. Full ratcheting according to the Pigouvian rule ensures that the emissions price is correct *ex post* but at the same time distorts technology adoption through its impact on the elasticity of the patent holder's demand curve. It is generally not possible to achieve efficient pricing ex post and at the same time create the rights incentives for technology adoption *ex ante* using a single instrument.

All of our main results are derived in a rational expectations equilibrium context and we should comment on the reasonableness of that equilibrium concept. Rational expectations is a strong behavioral assumption. It places signigicant rationality and informational requirements on the regulated firms, requirements that real-world firms probably do not meet. Ideally, we would like to work with a model in which firms are forward-looking but boundedly rational. Unfortunately, models of bounded rationality are not yet developed to the point where they can be used to analyze the sort of policy problems we have examined here. One alternative is to assume that firms are completely myopic, as other models in this literature have done. We believe that this is probably an even poorer approximation to reality than our rational expectations assumption. Nonetheless, it is worth speculating briefly on the sensitivity of our results to deviations from rational expectations. In general, one would expect that small "mistakes" by firms in their technology adoption decisions are more likely to precipitate long run outcomes with more technology adoption than our equilibrium results indicate rather than less. The reason relates to the sunkness of technology adoption. In the event of a short run disequilibrium outcome with under-adoption (relative to the rational expectations equilibrium), firms can respond with further technology adoption. But the converse may not be true. If technology adoption is sunk then there may be no way of profitably undoing an adoption decision that is regretted ex post. That is, over-adoption (relative to the rational expectations equilibrium) may be an ex post equilibrium to the perturbed game if undoing technology adoption decisions is costly.[18]

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[18] We should stress that these claims are speculative. We have not examined the perturbed game formally.

We have not examined second-best pricing policies or multiple instrument policies in this paper. To do so is the natural next step in this avenue of research. The challenge is to design regulatory policies that go some way towards resolving the problems we have highlighted but at the same time are geared towards implementation in real regulatory settings. It seems clear that such policies will need to use more instruments than emissions pricing alone. In particular, direct taxes or subsidies applied to technological change, used in concert with emissions pricing, are likely to give regulators greater scope in creating appropriate dynamic incentives. Such instruments are already in widespread use, usually in the form of investment tax credits (for environmental R&D), accelerated depreciation provisions (for pollution control equipment), and the creation of environmental funds (for subsidizing the adoption of pollution control equipment).[19] Our results suggest that these direct incentives for technological change should be used with caution if emissions pricing is already in place; the incentives so created could in fact be excessive. It is crucial that all instruments in place be properly coordinated in recognition of their inter-related incentive effects. Further research that provides a clearer understanding of those effects can contribute usefully to the design of real policy.

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[19] See Lovei (1994) and Jenkins and Lamech (1992) for a thorough description of these fiscal incentives.

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FIGURE 1
Marginal abatement cost with old and new technologies

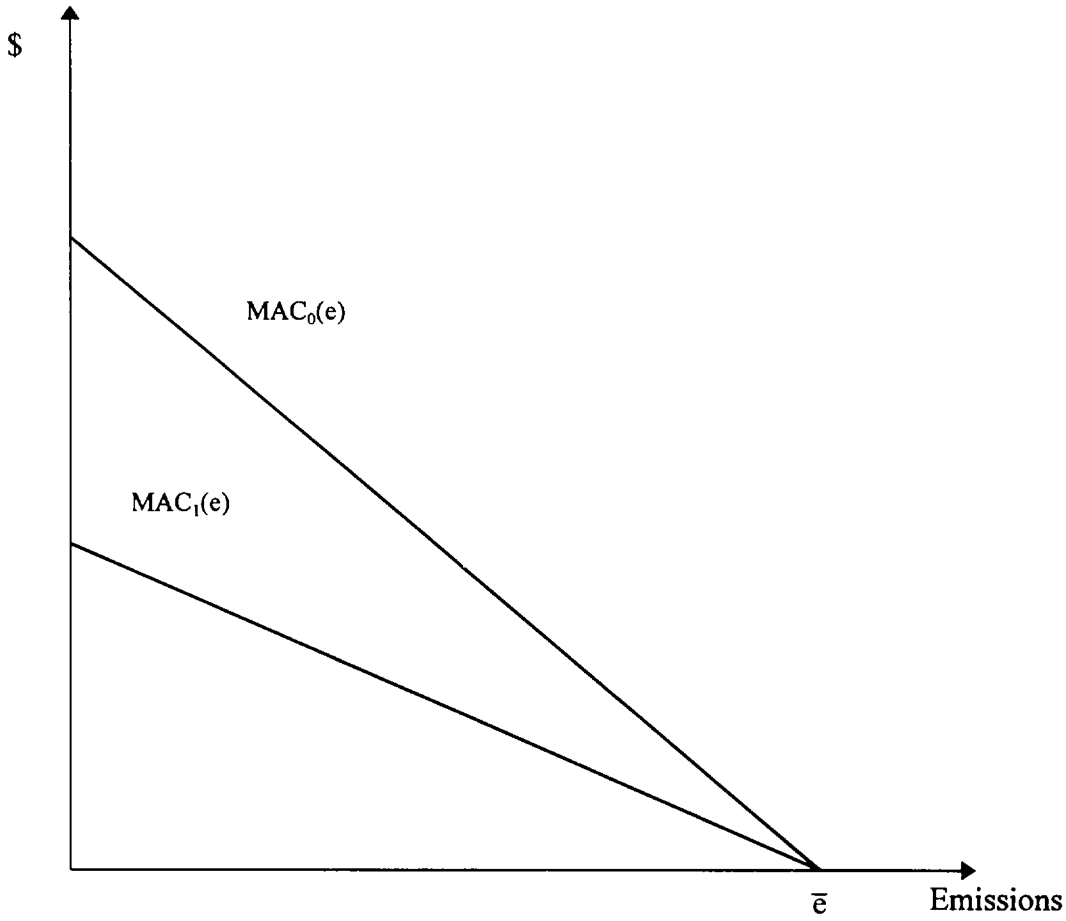


FIGURE 2
Social gain from technology adoption by one firm when N is large

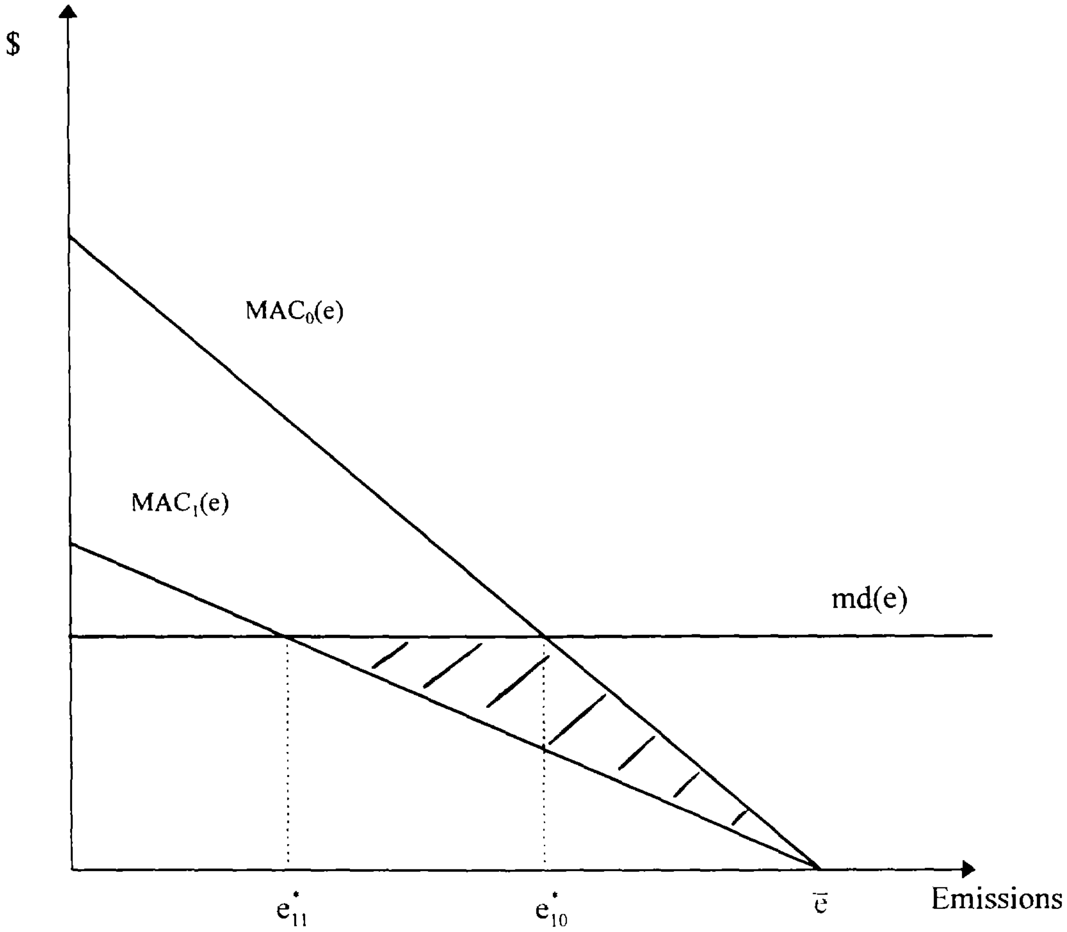


FIGURE 3
Interior equilibrium adoption level

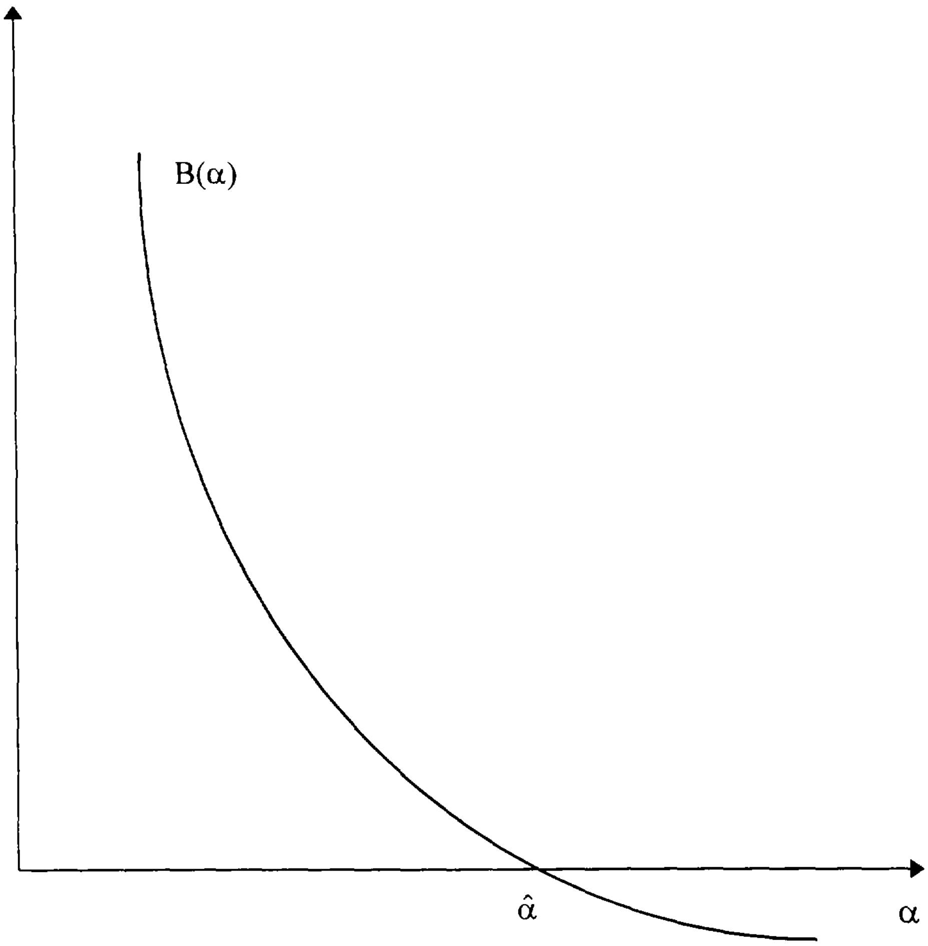


FIGURE 4
Social gain from technology adoption by one firm when N is small

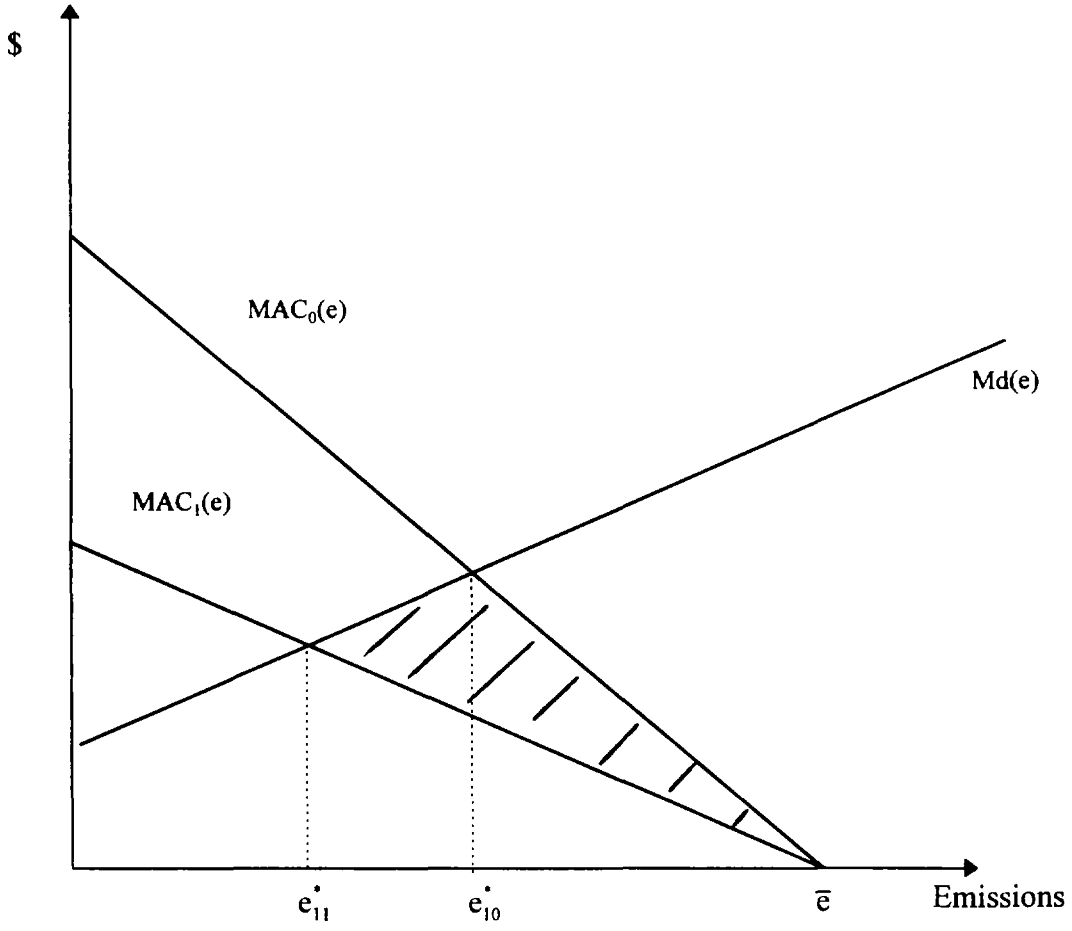


FIGURE 5
Private gain from technology adoption when N is small

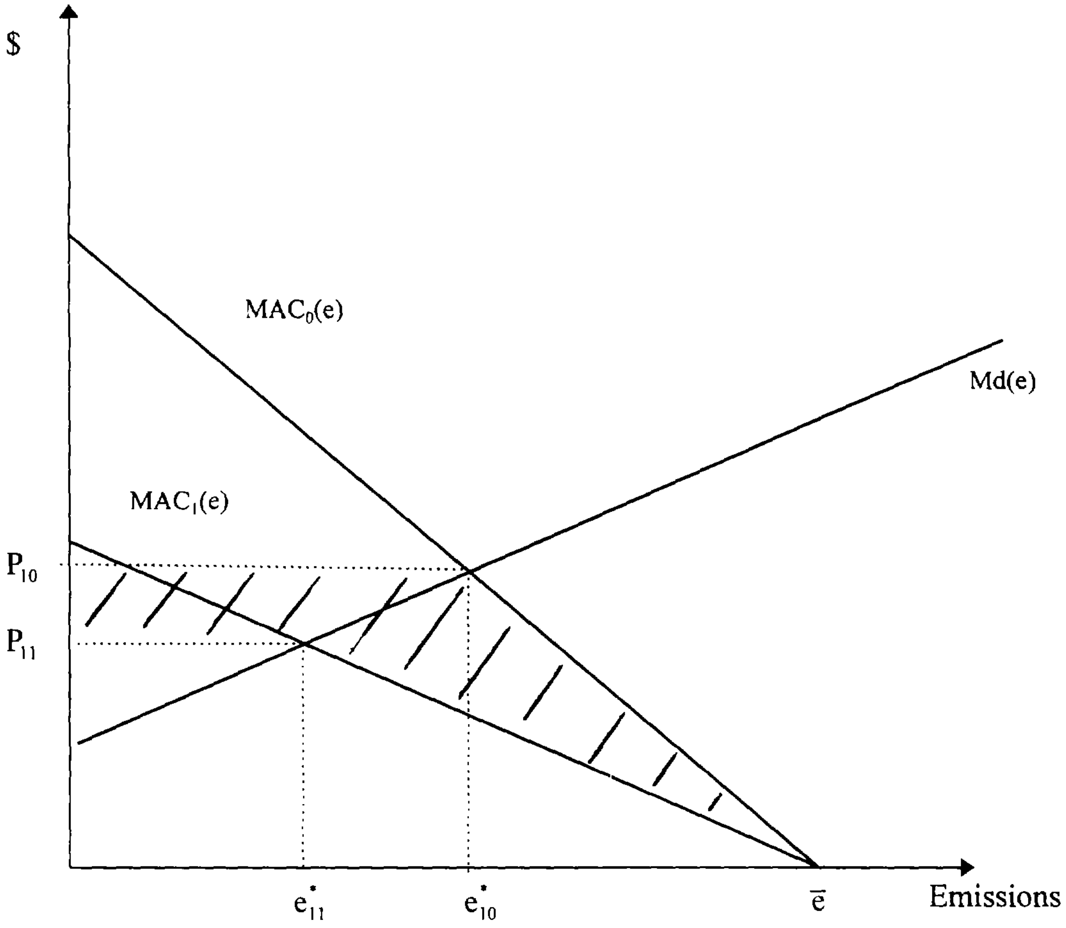


FIGURE 6
Perceived private gain from technology adoption for a large myopic firm

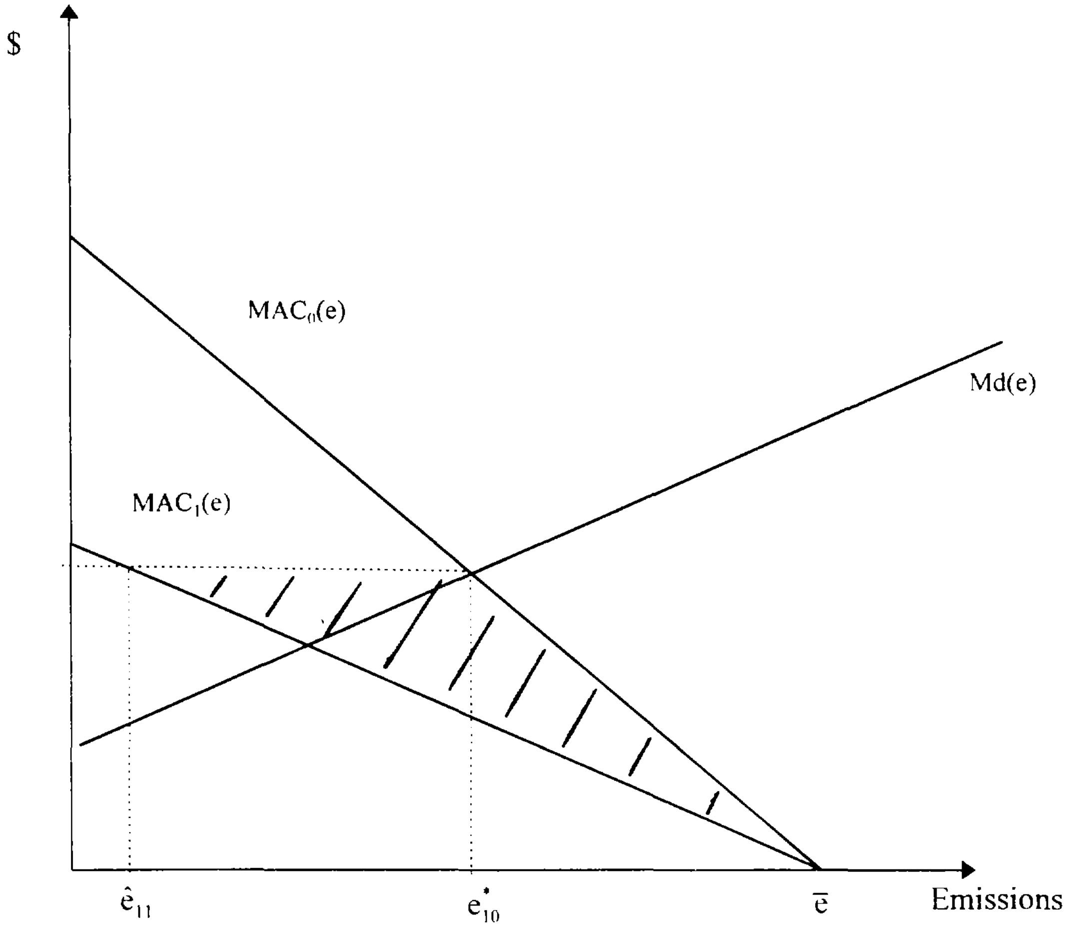


FIGURE 7
Net private gain to technology adoption by one more firm beyond M^*

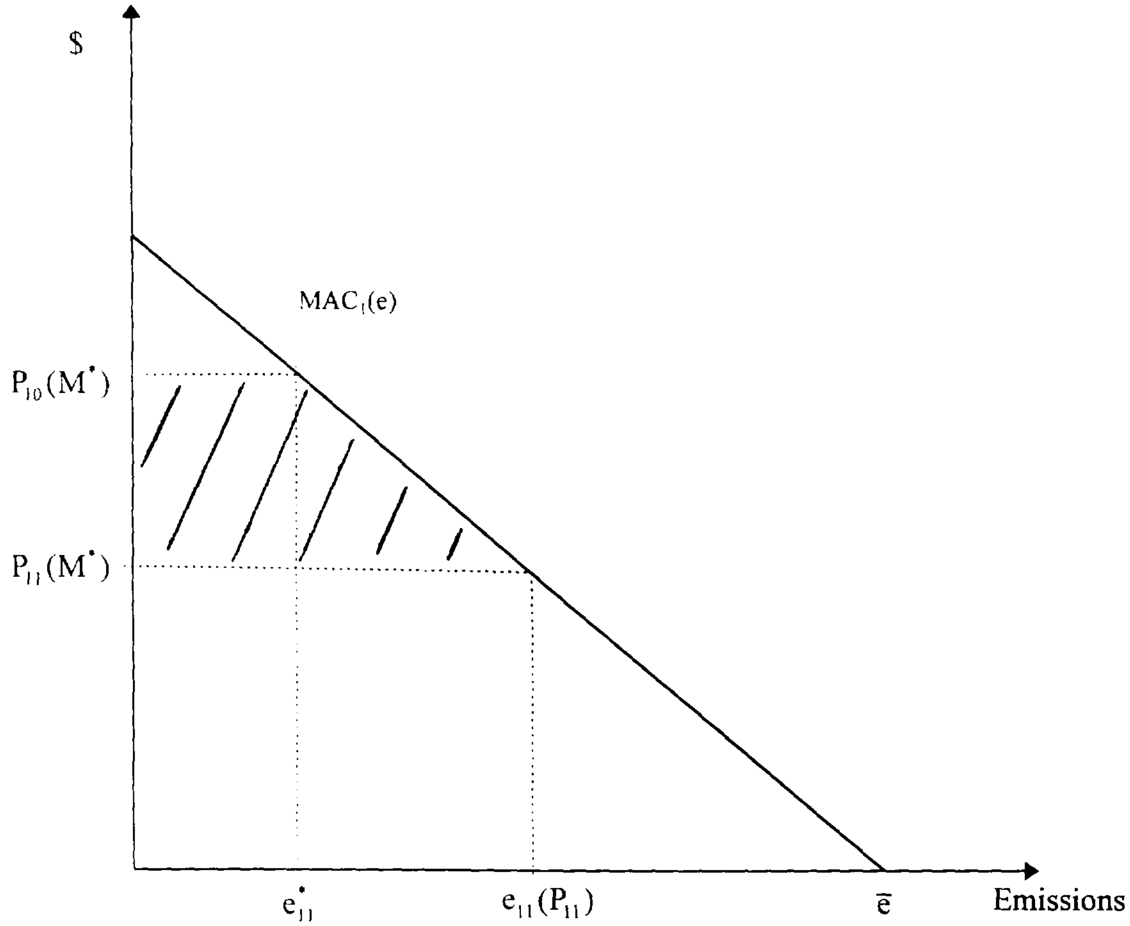
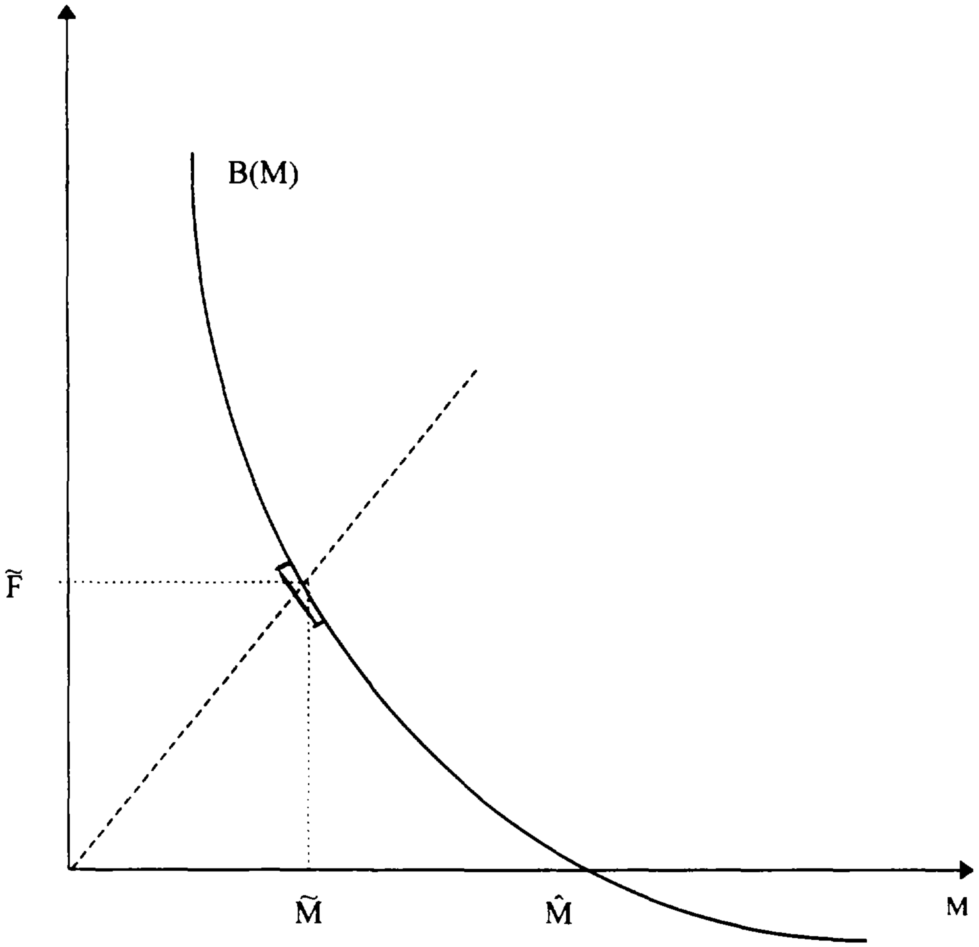


FIGURE 8
Equilibrium adoption of a patented innovation



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