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Environmental Policy Instruments: Technology Adoption Incentives with Imperfect Compliance

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Environmental Policy Instruments: Technology Adoption Incentives with Imperfect Compliance*

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Abstract

In this paper, we study the incentives to adopt advanced abatement technologies in the presence of imperfect compliance. Surprisingly, incentives to adopt advanced abatement technologies remain intact under emission taxes and pollution abatement subsidies when compared to the perfect compliance scenario. However, under emission standards imperfect compliance increases firms' incentives to invest under certain assumptions, whereas under an emission permit mechanism investment incentives decrease only if widespread non-compliance induces a (sufficient) reduction in the permit price. Our results are valid for fairly general characteristics of the monitoring and enforcement strategies commonly found in both, theoretical and empirical applications.

Key words: environmental policy, technology adoption, monitoring, non-compliance.

JEL codes: K42, L51, Q28.

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1 Introduction

The performance of environmental policy instruments under imperfect compliance has been analyzed, among others, in Downing and Watson [1974], Harford [1978], Jones [1989], Malik [1990], Keeler [1991], Stranlund and Dhanda [1999], Montero [2002], Sadmo [2002], Macho-Stadler and Perez-Castrillo [2006], Stranlund [2007], Arguedas [2008] and Rousseau and Proost [2009]. [1] All these studies analyze the static efficiency properties of marketable emission permits, pollution taxes, abatement subsidies and/or pollution standards under different alternatives of the monitoring and sanctioning policies. Generally, they analyze firms' incentives to abate pollution under given policy instruments with the possibility of non-compliance, and/or they determine optimal policies under imperfect compliance. However, none of these studies analyze the dynamic properties of these instruments with imperfect compliance, that is, firms' incentives to adopt new environmental abatement technologies. However, questions about adoption incentives might be particularly relevant in environmental programs with significant non-compliance, such as the emissions trading program for total suspended particles in Santiago, Chile (Montero et al. [2002]) or the EPA's National Pollutant Discharge Elimination System Program of the Clean Water Act (Harrington [2003]).

By contrast, the issue of the adoption incentives under the different environmental policy instruments (i.e., dynamic efficiency), has been deeply studied in the case of perfect compliance. In general, the ranking of optimal policy instruments when promoting the investment in cleaner technologies depends on the structure of the regulation schemes, such as the timing of the game (or behavior of the regulator), the output market (im)perfect competition, the damage function, etc.[2]

This paper links both literature strands by analyzing technology adoption incentives in the presence of imperfect compliance, and compares our novel results with those already obtained under perfect compliance. Our findings show that imperfect compliance does not alter adoption incentives in the case of either taxes or subsidies. However, investment incentives decrease under emission permits only if the market permit price is reduced as a result of significant

[1] See also Macho-Stadler [2008] for a recent overview of this literature.

[2] See, for example, Requate and Unold [2001, 2003] and Requate [2005] for a recent survey of the different ranking analyses established in the literature.

non-compliance, whereas firms' investment incentives increase under pollution standards.

The remainder of the paper is organized as follows. We present the basic model and analyze adoption incentives in the case of emission permits in section 2. In section 33 we consider pollution taxes and abatement subsidies, while in section 4 we study pollution standards. In each of these sections we present well-known theoretical results under perfect compliance and introduce their imperfect compliance counterparts. We conclude in Section 5.

2 Tradable Emission Permits

Consider an industry with n firms (with n large) that emit an homogeneous pollutant. Firms are indexed by i and the pollution discharge of firm $i \in n$ is denoted by $e_i \in [0, e_i^{\max}]$. In the absence of regulation firm i pollutes $e_i^{\max} > 0$. However, firm i can abate pollution by using its installed conventional pollution abatement technology, or by adopting a new advanced abatement technology at a fixed cost I_i.[3] The abatement technology of firm i is characterized by the abatement costs function $c_i^k(e_i)$, where $k = \{0, 1\}$ stands for the conventional and the new (cleaner) technology, respectively. Therefore, the pairwise abatement costs comparison satisfies the usual assumptions $c_i^0(e_i) > c_i^1(e_i) > 0$ and $-c_i^{0\prime}(e_i) > -c_i^{1\prime}(e_i) \geq 0$ for all $e_i \in [0, e_i^{\max})$, while $\lim_{e_i \to 0} c_i^{k\prime}(e_i) = -\infty$, $c_i^{0\prime}(e_i^{\max}) = 0$, and $c_i^{k\prime\prime}(e_i) > 0$ for all $e_i \in [0, e_i^{\max}]$.

We assume that the regulator sets an aggregate emission target $\bar{E}$ and then issues a number $S \leq \bar{E}$ of tradable permits, where $p(S)$ denotes the corresponding competitive permit market price and $s_i \geq 0$ the number of permits hold by firm i. For simplicity, we assume that initially the regulator allocates $\overline{s_i} \geq 0$ permits to firm i, such that $\sum_i s_i = \sum_i \overline{s_i} = S$.[4]

[3]The assumption of an exogenously fixed investment cost in a newer less polluting process is standard in the technology adoption literature, while there is a specific literature that studies the incentives to innovate in cleaner technologies undertaking research and development activities, therefore determining endogenously the cost of the new technologies. This is normally accomplished by considering alternative competitive structures (perfect or imperfect) in the output market (see, for example, Innes and Bial [2002] or Parry [1995, 1998]). Nevertheless, as Requate [2005] has pointed out, this terminological distinction is not always sharp in the literature, since Downing and White [1986] talk about innovation, whereas Milliman and Prince [1989] use the notion of technical change, although the real subject of both studies is the incentive for adopting a (cleaner) existing technology.

[4]The choice of the initial permit allocation mechanism (being them free or auctioned) does not affect our

Within this framework, a compliant firm pollutes no more than its permit holding, that is, $e_i \leq s_i$, whereas a non-compliant firm pollutes more than its permit holding and, therefore, firm's violation amount defines as $v_i = e_i - s_i > 0$.

The regulator observes the number of permits held by each firm and uses a monitoring strategy is characterized by an inspection probability which (weakly) depends on the violation size, $\pi_i(v_i) \in [0,1]$, with the usual properties $\pi_i(0) > 0$, $\pi_i'(v_i) \geq 0$ and $\pi_i''(v_i) \geq 0$. If firm i is inspected and found to be non-compliant, i.e., $v_i > 0$, then it is charged a monetary sanction, $f_i(v_i)$, where $f_i(0) = 0$, $f_i'(v_i) > 0$ and $f_i''(v_i) \geq 0$.[5]

Within this regulatory framework, each firm i decides on (a) the amount of pollution e_i, (b) the permit holding s_i, and (c) whether or not to invest in the advanced abatement technology.[6] Then, a risk-neutral firm i solves the following optimization problem:

$$\min_{c_i^0, c_i^1} \left\{ \begin{array}{c} \min_{e_i, s_i} c_i^0(e_i) + p\left[s_i - \overline{s_i}\right] + \pi_i(v_i) f_i(v_i); \\ \min_{e_i, s_i} c_i^1(e_i) + p\left[s_i - \overline{s_i}\right] + \pi_i(v_i) f_i(v_i) + I_i \end{array} \right\},$$

$$s.t. \quad e_i \geq s_i. \tag{1}$$

Once the corresponding optimal levels $\left(e_i^k, s_i^k, v_i^k\right)$ are obtained for each abatement technology $k = \{0, 1\}$, the firm decides whether to invest in the new technology by evaluation which option results in lower minimum expected costs.[7]

results, as in the perfect compliance case. See proposition 2 in Requate and Unold [2001].

[5]Note that we allow both the inspection probability and the firm to depend on the size of the violation and also to vary across firms. These assumptions are in line with the existing theoretical literature and consistent with the empirical evidence. For example, in a study about the structure of the penalties for water quality violations in Georgia, Olhaca et al. [1998] find that the seriousness of the violation, the historical compliance records and the size of the company strongly influence penalty levels. Among others, Rousseau and Proost [2005] and Shavell [1992] have defended, respectively, that the inspection probability and the fine depend on the degree of non-compliance.

[6]That is, whether to operate with abatement costs $c_i^1(e_i)$ or $c_i^0(e_i)$.

[7]Note that a compliant firm has no incentive to choose an emission level (strictly) lower than its permit holding, i.e. $e_i < s_i$, since in that case the firm faces higher abatement costs with no additional revenue.

2.1 Firm's Compliance Decision

Once the investment decision is made, for a given technology $k = \{0, 1\}$, the firm solves the following problem:

$$\min_{e_i, s_i} \quad c_i^k(e_i) + p[s_i - \overline{s_i}] + \pi_i(v_i) f_i(v_i)$$
$$s.t. \quad v_i \geq 0; \; s_i \geq 0. \tag{2}$$

The lagrangian of problem (2) is the following:

$$L = c_i^k(e_i) + p[s_i - \overline{s_i}] + \pi_i(v_i) f_i(v_i) - \mu v_i - \lambda s_i,$$

where $\mu \geq 0$ and $\lambda \geq 0$ are the respective Kuhn-Tucker multipliers associated with the inequality restrictions in problem (2). The necessary and sufficient conditions for an optimum are:[8]

$$c_i^{k\prime}(e_i) + \pi_i'(v_i) f_i(v_i) + \pi_i(v_i) f_i'(v_i) - \mu = 0; \tag{3}$$

$$p - \pi_i'(v_i) f_i(v_i) - \pi_i(v_i) f_i'(v_i) + \mu - \lambda = 0; \tag{4}$$

$$\mu v_i = 0; \; \mu \geq 0; \; v_i \geq 0; \tag{5}$$

$$\lambda s_i = 0; \; \lambda \geq 0; \; s_i \geq 0. \tag{6}$$

Assuming a positive permit holding (i.e., $s_i^k \geq 0$ and $\lambda = 0$), and adding up conditions (3) and (4), we obtain:

$$c_i^{k\prime}\left(e_i^k\right) + p = 0, \tag{7}$$

that is, for a given permit price, the optimal pollution decision is independent of the monitoring strategy.

Now, combining conditions (4) and (5), we have compliance ($e_i^k = s_i^k$) if and only if $\mu = \pi_i(0) f_i'(0) - p \geq 0$, that is, whenever the marginal penalty of an infinitesimal violation exceeds

[8] This is so because our assumptions ensure that the objective function in (2) is strictly convex and the inequality constraints are linear. Our model assumptions also ensure that the selected pollution level is strictly positive.

the permit price. Otherwise, we have non-compliance ($e_i^k > s_i^k$) with the optimal violation level given by:

$$p = \pi_i' \left(v_i^k\right) f_i \left(v_i^k\right) + \pi_i \left(v_i^k\right) f_i' \left(v_i^k\right), \tag{8}$$

and the cost of buying an additional permit must equal the marginal penalty savings. Interestingly, the amount of the violation for each firm is independent of the choice of technology, that is, $v_i^0 = v_i^1$.

These results are well-known in the literature on emission trading with imperfect compliance.[9] Therefore, under a tradable permit mechanism with perfect competition, firms' positive amounts of permit holdings and plausible assumptions on the monitoring and enforcement strategies, (a) the incentives to pollute do not change under imperfect compliance −unless extended non-compliance induced a reduction in the permit price; and (b) firms' compliance decisions are crucially affected by the monitoring and enforcement strategies applied to them, but they are independent on their specific technological characteristics.

2.2 Firm's Investment Decision

As of yet, the literature has not investigated the technology adoption incentives. We now analyze whether firm i has incentives to invest in the advanced abatement technology $k = 1$. Let:

$$C_i^k = c_i^k \left(e_i^k\right) + p \left[s_i^k - \overline{s_i}\right] + \pi_i \left(v_i^k\right) f_i \left(v_i^k\right), \tag{9}$$

be the minimum expected costs of firm i associated with technology k, where $\left(e_i^k, s_i^k, v_i^k\right)$ are the corresponding optimal pollution, permit holding and degree of violation decisions, respectively. Firm i invests in the new technology if and only if the associated expected cost savings of investing outweigh the investment costs. That is, if and only if:$\Delta C_i = C_i^0 - C_i^1 \geq I_i$.

From (9), we then have

$$\Delta C_i = c_i^0 \left(e_i^0\right) - c_i^1 \left(e_i^1\right) + p \left[s_i^0 - s_i^1\right] + \pi_i \left(v_i^0\right) f_i \left(v_i^0\right) - \pi_i \left(v_i^1\right) f_i \left(v_i^1\right). \tag{10}$$

We consider first the case of perfect compliance, i.e. $\pi_i (0) f_i' (0) \geq p$. Note that this situation induces full compliance regardless of the technology choice, that is, $v_i^0 = v_i^1 = 0$.

[9]See, among others, Malik [1990], Keeler [1991], Stranlund and Dhanda [1999] and Stranlund [2007]. Also, these results have been recently tested experimentally, see Murphy and Stranlund [2006].

Therefore, equation (10) can be rewritten as:

$$\Delta C_i = c_i^0\left(e_i^0\right) - c_i^1\left(e_i^1\right) + p\left[e_i^0 - e_i^1\right], \tag{11}$$

which is the well-known expression for the cost savings found, for example, in Requate and Unold [2001, 2003], or Requate [2005].

Now in case of imperfect compliance, where $\pi_i(0)f_i'(0) < p$, for any individual firm the amount of violation is independent of the technology as shown in equation(8). That is:

$$v_i^0 = v_i^1, \text{ for all } i. \tag{12}$$

Hence, firm i's expected penalties do not depend on the technology choice either, that is:

$$\pi_i\left(v_i^0\right) f_i\left(v_i^0\right) = \pi_i\left(v_i^1\right) f_i\left(v_i^1\right). \tag{13}$$

Therefore, equation (10) trivially reduces to:

$$\Delta C_i = c_i^0\left(e_i^0\right) - c_i^1\left(e_i^1\right) + p\left[s_i^0 - s_i^1\right].$$

Again applying condition (12), we have $s_i^0 - s_i^1 = e_i^0 - e_i^1$, and therefore:

$$\Delta C_i = c_i^0\left(e_i^0\right) - c_i^1\left(e_i^1\right) + p\left[e_i^0 - e_i^1\right], \tag{14}$$

which is exactly equal to the cost savings in equation (11) expression under perfect compliance.

As a result, besides abatement and investments costs, i.e. technological characteristics, the only relevant variable in each firm's investment decision is the market permit price, and not whether the monitoring policy induces compliance or non-compliance. For a given permit price, the expected cost savings associated with the technology adoption only depend on the optimal pollution level, and the latter is independent of the monitoring strategy, as established in equation (7). The investment decision is thus independent of the monitoring strategy. That is, for a given permit price, firms that find it profitable to adopt the advanced abatement technology under perfect compliance will also adopt it under imperfect compliance, and *vice versa*.

Consequently, changes in both, the pollution level and the investment decision can only be due to changes in the permit price, which is determined endogenously. With non-compliance, the demand of permits is lower than the pollution level and given a fixed permit supply S, it fully conditions the market clearing price:

$$\sum_i s_i(p) = S.$$

Since $s_i'(p) < 0$, [10] a sufficient decrease in the demand of permits as compared to the case of perfect compliance will cause a decrease in the permit price enough to result in over-pollution and under-investment, as compared to the full compliance case.

Finally, an appealing implication of our study is the following. Assume two alternative scenarios, one which induces perfect compliance (where $S = \bar{E}$) and another one which induces imperfect compliance ($S < \bar{E}$), such that both lead to the same market permit price. These two alternative scenarios are illustrated in figure 2, where the second scenario corresponds to the particular case of full non-compliance. In the perfect compliance case the market demand for permits is given by the aggregate marginal abatement costs, -$\sum c_i^{k\prime}$, while permits supply is $\bar{E}$, yielding a clearing price of p. In the full non-compliance case permits' demand and supply are respectively given by $\sum \pi_i^{\prime} f_i + \pi_i f_i^{\prime}$ and S, resulting in the same clearing price. We could think of alternative-partial compliance-outcomes with permits' demand and supply laying in between these two extreme cases.

In all these cases our finding is that industry adoption incentives remain the same. Therefore, besides specific firm characteristics, the only relevant variable in the adoption decision is the permit price.

The results on adoption incentives under emission permits can be summarized in the following proposition:

Proposition 1: *Under emission permits, the incentives to adopt a new technology only depend on the firms' technological characteristics and the permit price. If two alternative monitoring policies, one inducing compliance and another one inducing non-compliance, lead to the same market price, adoption incentives remain intact.*

[10]This result is trivially obtained combining equations (7) and (8).

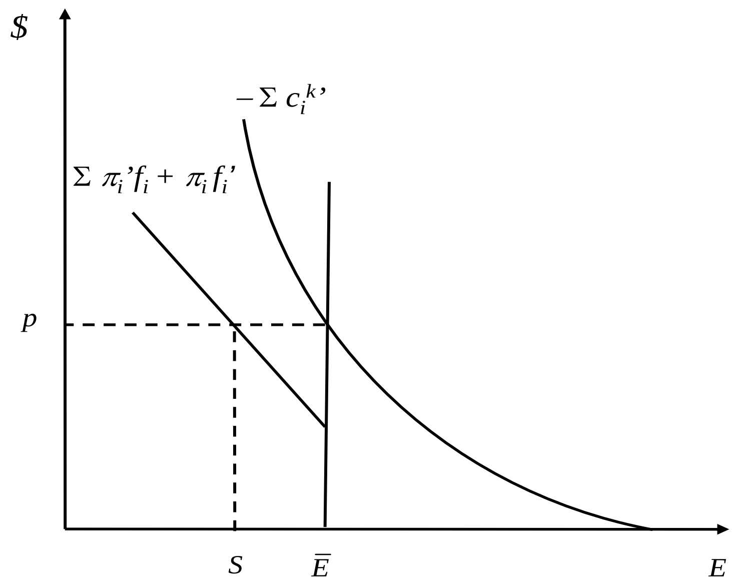

Figure 1: Tradable Permits

3 Pollution Taxes and Abatement Subsidies

After analyzing emission permits, we check how our results change under the alternative systems of pollution taxes and abatement subsidies.

Assume now that the regulator imposes a tax per unit of pollution, $\tau > 0$. In order to introduce the possibility of non-compliance in this context, we assume that the firm reports the pollution level to the regulator and pays taxes according to the reported level. Let r_i be the amount of pollution reported. The firm complies with the regulation if it reports the amount of pollution emitted ($r_i = e_i$), while it does not comply with the regulation if it reports a lower level than emitted, i.e. $r_i < e_i$. Thus, let $v_i = e_i - r_i$ be the amount of the violation. Now, the firm decides on (a) the amount of pollution e_i, (b) the reported level r_i, and (c) whether or not to invest in the advanced abatement technology. The optimization problem is now:

$$\min_{c_i^0, c_i^1} \quad \left\{ \begin{array}{c} \min_{e_i, r_i} c_i^0 (e_i) + \tau r_i + \pi_i (v_i) f_i (v_i) ; \\ \min_{e_i, r_i} c_i^1 (e_i) + \tau r_i + \pi_i (v_i) f_i (v_i) + I_i \end{array} \right\},$$

$$s.t. \qquad e_i \geq r_i.$$

It is straightforward to see that equation (7), (8) and (14) are obtained simply interchanging p by τ.[11] The only difference with the emission permit mechanism is that the pollution tax is exogenously given while the market clearing permit price is endogenously determined. As a result, the presence of imperfect compliance in this case only results in tax evasion (i.e., the possibility of under-reporting and paying less taxes), but it does not alter either the pollution levels or the technology adoption incentives.

The case of a subsidy per unit of abated pollution ($\sigma > 0$), with the possibility of reporting more abatement (or less pollution) than the actual level (i.e., $r_i \leq e_i$) is trivially obtained by simply substituting the tax τr_i by the subsidy $-\sigma\left(e_i^{\max} - r_i\right)$ for in the above objective function, and p by σ in equations (7), (8) and (14). Therefore, all the results concerning pollution levels and adoption incentives with abatement subsidies under imperfect compliance remain the same. The only difference now is that the presence of imperfect compliance results in over-subsidization.

4 Pollution Standards

Finally, we consider how technology adoption incentives change under a system of pollution limits or standards. Let $\overline{e}_i > 0$ be the pollution limit required for firm i. In this context, compliant firms select a pollution level of $e_i \leq \overline{e}_i$, while non-compliant firms exceed the pollution level, i.e. $e_i > \overline{e}_i$. Therefore, the degree of violation is now defined as $v_i = e_i - \overline{e}_i \geq 0$, which is detected only through monitoring.

Then, for a given standard $\overline{e}_i$, the firm decides on (a) the pollution level e_i and (b) whether or not to invest in the advanced abatement technology. The optimization problem is now:

$$\min_{c_i^0, c_i^1} \left\{ \begin{array}{c} \min_{e_i} c_i^0\left(e_i\right) + \pi_i\left(v_i\right) f_i\left(v_i\right); \\ \min_{e_i} c_i^1\left(e_i\right) + \pi_i\left(v_i\right) f_i\left(v_i\right) + I_i \end{array} \right\},$$

$$s.t. \quad e_i \geq \overline{e}_i.$$

Following a similar procedure to that of the previous sections, and for a given technology k, firm i complies with the standard as long as $\pi_i(0) f_i'(0) \geq -c_i^{k\prime}(\overline{e}_i)$, that is, as long as the

[11] This is true as long as $\pi_i(0) f_i'(0) - \tau \geq 0$. Otherwise, we obtain a corner solution $r_i = 0$.

marginal expected penalty of exceeding the first unit is larger than the abatement cost savings. In that case, we have $e_i^k = \overline{e}_i$, and then the firm decides to adopt the new technology if and only if the cost savings of adopting outweigh the investment costs, that is, if and only if:

$$\Delta C_i = c_i^0 \left(\overline{e}_i \right) - c_i^1 \left(\overline{e}_i \right) \geq I_i.$$

However, technology adoption incentives change ambiguously under imperfect compliance, as it could either decrease or increase them. Assume first that firm i is confronted with the same standard $\overline{e}_i$, but now the expected penalty for non-compliance is such that $-c_i^{0\prime}(\overline{e}_i) > \pi_i(0) f_i'(0) \geq -c_i^{1\prime}(\overline{e}_i)$. This means that the firm exceeds the standard under the conventional technology, but it complies with the standard under the new technology. Now, the cost savings of adopting are:

$$\Delta C_i = c_i^0 \left(e_i^0 \right) + \pi_i \left(v_i^0 \right) f_i \left(v_i^0 \right) - c_i^1 \left(\overline{e}_i \right),$$

where $e_i^0 > \overline{e}_i$ is the optimal non-compliance decision under the conventional technology, given by $c_i^{0\prime}(e_i^0) + \pi_i'(v_i^0) f_i(v_i^0) + \pi_i(v_i^0) f_i'(v_i^0) = 0$. Clearly, $c_i^0(e_i^0) + \pi_i(v_i^0) f_i(v_i^0) < c_i^0(\overline{e}_i)$ (since e_i^0 is the optimal decision, while $\overline{e_i}$ belongs to the choice set) and, therefore, adoption incentives decrease with respect to the situation of perfect compliance. As a consequence, given a fixed pollution standard, the induced pollution level increases and the incentive to adopt decreases under imperfect compliance, as compared to the situation of perfect compliance.

However, consider now the possibility of designing an imperfect monitoring policy which induces the same pollution level as that observed under perfect compliance. This can be better explained with the help of figure 2. The pollution standard under this alternative policy is $\overline{\overline{e}}_i < \overline{e}_i$, and the expected fine is such that the induced pollution level under the conventional technology is $e_i^0 = \overline{e}_i$. With perfect compliance, the adoption cost savings area is given by A (note that there are abatement costs only if the firm operates with the conventional technology $k = 0$). With imperfect compliance, the adoption cost savings area is given by $A + B$, where area B represents the fines savings associated with technology adoption. Therefore, adoption incentives are increased as a result of imperfect compliance.

Proposition 2: *Under an emission standard, for a given induced pollution level, imperfect compliance increases adoption incentives when compared to perfect monitoring.*

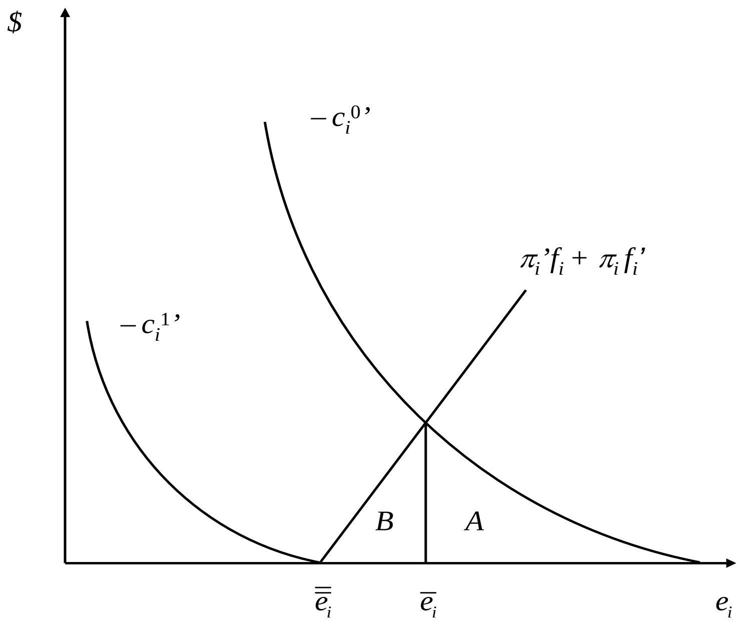

Figure 2: Pollution Standards

5 Conclusions

In this paper, we analyze the firms' incentives to invest in advanced abatement technologies under imperfect compliance comparing this scenario to the case of perfect monitoring. With regard to tradable permits, we show that adoption incentives in emission permit programs do not change, unless extended non-compliance causes a reduction in the permit price. Therefore, changes in adoption incentives are only due to the fact that the permit price is endogenously determined and could decrease as a consequence of a significant reduction in the permit demand. Clearly, under a system of exogenous pollution taxes or abatement subsidies with the possibility of under-reporting, the pollution levels as well as the investment decisions by the firms would not change. Imperfect compliance in these alternative contexts would only cause either tax evasion or over-subsidization. Finally, we do not find an unambiguous response with respect to pollution standards with imperfect compliance, as firm's adoption decision depends on the alternative imperfect monitoring policies that the regulator may implement. If both, the perfect and imperfect compliance policies, consider the same pollution standard, adoption incentives are lower under imperfect compliance. However, if both the perfect and imperfect compliance policies induce the same pollution level under the conventional technology, then adoption incentives with imperfect compliance increase when compared to the perfect monitoring scenario.

Our results contribute to relate two large strands of literature by setting up the framework to bridge the gap between them. The first one studies policy instruments under perfect and imperfect compliance but neglecting technology adoption (static setting) and the second one studies policy adoption incentives in a dynamic setting under alterative policy instruments, but neglecting the monitoring strategy of the regulator. With respect to the former, unresolved issues have to do with the welfare implications of allowing tax evasion (or over-subsidization) in dynamic settings that consider technology adoption. With respect to the latter, while do not intend to provide a ranking of optimal policy instruments, our results under imperfect compliance are quite robust as they would hold regardless of particular specific designs characterizing the structure of the regulation policy, including the timing of the game, the behavior of the regulator, or features of the damage functions.

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