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Targeted Enforcement and Aggregate Emissions
With Uniform Emission Taxes

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Abstract

In practice, targeted monitoring seems to be a strategy frequently used by regulators. In this paper, we study the effects of targeted monitoring strategies on the adoption of a new abatement technology and, consequently, on the aggregate emissions level when firms are regulated with uniform taxes. The results suggest that a regulator aiming to stimulate technology adoption should decrease the adopters' monitoring probability and/or increase the non-adopters' monitoring probability. In contrast to previous literature, we find that, in some cases, a regulator whose objective is to minimize aggregate emissions should exert a stronger monitoring pressure on firms with higher abatement costs.

Key words: technology adoption, environmental policy, imperfect compliance, targeted enforcement.

JEL classification: L51, Q55, K31, K42.

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1. Introduction

Previous theoretical literature on enforcement of environmental regulations has shown that a firm will comply with a regulation when its compliance costs are lower than the expected penalty associated with the violation (Hardford, 1978; Hardford, 1987; Stranlund and Dhanda, 1999; Stranlund and Chávez, 2000; Sandmo, 2002; Friesen, 2003). However, in many circumstances, the frequent monitoring and relatively high fines necessary to deter firms from violating regulations are not available, leading to imperfect enforcement. Imperfect enforcement may be driven by the lack of accurate monitoring technology (Segerson 1988 and Heyes, 1994), reticence to use high penalties (Harrington, 1988) and/or budget constraints (Rousseau, 2007). In fact, one common argument against the use of market-based approaches in developing countries is that these countries lack resources to properly monitor and enforce policies (Coria and Sterner, 2010; Bell, 2002, Blackman and Harrington, 2000). A suitable strategy for the regulator to deal with the budget constraints in the enforcement activity is to target enforcement and define a monitoring schedule to firms according to their past compliance records or to their potential emissions (Rousseau, 2007).

In practice, targeted enforcement is a strategy used by regulators. Gray and Deily (1996) use data on individual U.S. steel plants to test whether differences in firm characteristics and behavior affect enforcement decisions at the plant level. They find that regulators exert more enforcement pressure on plants expected not to be in compliance and firms producing large amounts of pollution irrespective of compliance status. Similarly, Rousseau (2007) empirically tests the targeting policy used by the Flemish Environmental Inspection Agency in Belgium and shows that the agency uses targeting to select the textile firms it will routinely inspect. The agency decides on routine inspections for water based on discharged waste load, the receiving medium of the discharge, the presence of hazardous pollutants, and the available budget and personnel. Given that targeted monitoring seems to be a practice used by regulators, the objective of the present paper is to analyze its effects on adoption of new abatement technology and, consequently, on the aggregate emission level when firms are regulated with uniform taxes.

Little attention has been paid to the relationship between diffusion of new technologies and the compliance behavior of risk-neutral firms. An exception is Villegas and Coria (2009), who focus on market-based regulations enforced through a uniform monitoring probability across firms. They find that in the case of uniform taxes the rate of adoption does not depend on the enforcement parameters. While this result relies on a uniform enforcement strategy, the monitoring probability can depend on firm characteristics as well (Macho-Stadler and Pérez-Castrillo, 2006), implying a targeted enforcement strategy. Previous theoretical literature has studied whether targeted enforcement based on specific firm characteristics, e.g., abatement cost parameters, is a plausible strategy to minimize violations. When firms are regulated by standards on emissions, a greater monitoring effort should be directed at firms with higher abatement costs (Garvie and Keeler, 1994). In contrast, when firms operate under tradable emission permits (TEPs), the distribution of optimal monitoring effort should be independent of differences in firms' abatement costs (Stranlund and Dhanda 1999)[1]. Murphy and Stranlund (2007) confirm these findings in an experimental setting. Consistent with theoretical predictions, they find that pursuing targeted enforcement strategies when firms face fixed emission standards is justified, but not in the case of TEPs.

Macho-Stadler and Pérez Castrillo (2006) show that when firms are regulated by uniform emission taxes, for a regulator who has as its objective to minimize aggregate emissions it is optimal to bias her monitoring strategy against firms that value pollution less, i.e., firms with low abatement costs. Nevertheless, they do not consider the fact that firms can change their type, i.e., that firms can adopt a new and more efficient abatement technology as a response to the monitoring strategy announced by the regulator. In this paper, we allow for such a response from firms, i.e., firms can make adoption decisions as a response to the enforcement strategy. In this setting, we analyze the influence of targeted enforcement policies on aggregate emissions.

[1]With respect to the theoretical approach to study targeted enforcement strategies, Harrington (1988) develops a dynamic repeated-game model of state-dependent enforcement of pollution standards. He shows how a regulatory agency using such an enforcement strategy can create stronger incentives to comply than when using a simple random monitoring strategy with fewer monitoring resources. Subsequent papers evaluate Harrington's results for social optimality (Harford 1991; Harford and Harrington 1991), evaluate the validity of Harrington's results under asymmetric information (Raymond 1999) and derive the optimal targeting scheme in Harrington's framework (Friesen 2003)

Particularly, we analyze how a regulator can use enforcement strategy to influence industry composition in terms of high and low abatement cost firms and the effect of this strategy on aggregate emissions.

The paper models the following interaction between a regulator and a set of firms. A regulator who has as its objective to minimize aggregate emissions sets and announces a uniform tax level per unit of pollutant released that firms should pay. The regulator establishes a self-report requirement that asks the regulated firms to report their emission levels. However, since the regulator cannot determine whether firms try to evade taxes by underreporting emissions, it is necessary to implement costly monitoring. The regulator therefore chooses the probability of monitoring firms based on firms' adoption status of a new available and more efficient abatement technology. The regulator sets and announces adopters' and non-adopters' monitoring probabilities. Based on the tax level and their monitoring probabilities, firms make their adoption decisions. After the adoption decisions have been made, firms decide on their actual and reported emission levels. Finally, the regulator monitors adopters and non-adopters based on the announced monitoring probabilities and imposes sanctions if non-compliance is detected.

The results of the model suggest that under uniform emission taxes, the rate of technology adoption is influenced by adopters' and non-adopters' monitoring probabilities. In contrast to previous literature, we find that, in some cases, a regulator whose objective is to minimize aggregate emissions should exert a stronger monitoring pressure on firms with higher abatement costs. A regulator aiming to stimulate technology adoption under a differentiated monitoring scheme should decrease the monitoring probability of adopters and/or increase that of non-adopters. This is good news for a regulator who wants to achieve a given level of aggregate emissions but has political constraints on the level of the tax to be imposed. Such a regulator may use a differentiated monitoring strategy that exerts a higher monitoring pressure on firms with high abatement costs in order to induce technology adoption and therefore reduces aggregate emissions for a given tax level.

The paper is organized in the logic of backwards induction. In our model, Section 2 presents the firm's optimal decisions on the actual and reported emission levels. Section 3 presents the model of adoption of the new abatement technology and analyzes the impact of monitoring strategy on rate of technology adoption. Section 4 studies the effects of a targeted monitoring strategy on aggregate emissions. Section 5 presents the problem of a regulator who chooses her monitoring strategy to minimize aggregate emissions. Finally, Section 6 concludes the paper.

2. The problem of the firm

Consider the following interaction between a regulator and a set of firms regulated by a uniform tax on emissions.

Stage 1. Consider a competitive industry consisting of a continuum of firms $\Lambda \subset [0,1]$ that are risk-neutral and initially homogeneous in abatement costs.[2] In the absence of environmental regulation, each firm emits a quantity e^0 of a homogeneous pollutant. The environmental authority sets the aggregate emissions target $\overline{E}$ before the arrival of the new technology and chooses a tax level t that firms are supposed to pay per unit of pollutant emitted. Since regulators very often face political constraints with respect to tax level, in this model the tax level chosen by the regulator does not necessarily coincide with the tax level that would be required to achieve the aggregate emissions target. Firms decide on their emission level e and are required to self-report their emissions. The quantity that is self-reported by the firm is denoted *r*. A firm could try to evade a fraction of its tax responsibilities by reporting a lower level of emissions, incurring in a violation given by $v = e - r$.

The regulator is unable to observe firms' emissions without implementing costly monitoring. In this model, the regulator has a fixed monitoring budget given by B, which is beyond its control, and the cost of an audit is given by ϖ. Let π_A denote the probability that the regulator audits an adopter and π_{NA} the probability of monitoring a non-adopter firm. We assume that these probabilities are common knowledge among firms before they make their adoption decisions. Once the regulator monitors a firm, it is able to perfectly determine the firm's compliance status. If the monitoring reveals that the firm is non-compliant, it faces a penalty

[2] This setting is close to that in Villegas and Coria (2009)

given by $\phi(v)$, where v is the level of the violation. This is a strictly convex function in the level of violation with $\phi'(v) > 0; \phi''(v) > 0$. For zero violation, the penalty is zero $\phi(0) = 0$, but the marginal penalty is greater than zero $\phi'(0) = 0$. We assume that the regulator commits to its policy announcement and does not modify the level of the environmental policy in response to the availability of the new technology.

Stage 2. Firms respond to policy parameters by making two kinds of decisions: They decide on extent of underreporting, which constitutes a continuous choice, and they make a dichotomous choice on whether to adopt the new abatement technology. We assume that adoption decisions made by firms are observable by the regulator. Let the abatement cost function of an individual firm be denoted $c(e)$, which is strictly convex and decreasing in emissions. A new and more efficient technology arrives and firms must decide, *after being informed about the vector of monitoring probabilities* (π_A, π_{NA}), whether or not to invest in the technology, and on actual and reported emission levels. The new technology allows firms to abate emissions at a lower cost $\theta c(e)$, where $\theta \in (0,1)$ is a parameter that represents the drop in abatement cost by adopting the new technology. After making the adoption decision, firms decide on actual and reported emission levels.

Firms decide on their emission and report levels in order to minimize their total expected costs subject to the fact that there are no economic incentives to over-report emissions since it implies a higher tax payment. We assume that each firm chooses non-negative emissions and report levels. Equation (1) displays the problem of the firms. For non-adopters, $\theta = 1$

(1) $$\begin{aligned} &Min_{e,r} \theta c(e) + tr + \pi\phi(e - r) \\ &s.t.\ e - r \geq 0 \end{aligned}$$.

The Lagrange equation for (1) is $\varphi = \theta c(e) + tr + \pi\phi(e-r) + \eta[e-r]$ and the Kuhn-Tucker conditions are[3]:

(2) $$\frac{\partial\varphi}{\partial e} = \theta c'(e) + \pi\phi'(e-r) - \eta = 0,$$

(3) $$\frac{\partial\varphi}{\partial r} = t - \pi\phi'(e-r) + \eta = 0,$$

(4) $$\frac{\partial\varphi}{\partial\eta} = r - e \geq 0; \eta \geq 0; \eta[r-e] = 0.$$

If the report is interior, i.e., $0 < r < e$, from equations (2) and (3) the firm selects an emission level that satisfies the following condition: $\theta c'(e) + t = 0$. This level coincides with the one the firm would select under perfect monitoring $e^{\min *}$, which corresponds to the minimum emission level that the regulator can achieve with its enforcement policy. From equation (4), if $r - e > 0$, it follows that $\eta = 0$; and from equation (3), the report level selected by the firm is given by $t = \pi\phi'(e^{\min *} - r)$. From the properties of the penalty function, we know that $\pi\phi'(0) < \pi\phi'(e-r) < \pi\phi'(e)$. This can be written as $\pi\phi'(0) < t < \pi\phi'(e)$.

If $\pi\phi'(e) \leq t$, the firm does not report any of its emissions $r = 0$ and selects an emission level such that $\theta c'(e^*) + \pi\phi'(e^*) = 0$. This implies $-\theta c'(e^*) \leq t$ and therefore $e^* > e^{\min *}$. If $\pi \geq \frac{t}{\phi'(0)}$, the firm will make a truthful report of its emissions. Therefore, the solution is interior if and only if $\pi\phi'(0) < t < \pi\phi'(e^{\min *})$. If $\pi = 0$, the firm reports zero emissions which from

[3] The first-order conditions are both necessary and sufficient since the second-order conditions are fulfilled: $\frac{\partial^2\varphi}{\partial e^2} = \theta c''(e) + \pi\phi''(e-r) > 0; \frac{\partial^2\varphi}{\partial r^2} = \pi\phi''(e-r) > 0$; $\frac{\partial^2\varphi}{\partial e^2}\frac{\partial^2\varphi}{\partial r^2} - \frac{\partial^2\varphi}{\partial e\partial r} = \theta c''(e)\pi\phi''(e-r) > 0$.

equation (4) implies $\eta = 0$. From equation (2), the firm will select an emission level such that $\theta c'(e) = 0$, which coincides with the initial emission level e^0.

Following Macho-Stadler and Pérez-Castrillo (2006), previous results about the optimal behavior of adopters and non-adopters of the new technology, summarized in Result 1, can be represented as in Figure 1:

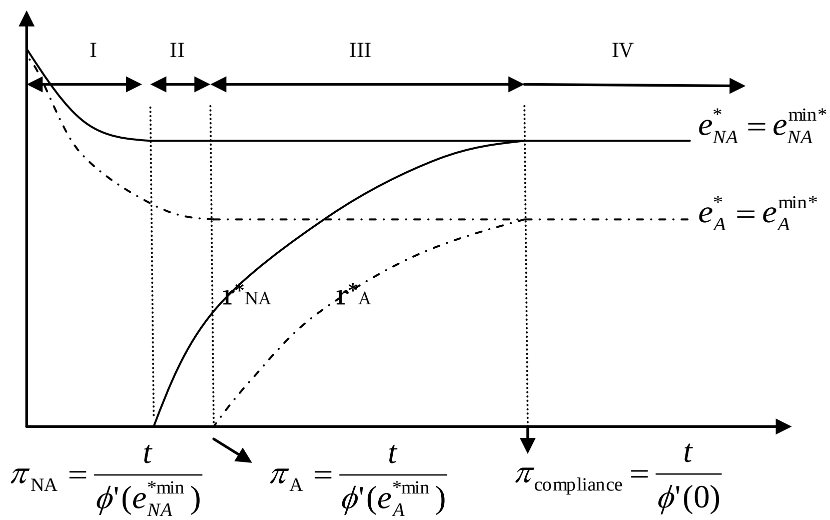

Figure 1. Optimal behavior of adopters and non-adopters under uniform taxes.

We can divide Figure 1 into four regions as follows: In Region I, defined by the interval $\left(0, \frac{t}{\phi'(e^{\min *}_{NA})}\right)$, both adopters and non-adopters report zero emissions, and their actual emission levels are decreasing in monitoring probabilities. In Region II, corresponding to the interval $\left[\frac{t}{\phi'(e^{\min *}_{NA})}, \frac{t}{\phi'(e^{\min *}_{A})}\right)$, non-adopters make a positive report of their emissions while adopters continue reporting zero emissions. In Region III, defined by interval $\left[\frac{t}{\phi'(e^{\min *}_{A})}, \frac{t}{\phi'(0)}\right)$, both adopters and non-adopters make a positive report of their emissions but still under-report a fraction of them. Finally, in Region IV, i.e., $\left[\frac{t}{\phi'(0)},1\right]$, firms make a truthful report of their emissions. In order to allow for perfect compliance to be a positive outcome, we assume that $\frac{t}{\phi'(0)} \leq 1$.

Result 1. *For a given tax rate, monitoring probabilities* π_A *and* π_{NA}, *and penalty function* $\phi(v)$, *the optimal actual and reported emission levels* (e^*, r^*) *of adopters and non-adopters of the new technology are:*

(a) If $\pi_A = \pi_{NA} = 0$, *then* $e_A^* = e_{NA}^* = e^0$ *and* $r_A^* = r_{NA}^* = 0$, *where sub-indexes A and NA represent adopters and non-adopters of the new abatement technology respectively.*

(b) If π_{NA} *is in Region I, then* $e_{NA}^* \in (e_{NA}^{\min *}, e^0)$ *with* e_{NA}^* *defined by* $C'(e_{NA}^*) + \pi_{NA}\phi'(e_{NA}^*) = 0$ *and* $r_{NA}^* = 0$.

If π_A *is in either Region I or II, then* $e_A^* \in (e_A^{\min *}, e^0)$ *with* e_A^* *defined by* $\theta C'(e_A^*) + \pi_A \phi'(e_A^*) = 0$ *and* $r_A^* = 0$.

(c) If π_{NA} *is in either Region II or III, then* $e_{NA}^* = e_{NA}^{\min *}$ *with* e_{NA}^* *defined by* $C'(e_{NA}^*) + t = 0$ *and*

r_{NA}^* *defined by* $\pi_{NA}\phi'(e_{NA}^* - r_{NA}^*) = t$.

If π_A *is in Region III, then* $e_A^* = e_A^{\min *}$ *with* e_A^* *defined by* $\theta C'(e_A^*) + t = 0$.

(d) If π_{NA} *is in Region IV, then* $e_{NA}^* = r_{NA}^*$ *is defined by* $C'(e_{NA}^*) + \pi_{NA}\phi'(0) = 0$.

If π_A *is in Region IV, then* $e_A^* = r_A^*$ *is defined by* $\theta C'(e_A^*) + \pi_A \phi'(0) = 0$.

Let us first analyze the results for the interval where both adopters and non-adopters make a positive report of their emissions, i.e., $\pi_A \wedge \pi_{NA} \in \left[\frac{t}{\phi'(e_A^{\min *})}, \frac{t}{\phi'(0)} \right)$, which corresponds to Region III in Figure 1. In this interval, each firm chooses its emissions such that the marginal abatement cost equals the tax rate $c'(e_{NA}) = \theta c'(e_A) = t$, implying that the firms' marginal abatement costs are equal irrespective of adoption status. Given that $\theta \in (0,1)$, $c'(e_{NA}) = \theta c'(e_A)$ implies that $e_A^{\min *} < e_{NA}^{\min *}$. The fact that $e_A^{\min *} < e_{NA}^{\min *}$ together with the properties of the penalty function implies that the monitoring probability required for the firms to start making a positive report of their emissions is higher for adopters than for non-adopters, i.e., $\frac{t}{\phi'(e_{NA}^{\min *})} < \frac{t}{\phi'(e_A^{\min *})}$. This means that adopters of the new technology can afford a higher monitoring probability before they start making a positive report of their emissions.

Note that, as Harford (1978) first stated, if the monitoring probability is high enough to guarantee positive reported emission levels, the actual emissions levels do not depend on the parameters of the enforcement problem. Additionally, in Region III, the expected marginal cost of violation is equalized among firms, i.e., $\pi_A \phi'(e_A - r_A) = \pi_{NA} \phi'(e_{NA} - r_{NA})$. In this context, if the regulator sets a targeted enforcement strategy such that firms that potentially pollute more are audited with a higher probability, i.e., $\pi_A < \pi_{NA}$, it follows that $v_A > v_{NA}$.[4] Hence, if the monitoring probabilities are high enough to guarantee positive reports of emissions of both adopters and non-adopters, but not sufficient to guarantee perfect compliance, the violation size of an adopter firm is higher than that of a non-adopter. The intuition is as follows. The marginal benefit from violations is represented by the tax rate and is the same for adopters and non-

[4] This is consistent with the empirical evidence that when targeted monitoring is used, regulators bias monitoring efforts against firms with higher potential emissions. In a set of firms that differ only in abatement costs, firms with high abatement costs have a higher level of potential emissions. Therefore, a regulator can define its targeting monitoring strategy based on technology adoption status. Section 5 presents a formal analysis of the convenience of this kind of targeted monitoring strategy from the regulator point of view.

adopters. The marginal cost of violating the regulation is given by the marginal expected sanction. Given that the tax rate is independent of adoption status, the marginal expected benefit is equal for adopters and non-adopters and so is the marginal expected cost of violation. Since the monitoring probability of adopters is lower than that of non-adopters, adopters can afford a higher fine for violation. A higher fine implies that the violation of adopters' is higher than the violation of non-adopters'. In contrast, when $\pi_A \wedge \pi_{NA} \geq \frac{t}{\phi'(0)}$, i.e., Region IV in Figure 1, the extent of violation of adopters and non-adopters equals zero since both types of firms truthfully report their emissions.

If the monitoring probabilities of both adopters and non-adopters are in Region I in Figure 1, i.e., $\pi_A \wedge \pi_{NA} \in \left(0, \frac{t}{\phi'(e_{NA}^{\min *})}\right)$, both types of firms report zero emissions and therefore their extent of violation coincides with their level of emissions. In this interval, the level of emissions is determined such that the marginal cost of abatement, which also represents the marginal benefit from violation, equals the marginal expected marginal fine. In contrast to the other intervals, in this interval the marginal benefit from violation is not necessarily equal between adopters and non-adopters, and the extent of violation before adoption can therefore be higher than, lower than, or equal to the extent of violation after adoption. It depends on the difference between the monitoring probabilities π_A and π_{NA} as well as on the size of the parameter θ. Result 2 follows from the previous analysis:

Result 2. *For a given tax rate, a pair of adopters' and non-adopters' monitoring probabilities and a penalty function $\phi(v)$, the extent of violation v^* of adopters and non-adopters of the new technology is:*

(a) If $\pi_A = \pi_{NA} = 0$, then $v_A^* = v_{NA}^* = e^0$ where sub-indexes A and NA represent adopters and non-adopters of the new abatement technology respectively.

(b) If π_A is in Region I, then $v_A^* = e_A^*$.

If π_{NA} *is in Region I, then* $v_{NA}^{*} = e_{NA}^{*}$.

(c) If π_{A} *is in Region II, then* $v_{A}^{*} = e_{A}^{*}$ *and is defined by* $\theta c'(e_{A}^{*}) + \pi_{A}\phi'(e_{A}^{*}) = 0$.

If π_{NA} *is in Region II, then* v_{NA}^{*} *is defined by* $\pi_{NA}\phi'(e_{NA}^{\min *} - r_{NA}^{*}) = t$.

(d) If π_{A} *is in Region III, then* v_{A}^{*} *is defined by* $\pi_{A}\phi'(e_{A}^{\min *} - r_{A}^{*}) = t$.

If π_{NA} *is in Region III, then* v_{NA}^{*} *is defined by* $\pi_{NA}\phi'(e_{NA}^{\min *} - r_{NA}^{*}) = t$.

(e) If π_{A} *is in Region IV, then* $v_{A}^{*} = 0$.

If π_{NA} *is in Region IV, then* $v_{NA}^{*} = 0$.

3. The model of adoption

We assume that buying and installing the new technology implies a fixed cost that differs among firms.[5] Let k_i denote the fixed cost of adoption for firm i, and assume that it is uniformly distributed on the interval $(\underline{k}, \overline{k})$.

Let μ_{NAi} and μ_{Ai} be firm i's total expected costs of abatement and compliance when using the current abatement technology (non-adoption) and new technology (adoption). Total abatement costs of abatement and compliance are composed of the abatement costs, the tax liabilities given the self-reported level of emissions, and the expected fines in case the firm is caught under-reporting emissions. The savings in total expected cost of abatement and compliance generated with adoption is given by $\mu_{NAi} - \mu_{Ai}$. Any firm whose savings in total

[5] The assumption that adoption costs differ among firms is not new in the literature analyzing the effects of choice of policy instruments on rate of adoption of new technologies. See for example Requate and Unold (2001). On the other hand, Stoneman and Ireland (1983) point out that although most theoretical and empirical literature on technological adoption focuses on the demand side alone, supply-side forces might be very important explaining patterns of adoption in practice. Thus, for example, costs of acquiring new technology might vary among firms due to firm characteristics, e.g., location and output, or because of competition among suppliers of capital goods.

expected costs offsets its adoption cost will adopt the new technology[6]. In the continuum of firms $\Lambda \subset [0,1]$, the marginal adopter is then identified by the arbitrage condition $\tilde{k}_i = \mu_{NAi} - \mu_{Ai}$. Hence, the rate of firms λ ∈ [0,1] adopting the new technology is defined by the integral $\lambda = \int_{\underline{k}}^{\tilde{k}} f(k_i)dk = F(\tilde{k}_i)$. From the definition of the uniform cumulative distribution of $k_i \sim U(\underline{k}, \bar{k})$ it follows that $F(\tilde{k}_i) = \frac{\mu_{NAi}^x - \mu_{Ai}^x - \underline{k}}{\bar{k} - \underline{k}}$, and the rate of technology adoption can be defined as shown in equation (5) :[7]

(5) $$\lambda = \psi(\mu_{NAi} - \mu_{Ai}) - \zeta \in [0,1], \text{ where } \psi = \frac{1}{\bar{k} - \underline{k}} \text{ and } \zeta = \psi \underline{k}.$$

The technology adoption rate is therefore a function of the shift in abatement costs θ, the tax level t, the enforcement policy reflected in the sanctions structure ϕ, and the monitoring probabilities π_A and π_{NA}: $\lambda(\theta, t, \pi_A, \pi_{NA}, \phi)$. It is sufficient to keep track of the marginal adopter's optimal choices of emissions and reporting in order to derive the rate of adoption; therefore, the subscript *i* is omitted hereafter. [8]

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[6] We assume that firms minimize their costs for any level of output, but do not treat the output decision explicitly.

[7] This follows Coria's (2009) approach when analyzing the impacts of the interaction of multiple policy instruments on technology adoption rate.

[8] We assume that firms are initially homogeneous in terms of abatement costs. Nevertheless, the results still hold in the case of heterogeneous abatement costs. For example, following Coria 2009b, we could have assumed that firms' current abatement costs are heterogeneous and that firms can be ordered according to their adoption savings from the firm with the highest to the firm with the lowest current abatement cost. Therefore, the arbitrage condition that states that for the marginal adopter the adoption savings offsets the adoption costs still holds. In such a setting, and as is shown later, adopters will increase their abatement effort due to the availability of the new technology and will reduce their demands for emissions.

To account for effects of targeted enforcement on the rate of technology adoption, we calculate the expected costs of abatement and compliance for the marginal adopter before adoption μ_{NA} and after adoption μ_A and replace them in equation (6) to get:

$$\text{(6)} \qquad \lambda = \psi\{[c(e_{NA}) - \theta c(e_A)] + t[r_{NA} - r_A] + [\pi_{NA}\phi(e_{NA} - r_{NA}) - \pi_A\phi(e_A - r_A)]\} - \zeta \quad .$$

The first term in brackets in (6) gives account of the savings on the abatement costs from adopting the new technology. The second term in brackets accounts for the difference in payment on reported emissions. The last term in brackets represents the difference in expected fines between non-adoption and adoption status. Note that in the presence of targeted monitoring policy, the rate of technology adoption under uniform taxes is a function of the monitoring probabilities of adopters and non-adopters. This is in contrast to the case of uniform monitoring probability where under uniform taxes the rate of technology adoption is not affected by enforcement policy (Villegas and Coria, 2009).

Take partial derivatives of equation (6) with respect to π_A and π_{NA} to get (see appendix A for derivation):

$$\text{(7)} \qquad \begin{aligned} \frac{\partial \lambda}{\partial \pi_{NA}} &= \psi\phi(e_{NA} - r_{NA}) \geq 0 \\ \frac{\partial \lambda}{\partial \pi_A} &= -\psi\phi(e_A - r_A) \leq 0 \end{aligned} \quad .$$

When firms perfectly comply with the regulation, i.e., monitoring probabilities are in Region IV in Figure 1, the size of the fine $\phi(0)$ equals zero and, therefore, the rate of technology adoption is not affected by changes in monitoring probabilities. The rate of technology adoption increases in non-adopters' monitoring probability when this probability is in Regions I, II, or III.

Analogously, the rate of technology adoption decreases in adopters' monitoring probability when this probability is in Regions I, II, or III.[9]

Result 3. Under uniform taxes and targeted enforcement, the adoption rate is increasing in non-adopters' monitoring if and only if $\pi_{NA} \in \left[0, \frac{t}{\phi'(0)}\right)$. Analogously, the adoption rate is decreasing in adopters' monitoring probability if and only if $\pi_A \in \left[0, \frac{t}{\phi'(0)}\right)$.

4. Targeted enforcement and aggregate emissions

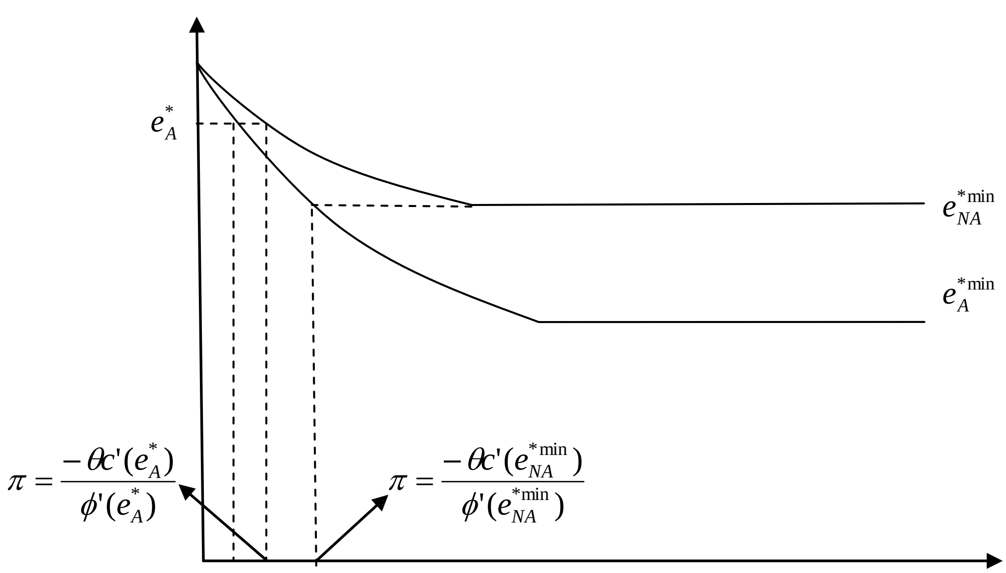
Let us now study the influence of monitoring probabilities on aggregate emissions. The aggregate emissions level E is the weighted average between emissions of adopters and non-adopters, i.e., $E = \lambda(\pi_A, \pi_{NA}, t, \phi)e_A + [1 - \lambda(\pi_A, \pi_{NA}, t, \phi)]e_{NA}$. Taking the partial derivative of aggregated emissions with respect to π_A, i.e., $\frac{\partial E}{\partial \pi_A}$, yields :

(8) $$\frac{\partial E}{\partial \pi_A} = \underbrace{\lambda \frac{\partial e_A}{\partial \pi_A}}_{\text{Direct effect}} + \underbrace{\frac{\partial \lambda}{\partial \pi_A}\left[e_A^* - e_{NA}^*\right]}_{\substack{\text{Indirect effect through} \\ \text{technologyadoptrionrate}}}$$

The change in aggregate emissions from a change in adopters' monitoring probability is given by two effects, a direct effect and an indirect effect through technology adoption rate. When adopters' monitoring probability is in Region IV in Figure 1, both the direct and the indirect effect are equal to zero and, thus, aggregate emissions do not change with adopters' monitoring probability. When adopters' monitoring probability is in Region III in Figure 1, the

[9] Note that the conditions in (7) only hold for rate of technology adoptions such that $\lambda \in (0,1)$. When monitoring probabilities are such that all the firms already adopted the new technology, an increase in non-adopters' monitoring probability does not change the rate of technology adoption. Analogously, if the rate of technology adoption is zero, even if adopters' monitoring probability is increased, it is not possible that the rate of technology adoption goes down.

direct effect $\lambda \frac{\partial e_A}{\partial \pi_A}$ equals zero and the indirect effect through technology adoption is increasing in π_A. Therefore, if the monitoring pressure is high enough for adopters to make a positive report of their emissions, exerting a higher monitoring pressure on adopters will decrease the rate of technology adoption, leading to a higher level of aggregate emissions. When adopters' monitoring probability is in Region II, their emissions decrease with monitoring probability and, therefore, the direct effect is decreasing in π_A. In Region II, a higher monitoring pressure on adopters reduces the rate of technology adoption, which increases aggregate emissions; therefore, the indirect effect through adoption rate is increasing in π_A. In this region, aggregate emissions are decreasing in adopters' monitoring probability if and only if the direct effect offsets the indirect effect. If adopters' monitoring probability is in Region I, adopters' emissions decrease with monitoring probability. The indirect effect through the adoption rate $\frac{\partial \lambda}{\partial \pi_A}\left[e_A^* - e_{NA}^*\right]$ is decreasing in π_A if and only if $\left[e_A^* - e_{NA}^*\right]$>0. If we zoom in on Region I, as in Figure 2 and use result 1 (b), we can derive the necessary conditions for $\left[e_A^* - e_{NA}^*\right]$ to be positive. The two necessary conditions are $\pi_A < \frac{-\theta c'(e_{NA}^{\min *})}{\phi'(e_{NA}^{\min *})}$ and, for a given π_A^* that satisfies such a condition, the probability of non-adopters should satisfy $\pi_{NA}^* > \frac{-\theta c'(e_A^*)}{\phi'(e_A^*)}$.



π_A^*

Figure 2. Necessary conditions for adopters' emissions to be higher than non-adopters' emissions in Region I.

Analogously, the effect of non-adopters' monitoring probability on aggregated emissions is given by two effects as shown in equation (9).

$$\textbf{(9)} \qquad \frac{\partial E}{\partial \pi_{NA}} = \underbrace{[1-\lambda]\frac{\partial e_A}{\partial \pi_{NA}}}_{\text{Direct effect}} + \underbrace{\frac{\partial \lambda}{\partial \pi_{NA}}}_{\substack{\text{Indirect effect through} \\ \text{technologyadoptrionrate}}} \left[e_A^* - e_{NA}^*\right]$$

If non-adopters' monitoring probability is in Region IV in Figure 1, aggregate emissions do not change in non-adopters' monitoring probability, since in this region both the direct effect and the indirect effect equal zero. If non-adopters' monitoring probability is in Region II or III, the direct effect equals zero. In these regions, increasing non-adopters' monitoring probability leads to a higher adoption rate and, hence, lower aggregate emissions, i.e., the indirect effect through the adoption rate $\frac{\partial \lambda}{\partial \pi_{NA}}\left[e_A^* - e_{NA}^*\right]$ is decreasing in π_{NA}. When non-adopters' monitoring probability is in Region I, the direct effect is decreasing in π_{NA} and the indirect effect is decreasing as long as $\left[e_A^* - e_{NA}^*\right]$ is negative. Analogous to the previous case, if we zoom in on Region I, as in Figure 3, and use result 1(b), we can derive the necessary condition for $\left[e_A^* - e_{NA}^*\right]$ to be negative. For a given non-adopters' monitoring probability, $\left[e_A^* - e_{NA}^*\right] < 0$ if $\pi_A^* > \frac{-\theta c'(e_{NA}^*)}{\phi'(e_{NA}^*)}$.

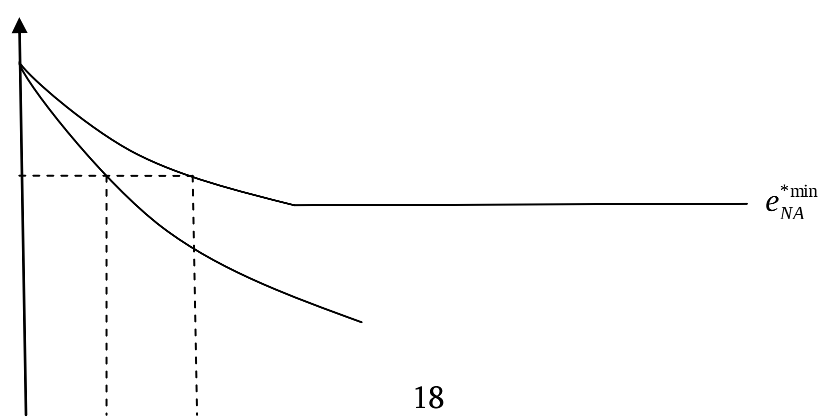


Figure 3. Necessary conditions for adopters' emissions to be lower than non-adopters' emissions in Region I.

The analysis is summarized in Result 4 as follows:

Result 4. *Under uniform taxes, aggregate emission level changes with adopters' and non-adopters' monitoring probability as follows:*

(a) If π_A is in Region I:

$\frac{\partial E}{\partial \pi_A} < 0$ *if either of following two conditions holds:*

(a1) $\left[e_A^* - e_{NA}^*\right] > 0$,

(a2) $\left[e_A^* - e_{NA}^*\right] < 0$ *and* $\underbrace{\frac{\partial \lambda}{\partial \pi_A}\left[e_A^* - e_{NA}^*\right]}_{\text{Indirect effect through technology adoption rate}} < -\underbrace{\lambda \frac{\partial e_A^*}{\partial \pi_A}}_{\text{Direct effect}}$.

(b) If π_A is in Region II:

$\frac{\partial E}{\partial \pi_A} < 0$ *if and only if* $\underbrace{\frac{\partial \lambda}{\partial \pi_A}\left[e_A^* - e_{NA}^*\right]}_{\text{Indirect effect through technology adoption rate}} < -\underbrace{\lambda \frac{\partial e_A^*}{\partial \pi_A}}_{\text{Direct effect}}$.

(c) If π_A is in Region III:

$$\frac{\partial E}{\partial \pi_A} = \frac{\partial \lambda}{\partial \pi_A}\left[e_A^* - e_{NA}^*\right] > 0.$$

(d) If π_A is in Region IV:

$$\frac{\partial E}{\partial \pi_A} = 0\,.$$

(e) If π_{NA} is in Region I:

$$\frac{\partial E}{\partial \pi_{NA}} < 0 \textit{ if either of following two conditions holds:}$$

(e1) $\left[e_A^* - e_{NA}^*\right] < 0$,

(e2) *If* $\left[e_A^* - e_{NA}^*\right] > 0$ *and* $\underbrace{\frac{\partial \lambda}{\partial \pi_{NA}}\left[e_A^* - e_{NA}^*\right]}_{\substack{\text{Indirect effect through} \\ \text{technology adoption rate}}} < -\underbrace{\left[1-\lambda\right]\frac{\partial e_{NA}^*}{\partial \pi_{NA}}}_{\text{Direct effect}}$.

(f) If π_{NA} is either in Region II or in Region III:

$$\frac{\partial E}{\partial \pi_{NA}} = \frac{\partial \lambda}{\partial \pi_{NA}}\left[e_A^* - e_{NA}^*\right] < 0\,.$$

(g) If π_{NA} is in Region IV:

$$\frac{\partial E}{\partial \pi_{NA}} = 0\,.$$

The results of the influence of monitoring probabilities on aggregate emissions bring a new element to the analysis. It considers the fact that under targeted monitoring, firms can change their type by adopting a new abatement technology as a response to the monitoring pressure. By this means, a regulator may influence the aggregated emissions using enforcement pressure.

5. The problem of the regulator

In this section, we consider the optimal monitoring policy of a regulator whose only objective is to minimize total emissions.[10] The regulator decides on a pair of non-negative monitoring probabilities π_A and π_{NA} that minimize aggregated emissions *E*. The regulator is subject to a

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[10] This assumption is not new in the literature. See Macho-Stadler and Pérez-Castrillo (2006) and Garvie and Keeler (1994).

monitoring budget constraint B and a rate of technology adoption that cannot be higher than one. The problem of the regulator is:

$$(10)\quad \begin{aligned} &\underset{\pi_A,\pi_{NA}}{Min}\ \lambda(\pi_{\mathrm{A}},\pi_{NA})e_A+\left[1-\lambda(\pi_{\mathrm{A}},\pi_{NA})\right]e_{NA}\\ &s.t.\ \ \varpi\pi_{\mathrm{A}}\lambda+\varpi\pi_{\mathrm{NA}}\left[1-\lambda\right]\le B\\ &\lambda\le 1 \end{aligned}$$

The Lagrange equation for this minimization problem is given by $L=\lambda e_A+\left[1-\lambda\right]e_{NA}+\gamma\left[B-\varpi\pi_{\mathrm{A}}\lambda-\varpi\pi_{\mathrm{NA}}\left[1-\lambda\right]\right]+\eta\left[1-\lambda\right]$ with the following Kuhn-Tucker conditions:

$$(11)\ \frac{\partial L}{\partial\pi_A}=\frac{\partial E}{\partial\pi_A}+\gamma\left[-\varpi\lambda-\pi_A\varpi\frac{\partial\lambda}{\partial\pi_A}+\pi_{NA}\varpi\frac{\partial\lambda}{\partial\pi_A}\right]-\eta\frac{\partial\lambda}{\partial\pi_A}\le 0;\ \pi_A\ge 0;\ \pi_A\frac{\partial L}{\partial\pi_A}=0$$

(12)

$$\frac{\partial L}{\partial\pi_{NA}}=\frac{\partial E}{\partial\pi_{NA}}+\gamma\left[-\varpi\left[1-\lambda\right]-\pi_A\varpi\frac{\partial\lambda}{\partial\pi_{NA}}+\pi_{NA}\varpi\frac{\partial\lambda}{\partial\pi_{NA}}\right]-\eta\frac{\partial\lambda}{\partial\pi_{NA}}\le 0;\ \ \pi_{NA}\ge 0;\ \ \pi_{NA}\frac{\partial L}{\partial\pi_{NA}}=0$$

$$(13)\quad \frac{\partial L}{\partial\gamma}=B-\varpi\pi_{\mathrm{A}}\lambda-\varpi\pi_{\mathrm{NA}}\left[1-\lambda\right]\ge 0;\qquad \gamma\ge 0;\qquad \gamma\left[B-\varpi\pi_{\mathrm{A}}\lambda-\varpi\pi_{\mathrm{NA}}\left[1-\lambda\right]\right]=0$$

$$(14)\quad \frac{\partial L}{\partial\eta}=\left[1-\lambda\right]\ge 0;\qquad \eta\ge 0;\qquad \eta\left[1-\lambda\right]=0\,.$$

In order to solve the minimization problem, first it is necessary to establish which of the possible combinations of π_A and π_{NA} constitutes the feasible set, i.e., which of the combinations satisfies all the constraints (see appendix B for derivation). Once the feasible set is established, it is necessary to study which of the solutions in the feasible set are dominated solutions, i.e., in which of them aggregate emissions are definitely not minimized. Such an analysis is presented in Table 1.

From Table 1, combinations A, B, and D constitute the feasible set to solve the minimization problem. However, by comparing aggregate emissions under combinations A, B, and D, it is straightforward to see that combinations B and D are dominated by combination A.[11] Therefore, the pair of adopters' and non-adopters' monitoring probabilities that minimize aggregate emissions should satisfy the conditions in (15a) or in (15b):

(15a) $\pi_A^* = \dfrac{t}{\phi'(e_A^{\min *})}$ and $\pi_{NA}^* \geq \dfrac{t}{\phi'(e_{NA}^{\min *})}$ with non-binding restriction: $\varpi\pi_A^*\lambda + \varpi\pi_{NA}^*[1-\lambda] < B$,

(15b) $\pi_A^* = \dfrac{t}{\phi'(e_A^{\min *})}$ and $\pi_{NA}^* > 0$ such that $\lambda = 1$ with non-binding restriction: $\varpi\pi_A^*\lambda + \varpi\pi_{NA}^*[1-\lambda] < B$.

Table 1. Solution to the problem of the regulator

Combination	π_A	π_{NA}	Does this combination satisfy the restriction?	Aggregate emissions $E = \lambda e_A^* + [1-\lambda]e_{NA}^*$
A	Positive	Positive	This combination satisfies the restrictions if : (a) $\pi_A = \dfrac{t}{\phi'(e_A^{\min *})}$ and $\pi_{NA} \geq \dfrac{t}{\phi'(e_{NA}^{\min *})}$ with non-binding budget restriction, or	$E_{\text{CombinationA}} = \lambda e_A^{\min *} + [1-\lambda]e_{NA}^{\min *}$ $E_{\text{CombinationA}} \in [e_A^{\min *}, e_{NA}^{\min *}]$

[11] There is one special case in which $E_{\text{CombinationB}} = E_{\text{CombinationA}} = e_{NA}^{\min *}$. It requires zero technology adoption in combination A together with a π_{NA} in either Region II, III, or IV.

			(b) $\pi_A = \frac{t}{\phi'(e_A^{\min *})}$ and $\pi_{NA} > 0$ such that $\lambda = 1$ with non-binding budget restriction.	
B	Zero	Positive	This combination always satisfies the restrictions	$E_{\text{CombinationB}} \in \left[e_{NA}^{\min *}, e^0\right]$
C	Positive	Zero	This combination never satisfies the restrictions	
D	Zero	Zero	This combination always satisfies the restrictions	$E_{\text{CombinationD}} = e^0$

The fact that in this model we do consider that the rate of technology adoption is a function of the monitoring probabilities of adopters and non-adopters explains why the optimal monitoring policy in the present paper is not guaranteed by the strict equality in conditions (15a) and (15b). The intuition is as follows. Let us for a moment assume that the parameters of the rate of technology adoption function are such that $\lambda < 1$ for all possible combinations (π_A, π_{NA}). In such a scenario, condition (16b) is not feasible. Therefore, following condition (15a), a regulator who sets $\pi_A^* = \frac{t}{\phi'(e_A^{\min *})}$ can increase non-adopters' monitoring probability to a level higher than $\frac{t}{\phi'(e_{NA}^{\min *})}$ to increase the rate of technology adoption and, by this means, decrease aggregate emissions[12]. In a similar setting, Macho-Stadler and Pérez-Castrillo (2006) derive the optimal monitoring policy of a regulator whose objective is to minimize aggregated emissions. They find that adopters and non-adopters of the new abatement technology should be monitored with probabilities $\pi_A = \frac{t}{\phi'(e_A^{\min *})}$ and $\pi_{NA} = \frac{t}{\phi'(e_{NA}^{\min *})}$. The fact that they do not consider that firms can react to the monitoring probabilities by adopting a new abatement technology explains why,

[12] Remember that $\frac{\partial \lambda}{\partial \pi_{NA}} > 0$ as long as $\pi_{NA} < \frac{t}{\phi'(0)}$.

in their model, monitoring non-adopters with a probability higher than $\pi_{NA} = \dfrac{t}{\phi'(e_{NA}^{\min *})}$ does not lead to a reduction in aggregate emissions. In my model, for certain sets of parameters it might be optimal for a regulator to exert a pressure on non-adopters that is higher than that suggested by their model, and, eventually, bias its strategy against firms that value pollution more, i.e., $\pi_{NA}^{*} > \pi_{A}^{*}$.

6. Conclusion

A significant fraction of the literature on environmental regulation has been devoted to studying how environmental policies should be and are enforced. Empirical studies have shown that a suitable strategy for the regulator to deal with the budget constraints in the enforcement activity is to target enforcement. Regulators can define a monitoring schedule for firms according to their past compliance records or to their potential emissions. If firms face a targeted enforcement strategy in which those with higher potential emissions are monitored more closely, a plausible response may be to adopt a new and more efficient abatement technology that allows them to reduce potential emissions and thus to avoid a more stringent monitoring pressure. Using a conventional model of non-compliant firms in a setting of uniform taxes, we have analyzed the effects of a targeted enforcement strategy on rate of technology adoption and aggregate emission level.

The results suggest that, with a targeted enforcement strategy based on adoption status, a regulator might stimulate or slow down the adoption of the new technology through monitoring pressure on both types of firms when firms are non-compliant. An increase in non-adopters' monitoring probability induces a higher rate of technology adoption while increasing adopters' monitoring probability induces a lower rate of technology adoption.

In addition, we analyze the optimal strategy for a regulator whose objective is to minimize aggregate emissions. In contrast to previous literature, we find that, for certain sets of parameters, it might be optimal for a regulator to bias its monitoring strategy against those firms that value pollution more.

The interaction between technology adoption rate and targeted enforcement also has consequences on aggregate emissions, and brings some issues to the policy arena. The model in this paper considers that firms can adopt a new abatement technology as a response to the monitoring probabilities set by the regulator. Therefore, the actions of the regulator in terms of monitoring probabilities have consequences on the aggregate emission level through the rate of technology adoption. If the regulator increases the monitoring probability of non-adopters, the rate of technology adoption increases, causing an additional deterrent effect on aggregate emissions. In this setting, a regulator who instead focuses its monitoring efforts on adopters of the new technology slows down the spread of the new abatement technology and faces a higher level of aggregate emissions than achieved with the opposite enforcement policy. The fact that the technology adoption rate is influenced by monitoring strategy is good news for a regulator who wants to achieve a given level of aggregate emissions but has political constraints on the level of the tax to be imposed. Such a regulator may use a differentiated monitoring strategy to induce technology adoption and therefore to reduce aggregate emissions for a given politically feasible tax level. Consequently, targeted monitoring strategies should not be ruled out as a plausible enforcement policy if the interaction between monitoring probabilities and technology adoption is taken into consideration.

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Appendix A

The rate of technology adoption under uniform taxes is given by:

(A1)
$$\lambda^{TAX} = \psi\left[c(e_{NA}(t)) - \theta c(e_A(t))\right] + \psi\left[tr_{NA}(t,\pi_{NA},F) - tr_A(t,\pi_A,F)\right] + \psi\left[\pi_{NA}F(v_{NA}) - \pi_A F(v_A)\right] - \zeta$$

Taking the partial derivative of λ^{TAX} with respect to adopters' monitoring probability yields:

(A2) $$\frac{\partial \lambda^{TAX}}{\partial \pi_A} = \psi\left[-t\frac{\partial r_A}{\partial \pi_A} - \pi_A F'(v_A)\frac{\partial v_A}{\partial \pi_A} - F(v_A)\right].$$

Taking into consideration that $\pi_A F'(v_A) = t$ and $\frac{\partial v_A}{\partial \pi_A} = -\frac{\partial r_A}{\partial \pi_A}$ and rewriting:

(A3) $$\frac{\partial \lambda^{TAX}}{\partial \pi_A} = -\psi F(v_A).$$

Analogously, taking the partial derivative of λ^{TAX} with respect to non-adopters' monitoring probability yields:

(A4) $$\frac{\partial \lambda^{TAX}}{\partial \pi_{NA}} = \psi\left[t\frac{\partial r_{NA}}{\partial \pi_{NA}} + \pi_{NA} F'(v_{NA})\frac{\partial v_{NA}}{\partial \pi_{NA}} + F(v_{NA})\right].$$

Taking into consideration that $\pi_{NA} F'(v_{NA}) = t$ and $\frac{\partial v_{NA}}{\partial \pi_{NA}} = -\frac{\partial r_{NA}}{\partial \pi_{NA}}$ and rewriting:

(A5) $$\frac{\partial \lambda^{TAX}}{\partial \pi_{NA}} = \psi F(v_{NA}).$$

Appendix B

The problem of the regulator is to minimize aggregate emissions subject to a budget constraint. Aggregate emissions are given by the weighted average between adopters' and non-adopters' emissions where the weights are given by the fraction of firms that adopt the new technology and the fraction that do not.

$$\underset{\pi_A,\pi_{NA}}{Min} \ \lambda(\pi_{\mathrm{A}},\pi_{NA})e_A + [1-\lambda(\pi_{\mathrm{A}},\pi_{NA})]e_{NA}$$
$$s.t.$$
$$\varpi\pi_{\mathrm{A}}\lambda + \varpi\pi_{\mathrm{NA}}[1-\lambda] \le B$$
$$\lambda \le 1$$

The Lagrange equation for this minimization problem is given by:

$$L = \lambda e_A + [1-\lambda]e_{NA} + \gamma[B - \varpi\pi_{\mathrm{A}}\lambda - \varpi\pi_{\mathrm{NA}}[1-\lambda]] + \eta[1-\lambda].$$

The Kuhn-Tucker conditions are as follows:

(B1)

$$\frac{\partial L}{\partial \pi_A} = \frac{\partial E}{\partial \pi_A} + \gamma\left[-\varpi\lambda - \pi_A\varpi\frac{\partial \lambda}{\partial \pi_A} + \pi_{NA}\varpi\frac{\partial \lambda}{\partial \pi_A}\right] - \eta\frac{\partial \lambda}{\partial \pi_A} \le 0; \qquad \pi_A \ge 0; \qquad \pi_A\frac{\partial L}{\partial \pi_A} = 0$$

(B2)

$$\frac{\partial L}{\partial \pi_{NA}} = \frac{\partial E}{\partial \pi_{NA}} + \gamma\left[-\varpi[1-\lambda] - \pi_A\varpi\frac{\partial \lambda}{\partial \pi_{NA}} + \pi_{NA}\varpi\frac{\partial \lambda}{\partial \pi_{NA}}\right] - \eta\frac{\partial \lambda}{\partial \pi_{NA}} \le 0; \quad \pi_{NA} \ge 0; \qquad \pi_{NA}\frac{\partial L}{\partial \pi_{NA}} = 0$$

(B3)

$$\frac{\partial L}{\partial \gamma} = B - \varpi\pi_{\mathrm{A}}\lambda - \varpi\pi_{\mathrm{NA}}[1-\lambda] \ge 0; \qquad \gamma \ge 0; \qquad \gamma\,[B - \varpi\pi_{\mathrm{A}}\lambda - \varpi\pi_{\mathrm{NA}}[1-\lambda]] = 0$$

(B4)

$$\frac{\partial L}{\partial \eta} = [1-\lambda] \ge 0; \qquad \eta \ge 0; \qquad \gamma\,[1-\lambda] = 0.$$

In order to obtain the feasible set of solutions, let us now explore the different possible combinations of π_{A} and π_{NA} that are candidate solutions to the minimization problem.

CASE A. Let us assume $\pi_{\mathrm{A}} > 0$ ***and*** $\pi_{\mathrm{NA}} > 0$.

From (B1):

(B5) $$\lambda \frac{\partial e_A}{\partial \pi_A} + e_A \frac{\partial \lambda}{\partial \pi_A} - e_{NA} \frac{\partial \lambda}{\partial \pi_A} + \gamma \left[-\varpi\lambda - \pi_A \varpi \frac{\partial \lambda}{\partial \pi_A} + \pi_{NA} \varpi \frac{\partial \lambda}{\partial \pi_A} \right] - \eta \frac{\partial \lambda}{\partial \pi_A} = 0 .$$

From (B2):

(B6)
$$[1-\lambda] \frac{\partial e_A}{\partial \pi_{NA}} + e_A \frac{\partial \lambda}{\partial \pi_{NA}} - e_{NA} \frac{\partial \lambda}{\partial \pi_{NA}} + \gamma \left[-\varpi[1-\lambda] - \pi_A \varpi \frac{\partial \lambda}{\partial \pi_{NA}} + \pi_{NA} \varpi \frac{\partial \lambda}{\partial \pi_{NA}} \right] - \eta \frac{\partial \lambda}{\partial \pi_{NA}} = 0 .$$

Multiplying (B5) by $\frac{\partial \lambda}{\partial \pi_{NA}}$ yields:

(B7)
$$\left[\lambda \frac{\partial e_A}{\partial \pi_A} + [e_A - e_{NA}] \frac{\partial \lambda}{\partial \pi_A} \right] \frac{\partial \lambda}{\partial \pi_{NA}} + \gamma \frac{\partial \lambda}{\partial \pi_{NA}} \left[-\varpi\lambda - \pi_A \varpi \frac{\partial \lambda}{\partial \pi_A} + \pi_{NA} \varpi \frac{\partial \lambda}{\partial \pi_A} \right] - \eta \frac{\partial \lambda}{\partial \pi_A} \frac{\partial \lambda}{\partial \pi_{NA}} = 0$$

Multiplying (B6) by $\frac{\partial \lambda}{\partial \pi_A}$ yields:

(B8)
$$\left[[1-\lambda] \frac{\partial e_A}{\partial \pi_{NA}} + [e_A - e_{NA}] \frac{\partial \lambda}{\partial \pi_{NA}} \right] \frac{\partial \lambda}{\partial \pi_A} + \gamma \frac{\partial \lambda}{\partial \pi_A} \left[-\varpi[1-\lambda] - \pi_A \varpi \frac{\partial \lambda}{\partial \pi_{NA}} + \pi_{NA} \varpi \frac{\partial \lambda}{\partial \pi_{NA}} \right] - \eta \frac{\partial \lambda}{\partial \pi_{NA}} \frac{\partial \lambda}{\partial \pi_A} = 0$$

Substracting (B8) from (B7) yields:

(B9)

$$\lambda\frac{\partial e_A}{\partial \pi_A}\frac{\partial \lambda}{\partial \pi_{NA}}-[1-\lambda]\frac{\partial e_{NA}}{\partial \pi_{NA}}\frac{\partial \lambda}{\partial \pi_A}-\gamma\frac{\partial \lambda}{\partial \pi_{NA}}\left[\varpi\lambda+\varpi\frac{\partial \lambda}{\partial \pi_A}[\pi_A-\pi_{NA}]\right]+\gamma\frac{\partial \lambda}{\partial \pi_A}\left[\varpi[1-\lambda]+\varpi\frac{\partial \lambda}{\partial \pi_{NA}}[\pi_A-\pi_{NA}]\right]=0$$

CASE A1. Assuming $\gamma=0$, i.e., the budget is not binding, from (B9) implies:

(B9a) $\lambda\frac{\partial e_A}{\partial \pi_A}\underbrace{\frac{\partial \lambda}{\partial \pi_{NA}}}_{\geq 0}-[1-\lambda]\frac{\partial e_{NA}}{\partial \pi_{NA}}\underbrace{\frac{\partial \lambda}{\partial \pi_A}}_{\leq 0}=0\cdot$

Condition (B9a) only holds when $\lambda\frac{\partial e_A}{\partial \pi_A}\frac{\partial \lambda}{\partial \pi_{NA}}=0$ and $-[1-\lambda]\frac{\partial e_{NA}}{\partial \pi_{NA}}\frac{\partial \lambda}{\partial \pi_A}=0$. Table A1 presents the conditions under which each of these two equalities hold:

Table A1.

$\lambda\frac{\partial e_A}{\partial \pi_A}\frac{\partial \lambda}{\partial \pi_{NA}}=0$ if one of the following two conditions holds:	$-[1-\lambda]\frac{\partial e_{NA}}{\partial \pi_{NA}}\frac{\partial \lambda}{\partial \pi_A}=0$ if one of the following three conditions holds:
(a) $\frac{\partial e_A}{\partial \pi_A}=0$. It requires: $\pi_A\geq\frac{t}{\phi'(e_A^{\min *})}$	(c) $\lambda=1$
(b) $\frac{\partial \lambda}{\partial \pi_{NA}}=0$. It requires: $\pi_{NA}\geq\frac{t}{\phi'(0)}$	(d) $\frac{\partial e_{NA}}{\partial \pi_{NA}}=0$. It requires: $\pi_{NA}\geq\frac{t}{\phi'(e_{NA}^{\min *})}$
	(e) $\frac{\partial \lambda}{\partial \pi_A}=0$. It requires: $\pi_A\geq\frac{t}{\phi'(0)}$

The following combinations of conditions in Table A1 satisfy condition (B9a): (a)-(c); (a)-(d); (a)-(e); (b)-(c); (b)-(d); (b)-(e). However, the following sets of combinations yield to the same conditions:

- Combination (b)-(c) and combination (a)-(e)
- Combination (b)-(c), combination (b)-(a), and combination (b)-(d).

Therefore, the following are the required combinations to fulfill condition (B9a):

(i) $\pi_A \geq \dfrac{t}{\phi'(e_A^{\min*})}$ and $\pi_{NA} > 0$ such that $\lambda = 1$. We know that $\dfrac{\partial \lambda}{\pi_A} \leq 0$ and it therefore is enough to monitor with $\pi_A = \dfrac{t}{\phi'(e_A^{\min*})}$. Under this combination, aggregate emissions are $E = e_A^{\min*}$.

(ii) $\pi_A \geq \dfrac{t}{\phi'(e_A^{\min*})}$ and $\pi_{NA} \geq \dfrac{t}{\phi'(e_{NA}^{\min*})}$. We know that $\dfrac{\partial \lambda}{\pi_A} \leq 0$, and it is therefore enough to monitor with $\pi_A = \dfrac{t}{\phi'(e_A^{\min*})}$. Under this combination, aggregate emissions are $E = \lambda e_A^{\min*} + [1-\lambda] e_{NA}^{\min*}$.

(iii) $\pi_A \geq \dfrac{t}{\phi'(0)}$ and $\pi_{NA} > 0$. Under this condition, aggregate emissions are $E = \lambda e_A^{\min*} + [1-\lambda] e_{NA}^{*}$.

(iv) $\pi_{NA} \geq \dfrac{t}{\phi'(0)}$ and $\pi_A > 0$. Under this condition, aggregate emissions are $E = \lambda e_A^{*} + [1-\lambda] e_{NA}^{\min*}$.

Comparing aggregate emissions under combinations (i)-(iv), it is straightforward to observe that alternatives (iii) and (iv) are dominated by alternatives (i) and (ii). Combinations (i) and (ii) are therefore feasible solutions to the minimization problem. In both combinations, since we are assuming that the budget is not binding, it should hold that $\varpi \pi_{\mathrm{A}} \lambda + \varpi \pi_{\mathrm{NA}} [1-\lambda] < B$.

Let us now analyze the case when the budget is binding:

CASE A2. Assuming $\gamma > 0$, i.e., the budget is binding, from (B9) implies:

(B9b) $$\lambda \frac{\partial e_A}{\partial \pi_A} \frac{\partial \lambda}{\partial \pi_{NA}} - [1-\lambda] \frac{\partial e_{NA}}{\partial \pi_{NA}} \frac{\partial \lambda}{\partial \pi_A} - \varpi \gamma \left[\lambda \frac{\partial \lambda}{\partial \pi_{NA}} - [1-\lambda] \frac{\partial \lambda}{\partial \pi_A} \right] = 0$$.

When $\frac{\partial e_A}{\partial \pi_A} = \frac{\partial e_{NA}}{\partial \pi_{NA}} = 0$, for condition (B9b) to hold it is required that $\lambda > 1$, which contradicts one of the restrictions.

When $\frac{\partial e_A}{\partial \pi_A} < 0$ and $\frac{\partial e_{NA}}{\partial \pi_{NA}} = 0$, for condition (B9b) to hold it is required that $\lambda > 1$, which contradicts one of the restrictions.

When $\frac{\partial e_A}{\partial \pi_A} = 0$ and $\frac{\partial e_{NA}}{\partial \pi_{NA}} < 0$, for condition (B9b) to hold it is required that $\lambda > 1$, which contradicts one of the restrictions.

When $\frac{\partial e_A}{\partial \pi_A} < 0$ and $\frac{\partial e_{NA}}{\partial \pi_{NA}} < 0$, for condition (B9b) to hold it is required that one of the following conditions holds:

(i) $\lambda > 1$, which contradicts one of the restrictions.

(ii) $\pi_{NA} \geq \frac{t}{\phi'(0)}$ and $\pi_A > 0$ such that $\lambda = 1$. Under this combination, aggregate emissions are $E = e_A^*$.

(iii) $\pi_A \geq \frac{t}{\phi'(0)}$ and $\pi_{NA} > 0$ such that $\lambda = 0$. Under this combination aggregate emissions are $E = e_{NA}^*$.

Clearly, combinations (i) and (ii) are dominated by the feasible combinations when the budget is not binding.

CASE B. Let us assume $\pi_{\mathrm{A}} = 0$ ***and*** $\pi_{\mathrm{NA}} > 0$.

From (B1):

(B10) $$\lambda \frac{\partial e_A}{\partial \pi_A} + e_A \frac{\partial \lambda}{\partial \pi_A} - e_{NA} \frac{\partial \lambda}{\partial \pi_A} + \gamma \left[-\varpi\lambda - \pi_{NA}\varpi \frac{\partial \lambda}{\partial \pi_A} \right] - \eta \frac{\partial \lambda}{\partial \pi_A} = 0$$

From (B2):

(B11) $$[1-\lambda]\frac{\partial e_A}{\partial \pi_{NA}}+e_A\frac{\partial \lambda}{\partial \pi_{NA}}-e_{NA}\frac{\partial \lambda}{\partial \pi_{NA}}+\gamma\left[-\varpi[1-\lambda]-\pi_{NA}\varpi\frac{\partial \lambda}{\partial \pi_{NA}}\right]-\eta\frac{\partial \lambda}{\partial \pi_{NA}}=0$$

Multiplying (B10) by $\frac{\partial \lambda}{\partial \pi_{NA}}$ yields:

(B12) $$\left[\lambda\frac{\partial e_A}{\partial \pi_A}+[e_A-e_{NA}]\frac{\partial \lambda}{\partial \pi_A}\right]\frac{\partial \lambda}{\partial \pi_{NA}}+\gamma\frac{\partial \lambda}{\partial \pi_{NA}}\left[-\varpi\lambda+\pi_{NA}\varpi\frac{\partial \lambda}{\partial \pi_A}\right]-\eta\frac{\partial \lambda}{\partial \pi_A}\frac{\partial \lambda}{\partial \pi_{NA}}\le 0$$

Multiplying (B11) by $\frac{\partial \lambda}{\partial \pi_A}$ yields:

(B13):
$$\left[[1-\lambda]\frac{\partial e_A}{\partial \pi_{NA}}+[e_A-e_{NA}]\frac{\partial \lambda}{\partial \pi_{NA}}\right]\frac{\partial \lambda}{\partial \pi_A}+\gamma\frac{\partial \lambda}{\partial \pi_A}\left[-\varpi[1-\lambda]+\pi_{NA}\varpi\frac{\partial \lambda}{\partial \pi_{NA}}\right]-\eta\frac{\partial \lambda}{\partial \pi_{NA}}\frac{\partial \lambda}{\partial \pi_A}=0$$

Subtracting (B13) from (B12) yields:

(B14) $$\lambda\frac{\partial e_A}{\partial \pi_A}\frac{\partial \lambda}{\partial \pi_{NA}}-[1-\lambda]\frac{\partial e_{NA}}{\partial \pi_{NA}}\frac{\partial \lambda}{\partial \pi_A}-\gamma\varpi\left[\frac{\partial \lambda}{\partial \pi_{NA}}\lambda-\frac{\partial \lambda}{\partial \pi_A}[1-\lambda]\right]\le 0$$

CASE B1. Assuming $\gamma=0$, i.e., the budget is not binding, from (B14) implies:

(B14a) $$\lambda\frac{\partial e_A}{\partial \pi_A}\frac{\partial \lambda}{\partial \pi_{NA}}-[1-\lambda]\frac{\partial e_{NA}}{\partial \pi_{NA}}\frac{\partial \lambda}{\partial \pi_A}\le 0.$$

Condition (B14a) holds for all $\pi_{NA}>0$.

CASE B2. Assuming $\gamma>0$, i.e., the budget is binding, from (B14) implies:

(B14b) $$\lambda\frac{\partial e_A}{\partial \pi_A}\frac{\partial \lambda}{\partial \pi_{NA}}-[1-\lambda]\frac{\partial e_{NA}}{\partial \pi_{NA}}\frac{\partial \lambda}{\partial \pi_A}\le\gamma\varpi\left[\frac{\partial \lambda}{\partial \pi_{NA}}\lambda-\frac{\partial \lambda}{\partial \pi_A}[1-\lambda]\right].$$

Condition (B14b) holds for all $\pi_{NA}>0$.

CASE C. Let us assume $\pi_{\mathrm{A}} > 0$ ***and*** $\pi_{\mathrm{NA}} = 0$**.**

From (B1):

$$\text{(B15)}\quad \lambda \frac{\partial e_A}{\partial \pi_A} + e_A \frac{\partial \lambda}{\partial \pi_A} - e_{NA} \frac{\partial \lambda}{\partial \pi_A} + \gamma \left[-\varpi \lambda - \pi_A \varpi \frac{\partial \lambda}{\partial \pi_A} \right] - \eta \frac{\partial \lambda}{\partial \pi_A} = 0$$

From (B2):

$$\text{(B16)}\, [1-\lambda] \frac{\partial e_A}{\partial \pi_{NA}} + e_A \frac{\partial \lambda}{\partial \pi_{NA}} - e_{NA} \frac{\partial \lambda}{\partial \pi_{NA}} + \gamma \left[-\varpi [1-\lambda] - \pi_A \varpi \frac{\partial \lambda}{\partial \pi_{NA}} \right] - \eta \frac{\partial \lambda}{\partial \pi_{NA}} \leq 0$$

Multiplying (B15) by $\dfrac{\partial \lambda}{\partial \pi_{NA}}$ yields:

$$\text{(B17)} \left[\lambda \frac{\partial e_A}{\partial \pi_A} + [e_A - e_{NA}] \frac{\partial \lambda}{\partial \pi_A} \right] \frac{\partial \lambda}{\partial \pi_{NA}} + \gamma \frac{\partial \lambda}{\partial \pi_{NA}} \left[-\varpi \lambda - \pi_A \varpi \frac{\partial \lambda}{\partial \pi_A} \right] - \eta \frac{\partial \lambda}{\partial \pi_A} \frac{\partial \lambda}{\partial \pi_{NA}} = 0$$

Multiplying (B16) by $\dfrac{\partial \lambda}{\partial \pi_A}$ yields:

(B18)

$$\left[[1-\lambda] \frac{\partial e_A}{\partial \pi_{NA}} + [e_A - e_{NA}] \frac{\partial \lambda}{\partial \pi_{NA}} \right] \frac{\partial \lambda}{\partial \pi_A} + \gamma \frac{\partial \lambda}{\partial \pi_A} \left[-\varpi [1-\lambda] - \pi_A \varpi \frac{\partial \lambda}{\partial \pi_{NA}} \right] - \eta \frac{\partial \lambda}{\partial \pi_{NA}} \frac{\partial \lambda}{\partial \pi_A} \leq 0$$

Substracting (B17) from (B18) yields:

$$\text{(B19)}\quad -\lambda \frac{\partial e_A}{\partial \pi_A} \frac{\partial \lambda}{\partial \pi_{NA}} + [1-\lambda] \frac{\partial e_{NA}}{\partial \pi_{NA}} \frac{\partial \lambda}{\partial \pi_A} \leq \gamma \varpi \left[\frac{\partial \lambda}{\partial \pi_A} [1-\lambda] - \lambda \frac{\partial \lambda}{\partial \pi_{NA}} \right]$$

Condition (B19) never holds.

CASE D. Let us assume $\pi_{\mathrm{A}} = 0$ ***and*** $\pi_{\mathrm{NA}} = 0$**.**

Given that adopters and non-adopters emit at e^0 when $\pi_{\mathrm{A}} = 0$ and $\pi_{\mathrm{NA}} = 0$, this combination is not a good candidate to minimize aggregate emissions.