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ORIGINAL ARTICLE

On the interaction between imperfect compliance and technology adoption: taxes versus tradable emissions permits

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Abstract This paper analyzes the effects of the interaction between technology adoption and incomplete enforcement on the extent of violations and the rate of abatement technology adoption. We focus on price-based and quantity-based emission regulations. First, we show that in contrast to uniform taxes, under tradable emissions permits (TEPs), the fall in permit price produced by technology adoption reduces the benefits of violating the environmental regulation at the margin and leads firms to modify their compliance behavior. Moreover, when TEPs are used, the deterrent effect of the monitoring effort is reinforced by the effect that technology adoption has on the extent of violations. Second, we show that the regulator may speed up the diffusion of new technologies by increasing the stringency of the enforcement strategy in the case of TEPs while in the case of uniform taxes, the rate of adoption does not depend on the enforcement parameters.

Keywords Technological adoption · Environmental policy · Imperfect compliance · Enforcement

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1 Introduction

In the long run, technological change is considered the primary solution to environmental problems (Kneese and Schultze 1978), and it has long been recognized that environmental policy creates incentives that affect the process of technological development (Jaffe et al. 2002; Requate 2005). Many scholars have therefore analyzed how alternative policy instruments affect the rate and direction of technological change. Among market-based policies, the analyses tend to support the use of emission taxes (price-based regulation) over tradable emission permits (TEPs) (quantity-based regulation), when the regulator is myopic and does not adjust the level of the policy in response to the advent of new technology.[1] The fact that the emission price is fixed under the tax while it decreases under permits creates a wedge between the two instruments and between the rates of adoption they induce.

Previous analyses of technology adoption under different policies share a common and implicit assumption: *Firms perfectly comply with environmental regulations*. However, reality generally differs from this assumption. In some cases, a fraction of firms do not comply with an environmental regulation and furthermore, the expected enforcement costs can be substantial. The intuition of the interaction between incomplete enforcement and technology adoption can be thought of in two ways: (i) incomplete enforcement, and therefore the possibility that firms do not comply with a regulation, may influence the profits of firms from technology adoption and thus the adoption decision, and (ii) the existence of a new technology that reduces the abatement costs may influence a firm's compliance decisions since the marginal benefit of violations is reduced.

The purpose of the present paper is to analyze the interaction between incomplete enforcement and technology adoption under price-based and quantity-based policies. We compare emission taxes and TEPs in terms of: (i) how compliance changes with the use of new technologies and (ii) how technology adoption is affected by enforcement parameters such as the probability of being monitored.

To our knowledge, the interaction between technology adoption and imperfect compliance and its effects on the comparison between uniform taxes and tradable permits when the rate of adoption is endogenous has not yet been directly addressed. Some literature has been devoted to comparing policy instruments when incomplete enforcement is an issue (Montero 2002; Rousseau and Proost 2005; Macho-Stadler 2008).[2] Recent work by Arguedas et al. (2010)

[1] See Milliman and Prince (1989), Jung et al. (1996), Kennedy and Laplante (1999), Requate and Unold (2001) and Requate and Unold (2003) for comparison of incentives provided by environmental policies.

[2] The ranking of priced-based versus quantity-based environmental regulation was first studied by Weitzman (1974), who analyzed the choice between these two types of instruments when there is uncertainty. After Weitzman (1974), the comparison between price- and quantity-based policies has been further developed (Roberts and Spence 1976; Yohe 1978; Finkelshtain and Kislev 1997; Hoel and Karp 2002; Montero 2002; Moledina et al. 2003; Baldursson and von der Fehr 2004; Quirion 2004; Stranlund and Ben-Haim 2008).

analyzes technology adoption incentives in the presence of imperfect compliance. They find that under uniform emission taxes the incentives to adopt a new abatement technology are the same as with perfect compliance whereas adoption incentives decrease under TEPs. Nevertheless, in contrast to our model, in their setting the rate of adoption is exogenous; therefore, they disregard the influence of the availability of the new technology on aggregate compliance as well as the effect of the enforcement strategy fostering further adoption.

To analyze the links between technology adoption and imperfect compliance, we model a competitive industry consisting of a continuum of firms that are subject to environmental regulation that could take the form of either emissions taxes or tradable permits. Before the arrival of new abatement technology, the firms' abatement costs are homogeneous. When the new technology becomes available, each firm can independently decide to invest or not invest in a new technology that shifts the firm's abatement cost function downwards at the expense of a fixed cost. The adoption decision is made based on the comparison of the expected costs of abatement and compliance under the current and the new technology. For simplicity, we focus on the analysis of interior solutions, i.e., firms provide positive reports of their emissions under taxes and hold a number of permits higher than zero under a scheme of TEPs.

Our results suggest that the interaction between technology adoption and incomplete enforcement have important implications in terms of the deterrence effect of the enforcement policies on violations and in terms of the effect of monitoring effort on the technology adoption rate.

It is shown that when taxes are used, the rate of technology adoption is not affected by enforcement strategy. In contrast, when TEPs are used, the rate of adoption is an increasing function of the monitoring probability.[3] Additionally, under TEPs, for a given monitoring probability, the fall in permit price produced by technology adoption reduces the benefits of violating the environmental regulation at the margin and ultimately leads both adopters and non-adopters to modify their compliance behavior. This is not the case under emissions taxes where the tax rate remains unchanged after technology adoption. Thus, in contrast to taxes, the extent of violations under TEPs decreases with the rate of adoption. Moreover, when TEPs are used, the deterrent effect of the monitoring effort on violations is reinforced by the effect that technology adoption has on the equilibrium permit price and consequently on the extent of violations. These results constitute good news for a regulator who, by choosing TEPs, may be able to obtain a higher reduction in the extent of violation due to the availability of new technologies. Also, the regulator may be able to use monitoring effort as a tool to influence the diffusion of new abatement technologies.

The paper is organized as follows. Section 2 presents the model of adoption, and Section 3 introduces the compliance analysis under emission taxes and TEPs. Section 4 explores the way in which the rate of technology adoption is affected by the enforcement strategy under both policy instruments, and how the influence of monitoring probability on technology adoption reinforces the effect of the former on the extent of violations under TEPs. Finally, Sect. 5 offers a discussion of the policy implications of our results and concludes the paper.

[3] This result is in line with Arguedas et al. (2010)

2 The model

We consider a competitive industry consisting of a continuum of firms $\Lambda \subset [0, 1]$ that are risk-neutral. In the absence of environmental regulation, each firm emits a quantity e_0 of a homogeneous pollutant. We assume there is an environmental authority that sets an environmental target—a maximum level of emissions—and then chooses a policy instrument to reach this target. Since the regulator cannot observe firms' emissions, costly monitoring is undertaken. In our model, the regulator has a fixed monitoring budget given by B, and the cost of an audit to a firm is given by w. The ratio between the number of possible audits given the regulator's budget $\left(\frac{B}{w}\right)$ and the size of the continuum of firms defines the probability of being monitored, π, which is known by firms. 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 the penalty $\varphi(v)$, where v represents the extent of the violation. This is a strictly convex function of the extent of violation: $\varphi'(v) > 0$; $\varphi''(v) > 0$.[4] For zero violation, the penalty is zero $\varphi(0) = 0$, but the marginal penalty is greater than zero: $\varphi'(0) > 0$.

Firms can reduce emissions through the current abatement technology. As Requate and Unold (2003), we assume that initially all firms are alike in abatement costs, $c(e)$. We assume that $c(e)$ is strictly convex and decreasing in emissions: $c'(e) < 0$; $c''(e) > 0$. A new and more efficient technology arrives and firms must decide whether or not to invest in it. The new technology allows firms to abate emissions at a lower cost, given by $\theta c(e)$, where $\theta \in (0, 1)$ is a parameter that represents the drop in abatement cost due to adoption of the new technology. As in Requate and Unold (2003), technology adoption implies a lower marginal abatement cost curve$-c'(e) > -\theta c'(e)$for all $\mathrm{e} < \mathrm{e}_0$.[5]

We assume that buying and installing the new technology implies a fixed cost that differs among firms.[6] Let k_i denote the fixed cost of adoption for firm i, where k_i is

[4] Stranlund et al. (2009) mention some authors who assume that the penalty function is strictly convex: (Hardford 1978, 1987; Sandmo 2002; Macho-Stadler and Pérez-Castrillo 2006). Stranlund et al. (2009) assume a linear penalty function in their model, an assumption that is not common in the literature. If the probability of being monitored is exogenous and the marginal penalty is constant, the decision on reporting emissions will be of the type reporting everything or reporting nothing (see Sandmo (2002) and Heyes (2000)).

[5] To keep the analysis mathematically tractable and simple, we assume that firms are homogeneous in terms of current abatement costs. Nevertheless, our results still hold in the case of heterogeneous abatement. For example, following Coria (2009a), 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 the adoption savings for the marginal adopter offset 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.

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

uniformly distributed on the interval $(\underline{k}, \overline{k})$, with density function $f(k_i)$ and cumulative distribution function $F(k_i)$.[7]

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), respectively, such that the expected cost savings from adopting are $\mu_{NAi} - \mu_{Ai}$. Any firm whose expected cost saving offsets its adoption cost will adopt the new technology.[8] 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, following Coria (2009b), the rate of firms $\lambda \in [0, 1]$ adopting the new technology is defined by the integral

$$\begin{aligned} \lambda &= \int_{\underline{k}}^{\tilde{k}_i} f(k_i)dk = F(\tilde{k}_i) = F(\mu_{NAi} - \mu_{Ai}) = \frac{\mu_{NAi} - \mu_{Ai} - \underline{k}}{\overline{k} - \underline{k}} \\ &= \psi\left[\mu_{NAi} - \mu_{Ai}\right] - \zeta \in (0, 1), \end{aligned} \tag{1}$$

where the right-hand side follows from the definition of the uniform cumulative distribution of $k_i \sim U(\underline{k}, \overline{k})$, $\psi = \frac{1}{\overline{k} - \underline{k}}$ and $\zeta = \psi \underline{k}$.

From Eq. 1, it is straightforward that the adoption rate depends on the total expected savings in the costs of abatement and compliance, which are endogenous to the choice of policy instrument, the stringency of the environmental policy, and the enforcement policy.

In the next section, we analyze the firms' compliance behavior when environmental regulation takes the form of a uniform emission tax or TEPs. It is sufficient to keep track of the marginal adopter's optimal choices of emissions and report in order to derive the rate of adoption; therefore the subscript i is hereinafter omitted.

3 Compliance behavior and technological adoption

In a uniform emission tax system, firms are required to self-report their emissions. A firm is non-compliant if it attempts to evade some part of its tax responsibilities by reporting an emission level that is lower than the true level. In the case of a regulation using permits, a firm should hold one permit for each unit of emissions. A firm that in equilibrium holds fewer permits than its emissions is a non-compliant firm.

The interaction between the regulator and firms is described by the following two-stage mechanism:

Stage 1. The regulator sets the environmental target before the arrival of the new technology and chooses a policy instrument to reach it. We assume that the regulator does not modify the level of the environmental policy in response

[7] Note that since $k_i \sim U(\underline{k}, \overline{k})$, $f(k_i) = \frac{1}{\overline{k} - \underline{k}}$ and $F(k_i) = \int_{\underline{k}}^{k_i} f(k_i)dk$.

[8] Since firms are small, they cannot influence the output prices. Therefore, there is no need to explicitly pay attention to the output market.

to the availability of the new technology. The enforcement strategy is exogenously determined and consists of a probability of being monitored and a sanctioning scheme. The enforcement strategy is set regardless of the regulatory scheme selected by the environmental authority; i.e., firms face the same enforcement policy regardless of policy instrument. This assumption does not contradict reality since, in many cases, the institutional arrangements separate the design of the regulatory instrument from the design of enforcement strategies.

Stage 2. Firms make compliance and adoption decisions. The adoption decision is made based on the comparison of the expected costs of abatement and compliance under the current and the new technology.

Let us now analyze the extent of violation of both adopters and non-adopters when regulated by either uniform emission taxes or TEPs.

3.1 Uniform emission tax

Let us assume that firms must pay a uniform tax t per unit of pollutant emitted and that they self-report their emissions. If a firm reports truthfully, the total amount of taxes to be paid is te. Since there is incomplete enforcement, the firm could try to evade a fraction of its tax payment by reporting a lower level of emissions. If the firm reports emissions equal to r, where $r < e$, then the total tax payment is given by tr. In this case, the firm's violation equals the difference between the actual emissions and reported emissions, $v = e - r$. If the firm is caught in violation, a penalty is imposed according to the penalty function explained above.

Adopters select the emissions and report levels that minimize their expected costs of abatement and compliance:[9]

$$Min_{e,r} \theta c(e) + tr + \pi \phi(e - r), \quad \text{s.}t.\ \ e - r \geq 0 \tag{2}$$

Note that the constraint in the optimization problem reflects the fact that there are no economic incentives to over-report emission levels.[10] Solving this minimization problem, if the solution is interior, a firm's choice of emission is given by $\theta c'(e) + t = 0$. Each firm chooses its emission levels such that the marginal abatement cost equals the tax rate. The emission levels for adopters and non-adopters are, respectively,

$$e_A(t) = \left\{ e |\, \theta c'(e) + t = 0 \right\}; \quad e_{NA}(t) = \left\{ e |\, c'(e) + t = 0 \right\}. \tag{3}$$

Since there is a uniform tax rate, in equilibrium firms' marginal abatement costs are equal irrespective of their adoption status: $c'(e_{NA}) = \theta c'(e_A)$. As $\theta \in (0, 1)$, it is necessary that $c'(e_{NA}) < c'(e_A)$, which is only possible, given the properties of the abatement cost function, if $e_{NA} > e_A$. Therefore, adopters' actual levels of emissions

[9] The problem of the firms that do not adopt the new abatement technology is analogous to problem (2); the main difference is that the abatement costs for these kinds of firms are given by $c(e)$ instead of $\theta c(e)$.

[10] We have omitted the calculations of the optimization problem. They are available upon request.

are reduced due to the availability of the new technology and—in this setting—are lower than those of non-adopters.[11] In addition, in line with previous literature analyzing the compliance behavior of firms under imperfectly enforceable taxes, we find that since the tax is exogenous and not influenced by the enforcement strategy, firms' actual emissions do not depend on the parameters of the enforcement problem (e.g., Hardford 1978). However, this result only holds when the monitoring probability is high enough to guarantee more than zero reported emissions. When firms report zero emissions, the level of emissions is decreasing in monitoring probability (see Macho-Stadler and Pérez-Castrillo (2006) for detailed analyses of corner solutions).

Let us now look at a firm's emission report and extent of violation. When the firm is noncompliant, then $e - r > 0$, which from the Kuhn Tucker conditions for (2) implies that $t - \pi\phi'(e - r) = 0$. The report levels of adopter and non-adopter firms are, respectively,

$$r_A(t, \pi, \phi) = \left\{ r \,|\, t - \pi\phi'(e_A - r_A) = 0 \right\};$$
$$r_{NA}(t, \pi, \phi) = \left\{ r \,|\, t - \pi\phi'(e_{NA} - r_{NA}) = 0 \right\}. \tag{4}$$

The equations in (4) state that firms choose to report a level of emissions such that the marginal expected fine equals the marginal benefit of non-compliance, i.e., the tax. Combining both equations, we obtain $e_A - r_A = e_{NA} - r_{NA}$. Note that $r_{NA} > r_A$ since $e_{NA} > e_A$. Hence, the emissions reported by adopters are lower than those reported by non-adopters. Working on comparative statics, it is possible to show that the report levels of adopters and non-adopters are decreasing in the tax rate and increasing in the monitoring probability.[12] This result is in line with previous findings in the literature on TEPs (see Stranlund and Dhanda 1999).

Proposition 1 *With uniform taxes, the extent of violation of firms is independent of the adoption status and is therefore the same for adopters and non-adopters of the new technology.*

Proof 1 The extent of a violation is given by $v(t, \pi, \phi) = e(t) - r(t, \pi, \phi)$. From equations in (4), we obtain that $\pi\phi'(e_A - r_A) = \pi\phi'(e_{NA} - r_{NA})$, and since the enforcement strategy is exogenously set and independent of the adoption status, it is straightforward to observe that $e_A - r_A = e_{NA} - r_{NA}$. □

The intuition behind this result is as follows. On one hand, since the enforcement strategy does not depend on adoption status, the expected marginal cost of evasion does not change with adoption. On the other hand, the marginal benefit of violation does not depend on adoption status either, since it is given by the unit tax rate. Therefore, given that the marginal benefits and expected marginal costs of disobeying the

[11] The fact that adopters' emissions are lower than non-adopters emissions is mainly due to the new technology being the most efficient alternative available. Indeed, adoption shifts every firm's abatement cost function downwards at the expense of a fixed cost. The introduction of some heterogeneity in the current abatement costs might imply that some firms do not obtain significant savings from adopting. However, it might still imply a lower level of emissions by non-adopters if no current technology is more efficient than the new one.

[12] The derivation is straightforward and available upon request.

law are the same for all firms, the extent of the violation is the same regardless of adoption status.

3.2 Tradable emissions permits

A firm regulated by TEPs can abate a fraction of its emissions and buy permits to compensate for the remaining fraction. The equilibrium price of each permit is represented by p, and a firm that emits e should spend pe on buying permits. Assume that the authority issues L emission permits each period and that the possession of a permit gives the legal right to emit one unit of pollutant. In the presence of imperfect compliance, polluters have an incentive to hold in equilibrium a quantity of permits lower than e to reduce their expenditure on permits. Let l denote the quantity of permits held by a firm in equilibrium and l_0 be the number of emissions permits, if any, initially allocated to it. A firm is non-compliant if after trade it holds a number of permits that is lower than its corresponding units of emissions. The extent of violation is then given by $v = e - l$. We assume that the enforcement authority keeps perfect track of each firm's permit holding.[13] Adopters select the emission level and demand for permits that minimize total expected costs:

$$Min_{e,l}\theta c(e) + p\,[l - l_0] + \pi\phi(e - l), \qquad s.t.\ \ e - l \geq 0. \tag{5}$$

From the solution to the optimization problem, if the solution is interior, the emissions levels for adopters and non-adopters are, respectively,

$$e_A(p) = \left\{e|\,\theta c'(e) + p = 0\right\};\ \ e_{NA}(p) = \left\{e|\,c'(e) + p = 0\right\}. \tag{6}$$

The equations in (6) state that in equilibrium, each firm chooses its emissions such that the marginal abatement cost equals the equilibrium permit price, which is the same for all firms regardless of adoption status. Since the adopters' marginal abatement cost function is lower than that of the non-adopters, $e_{NA}(p) > e_A(p)$. The number of permits held by adopters and non-adopters is, respectively,

$$\begin{aligned} l_A\,(p, \pi, \phi) &= \left\{l|p - \pi\phi'\,(e_A - l_A) = 0\right\}; \\ l_{NA}\,(p, \pi, \phi) &= \left\{l|p - \pi\phi'\,(e_{NA} - l_{NA}) = 0\right\}. \end{aligned} \tag{7}$$

The equations in (7) show that in equilibrium, firms hold a quantity of permits such that the marginal expected fine equals the marginal benefit of non-compliance, i.e., the equilibrium permit price. Since the permit price and the enforcement strategies faced by adopters and non-adopters are the same, we obtain that $e_A - l_A = e_{NA} - l_{NA}$. Given that $e_{NA} > e_A$, it follows that $l_{NA} > l_A$ for the equality to hold. Therefore,

[13] Assume, for instance, that all transactions performed in the market have to be registered with the authority. Since the authority has information about initial allocation, it is able to have perfect information about each firm's permit holding at any point in time.

with TEPs, the actual emissions and the quantity of permits that firms hold in equilibrium are reduced following adoption and are lower than the actual emissions and the quantity of permits held by non-adopters in equilibrium.[14]

Proposition 2 *With TEPs, a firm's extent of violation is independent of its adoption status and is therefore the same for adopters and non-adopters of the new technology. However, for a given monitoring probability, the extent of violation is decreasing in the rate of adoption.*

Proof 2 The extent of violation of a firm is determined by the arbitrage condition $\pi\phi'(v) = p$. Since the equilibrium permit price and the enforcement strategies faced by adopters and non-adopters are the same, we obtain that the extent of violation is the same regardless of adoption status, $e_A - l_A = e_{NA} - l_{NA}$. The fact that changes in abatement cost parameters do not affect the extent of violation as long as the enforcement strategy and the permit price remain the same is well known in the literature (see, e.g., Stranlund and Dhanda 1999 and Chavez et al. 2009). However, the adoption rate affects the extent of violation of adopters and non-adopters via the equilibrium permit price and hence the extent of the violation of adopters and non-adopters: $\frac{\partial v}{\partial \lambda} = \frac{\partial v}{\partial p}\frac{\partial p}{\partial \lambda}$.

Violations are an increasing function of permit price, $\frac{\partial v}{\partial p} > 0$.[15] The sign of $\frac{\partial v}{\partial \lambda}$ therefore depends on the sign of $\frac{\partial p}{\partial \lambda}$. To determine the influence of the adoption rate on the equilibrium permit price $\frac{\partial p}{\partial \lambda}$, consider the market equilibrium equation. The permit price that clears the market is given by the equilibrium between supply and total demand for permits:

$$L = \lambda l_A(p(\lambda, \pi)) + [1 - \lambda]\, l_{NA}(p(\lambda, \pi)). \tag{8}$$

Taking the total derivative of Eq. 8 with respect to the technology adoption rate—and given that the supply of permits is fixed—we observe in Eq. 9 that an increase in λ reduces the equilibrium permit price due to the fact that adoption decreases adopters' demand for permits and consequently the aggregate demand in $-[l_A - l_{NA}]$. This reduction in aggregate demand pushes the permit price down.

$$\frac{\partial p}{\partial \lambda} = \frac{-[l_A - l_{NA}]}{\left[\lambda \frac{\partial l_A}{\partial p} + (1 - \lambda)\frac{\partial l_{NA}}{\partial p}\right]} < 0. \tag{9}$$

Given that the permit price decreases with the rate of technology adoption $\left(\text{i.e., } \frac{\partial p}{\partial \lambda} < 0\right)$ and that a drop in permit price implies a reduction in the extent of violations,

[14] Analogous to the tax case, the introduction of some heterogeneity in current abatement costs might imply that adopters hold more permits than non-adopters if the new technology is not more efficient than all the current technologies available. However, the main results in this section remain the same since both adopters and non-adopters improve their compliance behavior due to the drop in equilibrium permit price given the availability of a new technology.

[15] Taking the total derivative of $p = \pi\phi'(v)$with respect to price, it is easy to derive $\frac{\partial v}{\partial p} = \frac{1}{\pi\phi''(v)}$, which, given the properties of the penalty function, is positive (see Stranlund and Dhanda (1999)).

it follows that *for a given monitoring probability*, violations are decreasing in the rate of adoption. □

Therefore, technology adoption does provide incentives to improve compliance when firms are regulated by TEPs. This is an important difference between uniform taxes and TEPs, which relates to the fact that taxes are fixed by the regulator while the equilibrium permit price will vary with the rate of technology adoption and the enforcement strategy.[16]

Note from Eq. (8) that the equilibrium permit price is linked not only to the adoption rate but also to the monitoring probability, π. Changes in the monitoring effort might therefore affect the rate of technology adoption and hence the extent of violation.

4 Monitoring probability and effects on technology adoption

As stated in the beginning of the present paper, the rate of adoption is determined by the difference between the expected costs of abatement and compliance under the current and the new technology. For the case of uniform taxes, these costs are expressed as:

$$\mu_A(t,\pi,\phi) = \theta c(e_A(t)) + t r_A(t,\pi,\phi) + \pi\phi(e_A(t) - r_A(t,\pi,\phi)), \quad (10)$$

$$\mu_{NA}(t,\pi,\phi) = c(e_{NA}(t)) + t r_{NA}(t,\pi,\phi) + \pi\phi(e_{NA}(t) - r_{NA}(t,\pi,\phi)). \quad (11)$$

Proposition 3 *When uniform emission taxes are used, the adoption rate does not depend on the enforcement strategy but is determined only by the tax rate.*

Proof 3 Subtracting (10) from (11) and considering that $r_{NA} - r_A = e_{NA} - e_A$, the adoption rate can be characterized as follows:

$$\lambda^{TAX} = \psi\,\{c(e_{NA}(t)) - \theta c(e_A(t)) + t\,[e_{NA}(t) - e_A(t)]\} - \zeta. \quad (12)$$

The term $c(e_{NA}(t)) - \theta c(e_A(t))$ in (12) gives account of the decrease in abatement costs when the firm adopts the new technology, and $t\,[e_{NA}(t) - e_A(t)]$ gives account of the difference in tax payment on reported emissions without and with adoption. From Eq. 12, it is straightforward that adoption savings are increasing in the tax rate but are not affected by monitoring probability or sanction structure. The enforcement strategy therefore does not affect the rate of adoption, since neither the emissions level nor the tax rate is a function of monitoring probability or of the sanction structure. □

Analogously to the case of taxes, the rate of adoption in the case of TEPs is determined by the difference between the expected costs of abatement and compliance under the current and the new technology.

[16] In a setting of perfect compliance, the adoption incentives provided by the policies will coincide when the regulator is forward looking and adjusts the level of the environmental policies in response to the advent of the new technology (Requate and Unold 2003; Coria 2009a). Nevertheless, since in the model of this paper there is imperfect compliance, the level of the tax will be higher than the permit price.

$$\mu_A(p(\pi,\lambda),\pi) = \theta c(e_A(p(\pi,\lambda))) + p(\pi,\lambda)l_A(p(\pi,\lambda),\pi) + \pi\phi(e_A(p(\pi,\lambda)) - l_A(p(\pi,\lambda),\pi)), \quad (13)$$

$$\mu_{NA}(p(\pi,\lambda),\pi) = c(e_{NA}(p(\pi,\lambda))) + p(\pi,\lambda)l_{NA}(p(\pi,\lambda),\pi) + \pi\phi(e_{NA}(p(\pi,\lambda)) - l_{NA}(p(\pi,\lambda),\pi)). \quad (14)$$

Proposition 4 *When tradable emissions permits are used, the adoption rate is an increasing function of the monitoring probability.*

Proof 4 Subtracting (13) from (14), the adoption rate can be characterized as follows:

$$\lambda^{TEP} = \psi \left\{ \begin{array}{l} c\left(e_{NA}\left(p\left(\pi,\lambda^{TEP}\right)\right)\right) - \theta c\left(e_A\left(p\left(\pi,\lambda^{TEP}\right)\right)\right) \\ +p\left(\pi,\lambda^{TEP}\right)\left[l_{NA}\left(p\left(\pi,\lambda^{TEP}\right),\pi\right) - l_A\left(p\left(\pi,\lambda^{TEP}\right),\pi\right)\right] \end{array} \right\} - \zeta. \quad (15)$$

The terms in Eq. 15 give account of the decrease in abatement costs and the difference in expenditure on permits when the firm adopts the new technology.

Since the permit price and the demand for permits by firms with and without the new technology are increasing functions of the monitoring probability, the rate of technology adoption depends on this parameter as well. However, given that the equilibrium permit price is, at the same time, a function of the rate of technology adoption, $p(\pi,\lambda^{TEP})$ and $\lambda^{TEP}(\pi, p)$ are therefore endogenous variables simultaneously determined in our model by Eqs. 8 and 15.

Formally, by taking the total derivative of Eq. 15 with respect to monitoring probability, we observe that the monitoring probability affects the adoption savings and hence the rate of adoption through two channels. First, it increases the demand for permits of the firms with and without the new technology. We call this the "direct effect." Second, it changes the equilibrium permit price and therefore affects the components of the adoption savings function (i.e., abatement costs and expenditures on permits). We call the "price effect." These two effects are shown in Eq. 16.

$$\frac{1}{\psi}\frac{d\lambda^{TEP}}{d\pi} = \underbrace{p\left[\frac{\partial l_{NA}}{\partial\pi} - \frac{\partial l_A}{\partial\pi}\right]}_{\text{Direct Effect}} + \underbrace{\begin{array}{l} \frac{dp}{d\pi}\left\{c'_{NA}\frac{\partial e_{NA}}{\partial p} - \theta c'_{A}\frac{\partial e_A}{\partial p} + [l_{NA} - l_A]\right\} \\ +\frac{dp}{d\lambda}\frac{d\lambda^{TEP}}{d\pi}\left\{c'_{NA}\frac{\partial e_{NA}}{\partial p} - \theta c'_{A}\frac{\partial e_A}{\partial p} + p\frac{\partial l_{NA}}{\partial p} - p\frac{\partial l_A}{\partial p} + [l_{NA} - l_A]\right\} \end{array}}_{\text{Price Effect}}. \quad (16)$$

Since in equilibrium, an increase in the monitoring probability affects the demand for permits with and without the new technology to the same extent, i.e., $\frac{\partial l_{NA}}{\partial\pi} = \frac{\partial l_A}{\partial\pi}$, the direct effect is equal to zero. Additionally, the price effect in Eq. 16 can be simplified considering that $c'_{NA} = \theta c'_A = -p$ and that the change in the extent of violation as a response to changes in the permit price is the same with and without the new technology, i.e., $\frac{\partial e_A}{\partial p} - \frac{\partial l_A}{\partial p} = \frac{\partial e_{NA}}{\partial p} - \frac{\partial l_{NA}}{\partial p}$ (see Appendix A). Therefore, Eq. 16 can be re-written as:

$$\frac{d\lambda^{TEP}}{d\pi}\left[\frac{1}{\psi} - [l_{NA} - l_A]\frac{dp}{d\lambda}\right] = \frac{dp}{d\pi}[l_{NA} - l_A]. \tag{17}$$

Since the equilibrium permit price is an increasing function of the monitoring probability (see Appendix B) and a decreasing function of the rate of technology adoption, and given that a firm that adopts the new technology reduces the number of permits it holds in equilibrium, i.e., $l_{NA} > l_A$, it follows that the rate of technology adoption is an increasing function of the monitoring probability. □

If the regulator increases the stringency of the monitoring strategy, and by doing so increases the equilibrium permit price, firms that adopt the new technology enjoy larger savings due to the reduction in the use of permits.[17]

Propositions 3 and 4 demonstrate another important difference between taxes and TEPs. In contrast to uniform taxes, the rate of technology adoption is an increasing function of monitoring probability when the regulation takes the form of TEPs. This result has interesting implications for the comparison of the adoption incentives provided by these two policy instruments. Indeed, it is well known in the literature that adoption of advanced abatement technologies depreciates the permit prices while the tax is fixed by the regulator. Since firms with higher costs of adoption can free ride on the decreased permit price caused by other firms' adoption, the private gains from adopting the technology under permits are reduced and so is the rate of adoption. However, the results in this section show that by increasing the monitoring probability, the regulator can offset the permit price depreciation while encouraging firms to reduce the extent of violation. Therefore, under permits, a more stringent enforcement strategy may increase the rate of adoption of new technology while still providing firms with larger incentives to increase compliance than taxes. This is good news for the regulators since by choosing TEPs, the continuous development of cleaner technologies may imply a larger rate of compliance with environmental regulations.

4.1 Monitoring probability and the extent of violation under TEPs

Clearly, the extent of violation also changes in response to increased monitoring probability. However, since in this setting the equilibrium permit price and the rate of

[17] It is worth mentioning that although we have assumed that firms are homogeneous in terms of current abatement costs, such an assumption could be removed without affecting the validity of our results. Indeed, let us assume for a moment that there are two groups of firms (group 1 and group 2) that differ in terms of current abatement costs ($c_1(e)$ and $c_2(e)$) and that adoption is profitable only for firms in group 1 ($c_1(e) > \theta c_1(e) > c_2(e)$; $\mu_{NAI} - \mu_{A1} \geq k_1, \mu_{NA2} - \mu_{A2} < k_2$). In such a setting, firms in group 1 (adopters) will hold more permits than firms in group 2 (non-adopters) in equilibrium, i.e., $l_{A1} > l_{NA2}$. However, Proposition 4 remains valid since the second term on the right-hand side in Eq. 17 is giving account of the reduced demand of permits by firms adopting the new technology. Since the new technology allows firms in group 1 to abate emissions to a lower cost, the use of permits by firms in group 1 decreases after adopting the new technology, i.e., $l_{NA1} > l_{A1}$.

adoption are endogenous, the monitoring probability affects the extent of the violation through several channels, as is clear in Eq. 18. Taking the total derivative of $v(\pi, p(\pi, \lambda^{TEP}))$ with respect to π yields:

$$\frac{dv}{d\pi} = \frac{\partial v}{\partial \pi} + \frac{\partial v}{\partial p}\frac{\partial p}{\partial \pi} + \frac{\partial v}{\partial p}\frac{\partial p}{\partial \lambda^{TEP}}\frac{\partial \lambda^{TEP}}{\partial \pi}. \tag{18}$$

Firstly, there is a direct effect that pushes the extent of violation down given that the expected cost of infringing the regulation increases $\frac{\partial v}{\partial \pi} < 0$. Secondly, there is an indirect effect through the permit price that increases the extent of violation: when the monitoring probability increases, so does the price of permits, increasing the marginal benefit of violation, $\frac{\partial v}{\partial p}\frac{\partial p}{\partial \pi} > 0$. Thirdly, there is an indirect effect through the adoption rate and the permit price. Increasing the monitoring probability leads to a higher adoption rate, which at the same time lowers the permit price, causing a decrease in the extent of violation, $\frac{\partial v}{\partial p}\frac{\partial p}{\partial \lambda^{TEP}}\frac{\partial \lambda^{TEP}}{\partial \pi} < 0$.

All the effects are negative except the indirect effect through the permit price. However, its size is lower than the absolute value of the direct effect $\left|\frac{\partial v}{\partial \pi}\right| > \left|\frac{\partial v}{\partial p}\frac{\partial p}{\partial \pi}\right|$ (see Appendix C for a demonstration). Murphy and Stranlund (2006) refer to the first two effects as the direct and the market effects. They conducted laboratory experiments to examine the two effects on pollution and compliance decisions, and their experimental data is consistent with the theoretical prediction that the direct effect is always larger, hence increased enforcement results in a lower extent of violations.

Therefore, the violation extent is decreasing in monitoring probability. Although this is a standard result in the literature, our analysis uncovers the fact that the deterrent effect of the monitoring effort is reinforced by the effect of the technology adoption rate on the extent of violations.

5 Conclusions and policy implications of our results

In this paper, we analyze the effects of the interaction between incomplete enforcement and technology adoption under each of two alternative policy instruments: uniform taxes and tradable emissions permits (TEPs). Our model is simple in many ways. We assume that firms are homogeneous in terms of current abatement costs and focus on the analysis of interior solutions, i.e., firms provide positive reports of their emissions under taxes and hold a number of permits that is higher than zero. In particular, we show three main results:

First, compliance incentives are affected by the technology adoption rate under TEPs but not under taxes. As is already well known from the technology adoption literature, in our model the adoption of advanced abatement technologies depreciates the price of emission under TEPs while it is fixed by the regulator under uniform taxes. Given that the equilibrium price of emissions represents the marginal benefits from adoption, such benefits are affected by the rate of technology adoption only under TEPs. The greater the rate of technology adoption, the lower the equilibrium permit price, and therefore the lower the marginal benefits of violation. This of course alters the compliance incentives under TEPs in the presence of technology adoption, leading to a reduction in individual violations under TEPs. In contrast, under uniform taxes, the incentive to comply remains the same as in the absence of technology adoption since the emissions price is set by the regulator and is not depreciated by the technology adoption.

Second, the adoption rate under taxes is not influenced by the enforcement strategy while the adoption rate under TEPs is an increasing function of monitoring probability. This is, again, related to the fact that the pollution price does not change under an emissions tax while under TPEs an increased monitoring pressure results in a higher permit price. When the permit price increases, the savings from adoption are higher and therefore the rate of technology adoption increases. This means that if under TEPs the regulator wants to stimulate use of a new abatement technology, he/she may use the monitoring probability as a tool. This decision of course depends on the benefits of increasing adoption versus the costs of increasing monitoring pressure.

Third, our paper shows that the extent of violation is decreasing in monitoring pressure. Although this is a standard result in the literature, our analysis reveals that the interaction between monitoring probability and rate of technology adoption is reinforced by the effect that the technology adoption rate has on the extent of violations. Previous literature has not explored this reinforcement effect. This is good news for an enforcement regulator who can achieve a higher reduction in the extent of violation with an increase in enforcement monitoring in the presence of technology adoption than in the absence of technology adoption. This lowers the enforcement costs of achieving a certain compliance level.

Although our paper shows several differences between uniform taxes and TEPs when technological adoption and imperfect compliance are present, the social welfare obtained with each policy instrument is not unambiguous. The ranking of the two instruments will depend on the relative weight given to emission damages compared to elements such as abatement costs, investment costs and expected enforcement costs. Furthermore, there are some other aspects that in practice do affect the welfare comparison but that are outside the present analysis, e.g., differences in distributional consequences and differences in political acceptance of the instruments. For example, the stringency of the tax and the TEP system is subject to a complicated political economy process. The regulator may know that permit prices will fall during the course of a TEPs program. He/she may therefore make the TEP scheme tougher than he/she would with a tax scheme, as a counteracting measure.

Appendix A

Effect of monitoring probability on rate of technology adoption under TEPs

Equation 16 can be written as:

$$\frac{1}{\psi}\frac{d\lambda^{TEP}}{d\pi} = p\left[\frac{\partial l_{NA}}{\partial \pi} - \frac{\partial l_A}{\partial \pi}\right] + \frac{dp}{d\pi}\left\{-p\left[\frac{\partial e_{NA}}{\partial p} - \frac{\partial e_A}{\partial p} - \frac{\partial l_{NA}}{\partial p} + \frac{\partial l_A}{\partial p}\right]\right\}$$
$$+\frac{dp}{d\lambda}\frac{d\lambda^{TEP}}{d\pi}\left\{p\left[\frac{\partial e_{NA}}{\partial p} - \frac{\partial e_A}{\partial p} - \frac{\partial l_{NA}}{\partial p} + \frac{\partial l_A}{\partial p}\right]\right\}$$

$$+ [l_{NA} - l_A] \left[\frac{\partial p}{\partial \pi} + \frac{\partial p}{\partial \lambda} \frac{\partial \lambda}{\partial \pi} \right].$$

Equation 16 can be simplified in the following way: Taking the partial derivative of the equilibrium condition $\pi\phi'(e_A - l_A) = \pi\phi'(e_{NA} - l_{NA})$ with respect to monitoring probability and rearranging terms, it is possible to show that the change in permit demand as a response to a changed monitoring probability is the same for adopters and non-adopters: $\frac{\partial l_A}{\partial \pi} = \frac{\partial l_{NA}}{\partial \pi}$. Therefore, the direct effect on permit demand cancels out.

Taking the partial derivative of $\pi\phi'(e_A - l_A) = \pi\phi'(e_{NA} - l_{NA})$ with respect to permit price, considering that $\frac{\partial c(e_{NA})}{\partial e_{NA}} = \theta \frac{\partial c(e_A)}{\partial e_A} = p$, and rearranging terms, it is possible to show that the change in the extent of violation in response to a change in the equilibrium permit price is the same for adopters and non-adopters: $\frac{\partial v_{NA}}{\partial p} = \frac{\partial v_A}{\partial p}$. This can be expressed as $\frac{\partial e_A}{\partial p} - \frac{\partial e_{NA}}{\partial p} = \frac{\partial l_A}{\partial p} - \frac{\partial l_{NA}}{\partial p}$.

Replacing and rearranging, Eq. 16 becomes:

$$\frac{d\lambda^{TEP}}{d\pi} \left[\frac{1}{\psi} - [l_{NA} - l_A] \frac{dp}{d\lambda} \right] = \frac{dp}{d\pi} [l_{NA} - l_A].$$

Appendix B

Total effect of monitoring probability on equilibrium permit price

The permit price that clears the market is given by the equilibrium between supply and total permit demand:

$$L = \lambda(p(\pi)) l_A(p(\pi), \pi) + [1 - \lambda(p(\pi))] l_{NA}(p(\pi), \pi).$$

Taking the total derivative of the market equilibrium equation with respect to monitoring probability and rearranging terms yields:

$$0 = \underbrace{\left[\lambda \frac{\partial l_A}{\partial \pi} + [1-\lambda] \frac{\partial l_{NA}}{\partial \pi} \right]}_{\text{Direct effect}} + \underbrace{\left[\lambda \frac{\partial l_A}{\partial p} + [1-\lambda] \frac{\partial l_{NA}}{\partial p} \right] \frac{dp}{d\pi}}_{\text{Indirect demand effect}} + \underbrace{[l_A + l_{NA}] \left[\frac{\partial \lambda}{dp} \frac{dp}{d\pi} \right]}_{\text{Indirect adoption effect}}.$$

Monitoring probability influences total permit demand via three channels.

(i) **The direct effect (DE)**, which shows how the permit demand of both adopters and non-adopters is directly affected by changes in the monitoring probability,
(ii) **The indirect demand effect (IDE)**, which reflects the influence of monitoring probability on the permit demand of adopters and non-adopters via permit price, and
(iii) **The indirect adoption effect (IAE)**, which indicates how the permit demand changes due to the influence of monitoring probability on the permit price and consequently on the adoption rate. Rewriting:

$$0 = \underbrace{\left[\lambda \frac{\partial l_A}{\partial \pi} + [1-\lambda] \frac{\partial l_{NA}}{\partial \pi}\right]}_{\text{Direct effect}>0} + \frac{dp}{d\pi} \left[\underbrace{\lambda \frac{\partial l_A}{\partial p} + [1-\lambda] \frac{\partial l_{NA}}{\partial p}}_{<0} + \underbrace{[l_A - l_{NA}] \frac{\partial \lambda}{\partial p}}_{<0} \right].$$

For the right-hand side of this equation to be zero, the permit price must increase with monitoring probability.

Appendix C

Effects of monitoring probability on extent of violation

From Eq. 18 we know that two of the effects of monitoring probability on extent of violation are called the direct effect (DE) $\frac{\partial v}{\partial \pi} < 0$ and the indirect effect through the permit price (IEP) which increases the extent of violation, $\frac{\partial v}{\partial p}\frac{\partial p}{\partial \pi} > 0$.

From $p = \pi \phi'(v)$ we get that $\frac{\partial v}{\partial p} = \frac{1}{\pi \phi''(v)}$ and $\frac{\partial v}{\partial \pi} = \frac{-\phi'(v)}{\pi \phi''(v)}$ and therefore $\frac{\partial v}{\partial \pi} = \frac{\partial v}{\partial p}\phi'(v)$.

Summing up DE and IEP, $DE + IEP = \frac{\partial v}{\partial p}\left[\frac{\partial p}{\partial \pi} - \phi'(v)\right]$.

To explore the sign of this equation, let us first derive an expression for $\frac{\partial p}{\partial \pi}$.

For a given technology adoption rate, the change in equilibrium permit price when the monitoring probability changes is given by:

$$\frac{\partial p}{\partial \pi} = \phi'(v) + \pi \phi''(v) \left[\frac{\partial v}{\partial \pi}\right].$$

This implies that $DE + IEP = \underbrace{\frac{\partial v}{\partial p}}_{(+)} \left[\underbrace{\pi \phi''(v) \frac{\partial v}{\partial \pi}}_{(-)} \right]$. Therefore, $DE + IEP < 0$.

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