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Taxes, Permits and the Adoption of Abatement Technology under Imperfect Compliance

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ABSTRACT

This paper analyzes the effects of the choice between price-based and quantity-based emission regulations on compliance incentives and social welfare in the presence of incomplete enforcement and technology adoption. We show that in contrast to taxes, the extent of violations under tradable emission permits (TEPs) decreases with the rate of technology adoption. However, in terms of welfare, the ranking of the instruments is not so straightforward: taxes induce lower emission damages while TEPs induce lower abatement, investment, and expected enforcement costs. Thereby, the overall ranking depends on the extent to which these effects offset each other.

Key words. Technological adoption, environmental policy, imperfect compliance, enforcement, social welfare.

JEL classifications: L51, Q55, K32, K42.

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I. INTRODUCTION

In the long run, technological change is considered the primary solution for 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). 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 transferable emission permits, or TEPs (quantity-based regulation).[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 obey environmental regulations and enforcement of policies is costless. However, reality generally differs from this assumption. In some cases a fraction of firms do not comply with an environmental regulation as a result of incomplete enforcement, and the expected enforcement costs can be quite significant.

The interaction between incomplete enforcement and technology adoption can be thought of in two ways: (1) Incomplete enforcement, and therefore the possibility that firms do not comply with a regulation, may influence the profits of firms from technology adoption and the adoption decision, and (2) 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. Therefore, inclusion of technology adoption considerations into a comparison of different policy instruments,

[1] Downing and Prince (1986), Milliman and Prince (1989), Jung, Krutilla and Boyd (1996), Keohane (1999), Kennedy and Laplante (1999), and Montero (2002).

in a world of imperfect compliance, may change the ranking of the instruments since such considerations induce different adoption-compliance behaviors.

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, (ii) how technology adoption is affected by enforcement parameters such as probability of being monitored and structure of sanctions imposed in case non-compliance is detected, and (iii) how the ranking of price-based and quantity-based policies using a social welfare measure is affected by the adoption-compliance output.

To our knowledge, the interaction between technology adoption and imperfect compliance and its effects has not yet been directly addressed. Rouseeau and Proost (2005) include rule making, implementation, monitoring, and enforcement costs for both firms and the government into the cost comparison of policy instruments. While they compare emission taxes, emission standards, and technology standards, they do not compare instruments within the market-based regulations as is the main focus of the present paper. Montero (2002) studies the impact of incomplete enforcement of a regulation on the choice between price and quantity instruments, and shows that both instruments perform equally good as long as the benefit and cost curves are known with certainty. However, if these curves are uncertain to the regulator, the quantity instrument performs relatively better than the price instrument.[2] Macho-Stadler (2006) compares total final emission level

[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 priced 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).

achieved with standards and with market-based instruments when imperfect compliance is present, and finds that taxes are superior to the other instruments. There are two important differences between her analysis and the present paper: First, when comparing market-based instruments, she considers the optimal audit policy to be one that minimizes total emissions subject to an enforcement budget constraint. We, on the other hand, consider that the enforcement authority's goal is to minimize the extent of violations. Second, she does not consider the effect of an enforcement policy on technology adoption, while we do.

In line with the previous literature on technology adoption (Milliman and Price, 1989; Jung et al., 1996; Requate 1995, 2001, 2003, and 2005), our results suggest that permits do not provide higher adoption incentives than emission taxes. However, under permits, the fall in the 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. Thus, in contrast to taxes, the extent of violations under TEPs decreases with the rate of adoption as well as with the enforcement efforts. In terms of welfare, the ranking of instruments is not straightforward. On one hand, there is less damage from emissions with taxes. On the other hand, abatement costs, investment costs, and expected enforcement costs under taxes are never lower than when using TEPs. Thereby, the overall and final ranking depends on the extent to which these effects offset each other.

The paper is organized as follows. Section 2 presents the model of adoption and Section 3 introduces the compliance behavior under emission taxes and TEPs. Section 4 compares these policies under three criteria: (1) the extent of environmental violation, (2) the required enforcement strategy for perfect compliance, and (3) the social welfare achieved under each scheme. Finally, Section 5 offers some concluding remarks.

II. ADOPTION INCENTIVES

We consider a competitive industry of size one consisting of a group of risk-neutral firms that are homogeneous in abatement costs. In the absence of environmental regulation, each firm emits one unit of a homogeneous pollutant. The abatement costs of a firm are a function of the firm's emissions level, e, and are denoted $c(e)$[3]. The abatement cost function is strictly convex and decreasing in emissions: $c'(e) < 0; c''(e) > 0$. Emissions generate damages represented by, the also strictly convex, function $D(e)$, with $D'(e) > 0$, $D''(e) > 0$.[4] 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.[5]

A new technology arrives and firms must decide whether or not to invest. The new technology allows firms to abate emissions at a lower cost, given by $kc(e)$, where $k \in (0,1)$ is a parameter that represents the drop in abatement cost.[6] Buying and installing the new technology implies a fixed cost that differs among firms. A fraction α of the firms in the industry, from now on called Group 1, have a lower fixed

[3] Henceforth, for the sake of notation we will use parentheses to denote a function and brackets to denote multiplication.

[4] Total abatement cost can also be denoted in terms of abatement level, $c(a_i)$. The function is then strictly convex and increasing in abatement, $c'(a) > 0; c''(a) > 0$. A reduction in damage from emissions can also be interpreted as a benefit from abatement. Abatement generates a concave benefit function, $B(a_i); B'(a) > 0; B''(a) < 0$.

[5] It is not necessary to assume that the targeted emission level is set at the optimum level, i.e., that it satisfies the conditions where the marginal damage from emissions equals the marginal cost of pollution abatement. The authority could have set a standard for aggregate emissions and decided to use a price-based or quantity-based instrument to achieve this level in an efficient way. However, the analysis of policy ranking would be affected by the chosen target emission level as is presented in subsequent sections.

[6] Since the interval in which k belongs is open, the new technology always reduces the abatement costs but never makes them equal to zero, i.e., there is no perfectly clean technology.

investment cost, $\underline{k}$. Firms in Group 2, which corresponds to a fraction 1-α of the industry, each have to invest a higher amount, represented by $\overline{k}$, if they want to adopt the new technology ($\underline{k} < \overline{k}$).

Firms can be regulated through uniform emission taxes or TEPs. In an emission tax system, firms are required to self-report their emissions. A firm is noncompliant if it attempts to evade some part of its tax responsibilities by reporting an emission level that is lower than its true level. In the case of regulation using permits, a firm should buy one permit for each unit of emissions. A firm that buys fewer permits than its emissions is out of compliance.

Let EC_A and EC_{NA} be the total expected costs of abatement and compliance for adopters and non-adopters of the new technology, respectively. These costs are composed of abatement costs and expected fines in case a firm is caught violating. Let $\Delta EC = EC_{NA} - EC_A$ be the expected savings from adoption. Firms will adopt the new technology if adoption implies savings larger than or equal to its fixed investment cost.

Let λ denote the fraction of firms adopting the new technology. There are three possible values for λ depending on the extent to which adoption savings offset the adoption costs:

(i) Zero technology adoption. No firm will adopt the technology if adoption savings do not offset the lowest fixed investment cost; i.e., if $\Delta EC < \underline{k}$, then adoption is not profitable for any firms and $\lambda = 0$.

(ii) Partial technology adoption. If adoption savings range from $\underline{k}$ to $\overline{k}$, then adoption is profitable only for firms in Group 1; i.e., $\lambda = \alpha$ if $\underline{k} \leq \Delta EC < \overline{k}$.

(iii) Universal technology adoption. If adoption savings are larger than the highest investment costs, then all firms in the industry will adopt the new technology; i.e., $\lambda = 1$ if $\Delta EC \geq \overline{k}$.

Notice that since adoption savings depend on the expected costs of abatement and compliance, the rate of adoption varies with the stringency of the policy, with the choice of policy instrument, and with the monitoring and enforcement design.

III. COMPLIANCE BEHAVIOR AND TECHNOLOGICAL ADOPTION.

In line with Malik (1990), Stranlund and Dhanda (1999), Stranlund and Chávez (2000), and Chávez et al. (2008), we assume that the regulator cannot observe a firm's emissions unless costly monitoring is undertaken. Let π denote the probability that the regulator audits a firm. We assume that π is known among firms and that once the regulator monitors a firm, it is able to determine the firm's compliance status perfectly. We assume that the probability of a firm being monitored is exogenous and uniform across firms.[7] If the monitoring reveals that the firm is non-compliant, it faces the penalty $F(v)$, where v is the extent of the violation. This is a strictly convex function in the level of violation: $F'(v) > 0; F''(0)$.[8] For zero violation, the penalty is zero *F(0)=0*, but the marginal penalty is greater than zero: *F'(0)>0*.[9]

[7] As Sandmo (2002) notes, the assumption of an exogenous probability of being monitored is a simplification. It is more realistic to assume that monitoring probability is a function of regulated firms' actions. We leave this point for future work.

[8] Standlund, Chávez, and Villena (2008) mention some authors who assume that the penalty function is strictly convex: Harford, 1978, 1987; Sandmo, 2002; Cremer and Gahvari, 2002; Macho-Stadler and Perez Castrillo, 2006. Strandlund, Chávez, and Villena 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. If the price of emissions is lower than the expected marginal fine (constant), a firm will report all of its emissions, while if the price of emissions is higher than the expected marginal fine, it will not report any of its emissions (see Sandmo, 2002, and Heyes, 2000).

[9] In order to allow perfect compliance to be a possible choice, we do not rule out the possibility that the marginal penalty when violation is zero is higher than the marginal abatement cost evaluated at the required emission level.

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

Stage 1. The environmental authority 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 to the availability of the new technology.[10] The enforcement strategy is exogenously determined and consists of a probability of being monitored and a sanction scheme. The enforcement strategy is set regardless of the regulatory scheme selected by the environmental authority; i.e., firms face the same enforcement policy independent of the regulation mechanism.[11]

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 old and the new technology.[12]

The next subsections analyze the rate of adoption and the adopters' and non-adopters' compliance behavior under both market-based instruments.

3.1 Uniform Emission Tax

[10] Requate and Unold (2003) analyze incentives through environmental-policy instruments to adopt advanced abatement technologies when the regulator anticipates new technologies, and show that taxes and permits are equivalent if the regulator moves just after firms have invested. If, by contrast, the regulator moves prior to the firms' investment decisions, only permits will succeed in inducing first best outcomes.

[11] 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. However, in a subsequent section of the present paper we will consider the case where the monitoring probability is set to guarantee perfect compliance according to the selected policy instrument.

[12] Authors like Lai et al. (2003) argue that a surprisingly large number of firms comply with pollution regulations even though the expected penalties for non-compliance are low. They establish environmental social norm models that consider collective environmental actions among firms. Our model does not include the effect of social norms or non-monetary sanctions in case of non-compliance; instead we consider the expected monetary fines imposed by the enforcement authority to be the only costs of non-compliance.

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 makes a truthful report, 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 liability 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, $v_i = e_i - r_i$. If the firm is caught in violation, a penalty is imposed according to the penalty function explained above.

Adopters select the emission and report levels that minimize their expected costs of abatement and compliance:[13]

(1) $$Min_{e,r} kc(e) + tr + \pi F(e-r)$$

$$s.t.\ e - r \geq 0 .$$

Notice that the constraint in the optimization problem reflects the fact that there are no economic incentives to over-report emission levels. The Lagrange equation for (1) is $\varphi = kc(e) + tr + \pi F(e-r) - \beta\left[e-r\right]$ and the Kuhn-Tucker conditions, which are necessary and sufficient to determine a firm's optimal choices of emissions and permits are:

(2) $$\frac{\partial \varphi}{\partial e} = kc'(e) + \pi F'(e-r) - \beta = 0 ,$$

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

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

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[13] The problem of the firms that do not adopt the new abatement technology is analogous to problem (1); the main difference is that the abatement costs for these kinds of firms are given by $c(e)$ instead of $kc(e)$.

Proposition 1: *With uniform emission taxes, adopters' actual and reported levels of emissions are lower than those of non-adopters. In addition, the actual level of emissions of firms is independent of the enforcement strategy while the reported level of emissions depends on the monitoring probability and on the sanctions structure.*

Proof 1: To obtain a firm's emission level, combine (1) and (2) to get $kc'(e)+t=0$. 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,

(5) $$e_A(t) = \{e \mid kc'(e)+t=0\},$$

(6) $$e_{NA}(t) = \{e \mid c'(e)+t=0\}.$$

Since there is a uniform tax rate, in equilibrium firms' marginal abatement costs are equal irrespective of their adoption status: $c'(e_{NA}) = kc'(e_A)$. Given that $k \in (0,1)$, it is necessary that $c'(e_{NA}) < c'(e_A)$, which is only possible (given the properties of the abatement cost function) if $e_{NA} > e_A$. Note that since the tax is exogenous and not influenced by the enforcement strategy, the actual emissions of firms do not depend on the parameters of the enforcement problem, which is in line with Harford (1978) and the standard in the literature.

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 (4) implies that $\beta=0$ and $\frac{\partial \varphi}{\partial r} = t - \pi F'(e-r) = 0$. The report levels of adopters and non-adopters firms are, respectively,

(7) $$r_A(t,\pi,F) = \{r \mid t - \pi F'(e_A - r_A) = 0\},$$

(8) $r_{NA}(t,\pi,F)=\left\{r\middle| t-\pi F'(e_{NA}-r_{NA})=0\right\}$.

Equations (7) and (8) 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 $e_A - r_A = e_{NA} - r_{NA}$. Notice that $r_{NA} > r_A$ since $e_{NA} > e_A$. Hence, the emissions reported by adopters are lower than the emissions reported by non-adopters. Q.E.D.

Proposition 2: *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 2: The size of violation is given by $v(t,\pi,F)=e(t)-r(t,\pi,F)$. From (7) and (8), we obtain that $\pi F'(e_A - r_A)=\pi F'(e_{NA}-r_{NA})$, and since the enforcement strategy is exogenously set and is independent of the adoption status, it is straightforward to observe that $e_A - r_A = e_{NA} - r_{NA}$. Q.E.D.

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 law are the same for all firms, the extent of the violation is the same regardless of adoption status. Then, technological adoption does not provide additional incentives for compliance when emission taxes are used.

The expected costs of abatement and compliance for adopters and non-adopters are expressed as:

(9) $EC_A(t,\pi,F)=kc(e_A(t))+tr_A(t,\pi,F)+\pi F(e_A(t)-r_A(t,\pi,F))$,

(10) $EC_{NA}(t,\pi,F)=c(e_{NA}(t))+tr_{NA}(t,\pi,F)+\pi F(e_{NA}(t)-r_{NA}(t,\pi,F))$.

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 (9) from (10), we obtain the adoption savings as follows:

(11) $$\Delta EC = c(e_{NA}(t)) - kc(e_A(t)) + t\left[r_{NA}(t,\pi,F) - r_A(t,\pi,F)\right].$$

Since $r_{NA}(t,\pi,F) - r_A(t,\pi,F) = e_{NA}(t) - e_A(t)$, equation (11) can be re-written as:

(12) $$\Delta EC = c(e_{NA}(t)) - kc(e_A(t)) + t\left[e_{NA}(t) - e_A(t)\right].$$

The first and second terms in (11) give account of the decreasing in abatement costs when the firm adopts the new technology. The third term gives account of the difference in tax payment on reported emissions without and with adoption. Note that adoption savings increase with the level of the tax and the extent of the reduction in abatement costs (i.e., they decrease in k). Incomplete enforcement 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 sanctions structure. Q.E.D

3.3 Tradable Emissions Permits

A firm regulated by TEPs can abate a fraction of its emissions and buy permits to compensate 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.[14]

In the presence of imperfect compliance, polluters have an incentive to buy a quantity of permits lower than e_i to reduce their expenditure in permits. Let l denote the quantity of permits held by a firm in equilibrium and l^0 be the number of

[14] For the sake of comparison between TEPs and uniform taxes, we say that the quantity of permits initially issued by the authority corresponds to the environmental target used by the authority to set the tax rate.

emissions permits, if any, initially allocated to a firm. A firm is noncompliant 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 $v = e - l$.[15]

The permit price is endogenously determined by the violation level and technology adoption rate. The larger the extent of violation, the lower the demand for permits and the lower the permit price. On the other hand, the diffusion of the new technology lowers the aggregate marginal abatement costs and therefore lowers the permit price. Since in the model the rate of adoption can take three discrete values, let us denote the price when no firm adopts the new technology p_{NA}, the price with partial adoption p_{PA}, and the price with universal adoption p_{UA}. By construction, p_{NA} coincides with the tax level set by the authority in a scenario of perfect compliance. It holds that $p_{NA} > p_{PA} > p_{UA}$ as will be shown in subsequent paragraphs.

Adopters select the emission level and demand for permits that minimize total expected costs:

(13) $$Min_{e,l}\, kc(e) + p\left[l - l^0\right] + \pi F(e - l),$$

$$s.t.\ \ e - l \geq 0.$$

The Lagrange equation for (13) is $\varphi = kc(e) + p\left[l - l^0\right] + \pi F(e-l) - \beta\left[e - l\right]$ and the Kuhn-Tucker conditions, which are necessary and sufficient to determine the firm's optimal choices of emissions and permits, are:

(14) $$\frac{\partial \varphi}{\partial e} = kc'(e) + \pi F'(e-l) - \beta = 0,$$

(15) $$\frac{\partial \varphi}{\partial l} = p - \pi F'(e-l) + \beta = 0,$$

[15] We assume that the enforcement authority keeps perfect track of each firm's permit holding but can not observe emissions without a costly audit. 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.

(16) $\dfrac{\partial \varphi}{\partial \beta} = e - l \geq 0; \beta \geq 0; \beta[l - e] = 0$.

Proposition 4: *With tradable emission permits, the actual emissions and the quantity of permits that adopters hold in equilibrium are lower than the actual emissions and the quantity of permits that non-adopters hold in equilibrium. In addition, the level of emissions of firms is independent of the enforcement strategy while the quantity of permits that firms hold in equilibrium depends on the permit price and on the monitoring probability and sanctions structure.*

Proof 4: From the solution to the optimization problem, the level of emissions for adopters and non-adopters are, respectively:

(17) $e_A(p) = \{e | kc'(e) + p = 0\}$,

(18) $e_{NA}(p) = \{e | c'(e) + p = 0\}$.

Equations (17) and (18) state that in equilibrium, each firm chooses its emissions such that the marginal abatement cost equals the permit price. Since the adopters' marginal abatement cost is lower, $e_{NA}(p) > e_A(p)$.

Let us now look at the quantity of permits firms hold in equilibrium. When the firm is non-compliant, then $e - l > 0$, which from (16) implies that $\beta = 0$ and $\dfrac{\partial \varphi}{\partial l} = p - \pi F'(e - l) = 0$. The number of permits held by adopters and non-adopters firms is, respectively:

(19) $l_A(p, \pi, F) = \{l | p - \pi F'(e_A - l_A) = 0\}$,

(20) $l_{NA}(p, \pi, F) = \{l | p - \pi F'(e_{NA} - l_{NA}) = 0\}$.

Equations (19) and (20) 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 permit price. Since the permit prices and the enforcement strategies faced by adopters and non-adopters are the same, from equations (19) and (20) 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, the quantity of permits held by adopters is lower than the quantity held by non-adopters. Q.E.D.

Proposition 5: *With tradable emission permits, 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, its extent of violation is decreasing in the rate of adoption.*

Proof 5: Equations (19) and (20) state that the extent of violation is determined by the condition stating that the marginal expected fine equals the permit price. The extent of violation in a scenario of universal adoption is given by $\pi F'(v_{UA}) = p_{UA}$ and in a scenario of partial adoption by $\pi F'(v_{pA}) = p_{pA}$. Given that the permit price is decreasing in the rate of adoption, $F'(v_{UA}) < F'(v_{PA})$. Since the marginal penalty is increasing in the extent of violation, $v_{PA} > v_{UA}$. Q.E.D.

The extent of violation for adopters and non-adopters is given by $v(p(\pi,\lambda),\pi,F) = e(p(\pi,\lambda)) - l(p(\pi,\lambda),\pi,F)$. This result is in line with Stranlund and Dhanda (1999) and Chávez et al. (2008), who find that changes in abatement cost parameters do not affect the extent of violation as long as enforcement and the permit price remain the same. The uniform monitoring effort should be tied only to the observable equilibrium permit prices.[16]

The fact that the extent of violation is decreasing in the rate of adoption means that technology adoption does provide incentives to improve compliance when firms

[16] Some authors have studied how targeting enforcement efforts to specific groups of firms can induce greater compliance with regulations (Harrington, 1988; Russell, 1990; Hardford, 1991; Hardford and Harrington, 1991; Livernois and McKenna, 1999; Hentschel and Randal, 2000; Friesen, 2003; Rousseau, 2007).

are regulated by TEPs. These incentives are directly related to the decrease in the permit price. Since the equilibrium price of permits falls with adoption, there is a decrease in the marginal benefit of violating and consequently the extent of violation is reduced.

The permit price that clears the market for each adoption rate is given by the equilibrium between supply and demand for permits. The supply of permits is determined by the total quantity of permits allocated by the environmental authority, and the demand for permits is the sum of the permits all firms decide to hold in equilibrium. The equilibrium permit price is given by:

$$(22)\qquad p = \begin{cases} \left\{ p_{NA} \middle| L = \sum_{i=1}^{k} l_{NA} \right\} \; if \;\; \lambda = 0 \\ \left\{ p_{PA} \middle| L = \sum_{i=1}^{\alpha n} l_A + \sum_{i=\alpha n}^{n} l_{NA} \right\} \; if \;\; \lambda = \alpha \\ \left\{ p_{UA} \middle| L = \sum_{i=1}^{n} l_A \right\} \; if \;\; \lambda = 1 \end{cases} .$$

The permit price is increasing in monitoring probability given that when the monitoring probability increases, the demand for permits increases. Permit price is decreasing in technology adoption: the larger the fraction of firms adopting the new technology, the lower the demand for permits and therefore the larger the reduction in permit price. Hence, $p_{NA} > p_{PA} > p_{UA}$.

The adoption savings are given by:

$$(21)\; \Delta EC = c(e_{NA}(p(\pi,\lambda)) - kc(e_{A}(p(\pi,\lambda))) + p(\pi,\lambda)\left[l_{NA}(p(\pi,\lambda),\pi,F) - l_{A}(p(\pi,\lambda),\pi,F)\right].$$

Adoption savings decrease as the new technology is diffused into the industry. The reduced price reduces the adoption savings and prevents high adoption cost firms from overinvesting since they can buy cheaper permits instead of investing. On the other hand, the adoption savings increase with the monitoring probability due to the increase in the permit price.

IV. POLICY INSTRUMENTS COMPARISON

In this section we compare taxes and TEPs under three criteria: (1) extent of violation in reported emissions and permit holdings of adopters and non-adopters of the new technology , (2) enforcement efforts, and (3) social welfare.

4.1 Extent of violation in reported emissions and permit holdings

In previous sections we analyzed the extent of violations in reporting and the quantity of permits held in equilibrium for the two alternative economic instruments in a context of technology adoption. The compliance incentives are given by the comparison between marginal expected costs of violation and marginal benefits of non-compliance. The marginal expected cost of non-compliance is the marginal expected sanction and is the same for adopters and non-adopters of the new technology since there are no targeted enforcement strategies. Therefore, the extent of violation is determined by the marginal benefits of non-compliance. If the tax rate is higher than the equilibrium permit price, then the extent of violation turns out to be higher under tax regulation.

4.2 Enforcement strategy for perfect compliance

So far we have assumed that the regulator sets the monitoring probability π regardless of the regulatory scheme. However, if the objective of the enforcement authority is to guarantee perfect compliance, and since the instruments differ in the violation they induce, monitoring probabilities must vary between instruments and rates of adoption.[17] Let us assume that the sanctioning structure $[f, g]$ is constant and

[17]Assuming perfect compliance is not a rare assumption in the literature; see e.g., Malik (1990), Malik (1992), Amacher and Malik (1998), Stranlund and Chávez (2000), and Chávez et al. (2008).

that the enforcement authority only adjusts the monitoring probability in order to guarantee perfect compliance.

Table 1 presents the minimum monitoring probabilities required for the extent of violation to be zero under the two alternative instruments and three possible rates of adoption.

Table 1. Minimum monitoring probabilities for comparison of extent of violation.

Adoption rate	Taxes	Tradable permits
Zero		$\pi_{\min\_NA}^{Permits} = P_{NA} / F'(0)$
Partial		$\pi_{\min\_PA}^{Permits} = P_{PA} / F'(0)$
Universal	$\pi_{\min\_NA}^{Taxes} = t / F'(0)$	$\pi_{\min\_UA}^{Permits} = P_{UA} / F'(0)$

Notice that under TEPs, but not under taxes, the minimum monitoring probability required for zero violation is a function of the rate of adoption. This result is in contrast to Amacher and Malik (1998), who find that the associated costs of enforcement faced by the regulator in a tax system depend on a firm's choice of technology. The key difference is driven by the assumption of a regulator engaging in ex-ante regulation. Amacher and Malik (1998) assume a bargaining process where the regulator offers the firm a less stringent policy if the firm agrees to employ a more environmentally friendly technology.

Thus, since compliance behavior is not affected by the adoption decision under taxes, the monitoring effort required to guarantee perfect compliance is independent of the adoption rate as well. In contrast, the enforcement effort to achieve perfect compliance decreases with the rate of adoption under TEPs.

4.3 Social Welfare

In order to compare instruments, we define a social welfare function, W. Social welfare is given by aggregate damages from emissions, $D(e)$, the abatement costs, $C(e)$, the investment costs, $I(\lambda)$, and the expected enforcement costs, $E(\pi)$:[18]

(29) $W = -D(e) - C(e) - I(\lambda) - E(\pi)$.

Damages from emissions and abatement costs are a function of emissions level, which in the case of partial technology adoption should be calculated as the weighted average of adopters' and non-adopters' emissions: $\left[(1-\alpha)e^{NA} + \alpha e^{A}\right]$.

Investment cost, in the case of partial adoption, is given by the expenditure of the lower adoption cost firms, $\alpha \underline{k}$. In the case of universal adoption, such investment is equal to $\alpha \underline{k} + (1-\alpha)\overline{k}$.

We assume that the enforcement efforts are intended to achieve perfect compliance.[19] Therefore, the monitoring probabilities are set in order to induce zero violations and the expected enforcement costs are given by the monitoring costs times the number of audits required to achieve perfect compliance.[20] If we assume that the fixed cost of auditing is equal to $\overline{x}$, then total expected enforcement costs are given by $E(\pi) = \overline{x}\pi_{mín}$.

[18] Notice that this is not an analysis of the cost-effectiveness of the instruments. Chávez et al. (2008) analyze the cost-effectiveness of a tradable emissions permit system in the presence of costly enforcement, and conclude that a conventional tradable permits program cannot be cost-effective since the individual firms under a transferable emissions permit system do not internalize the monitoring costs required to induce perfect compliance. We do not address this point in our analysis.

[19] If we keep the assumptions that the regulator sets the enforcement strategy regardless of the selected policy instrument and that it is not necessarily intended to achieve perfect compliance, the expected enforcement becomes equal across instruments and does not affect the ranking of instruments in terms of social welfare.

[20] If we instead assume, like in Sections 1 and 2 of the present paper, that the monitoring probability is exogenous and is set regardless of the regulatory instrument used, we would have the same expected enforcement for both policies in all the cases.

Since policy instruments differ in the adoption profits they induce, there are six potential alternative welfare scenarios to analyze, as shown in Table 2.

Table 2. Scenarios for welfare comparison.

Scenario	Adoption Rate	
	Taxes	Permits
1	Zero	Zero
2	Partial	Zero
3	Universal	Zero
4	Partial	Partial
5	Universal	Partial
6	Universal	Universal

See Appendix A for details of the components of the welfare function under each scenario of adoption

In Scenario 1, there is no adoption under either scheme. Therefore, there is no difference in provided social welfare between the two policy instruments, since they are both set at the same level and induce the same level of abatement, investment, and extent of violation.[21]

In Scenarios 2 and 3, there is no technological adoption under permits. The permit price remains equal to the tax. Hence, both policies imply the same extent of violation and expected enforcement costs. However, since there is more technology adoption under taxes, the investment costs are higher and emissions are lower with

[21] Remember that under perfect compliance and zero technology adoption, the permit price equals the tax rate and therefore the abatement levels under the two policy schemes coincide.

taxes than with permits, implying higher abatement costs. Finally, the lower emission level implies less damage from emissions.

In Scenarios 4 and 6, both schemes induce partial and universal adoption, respectively. Since the permit price is lower than the tax (with the gap being larger in Scenario 6), violations and expected enforcement costs are lower under permits. Investments costs are the same, while permits are preferred to taxes when it comes to abatement costs. Again, the lower emissions level under taxes induces less damage from emissions, as in the previous cases.

Finally, in Scenario 5, taxes lead to universal adoption while permits lead to partial adoption. The permit price is lower than the tax, implying less violation and lower expected enforcement costs. In addition, permits imply lower investment costs and more damage from emissions.

In conclusion, since abatement costs, investment costs, and expected enforcement costs are never larger under permits, the critical element determining the ranking between taxes and permits is the damages from emissions function. On one hand, there are lower damages from emissions with taxes. On the other hand, abatement costs, investment costs, and expected enforcement costs with taxes are never lower than with permits. If the reduction in damages generated by a lower level of emissions under taxes is higher than the increase in abatement costs, investment costs, and expected enforcement costs, then taxes outperform permits in the social welfare function. The steeper the marginal damage from emissions, the larger the drop in damages produced by a reduction in emissions and therefore the higher the probability that taxes perform better than permits. The emission level targeted by the policy also has an impact on the probability of taxes outperforming permits. If the policy is set such that the required final emission level is higher than the optimal level, then the marginal damages at the target level are higher than the marginal damages at the optimal level, and therefore, the probability for taxes to perform better than permits increases.

V. CONCLUDING REMARKS

The results presented in this paper are important for choosing and designing environmental regulations and their enforcement strategies. We analyze how the choice of policy instruments affects the incentives to comply with environmental regulations and to adopt new technologies in a context of technological change and incomplete enforcement. We have shown three main results:

First, compliance incentives are affected by the technology adoption rate under TEP regulation but not under taxes. Indeed, the larger the adoption rate in a TEP system, the lower the permit price and therefore the greater the incentives to comply with the regulation. The fact that the emissions price is fixed by the regulator under taxes while it decreases under TEP creates a wedge between them and between the rates of adoption and compliance they induce. Therefore, the expected enforcement costs necessary to guarantee perfect compliance under TEPs are lower than under taxes. This becomes relevant in a setting where expected enforcement costs are an important component of the regulation costs and when the regulatory agency is budget constrained and has as its main objective to achieve perfect compliance in reported emissions and emission permit holding.

Second, the adoption rate under taxes is not influenced by the compliance behavior of firms, while under TEPs it is. In a setting of imperfect compliance, if the main purpose of the regulator is to spread the use of a new abatement technology to achieve a lower level of final emissions, the traditional result that taxes are preferred over TEP regulations is not affected by the presence of weak enforcement and imperfect compliance.

Third, social welfare is composed of four elements that vary with the rate of adoption that each policy induces, i.e., (i) damages from emission, (ii) abatement costs (iii) investment cost, and (iv) expected enforcement costs, and we conclude that taxes never perform better than permits in terms of abatement costs, investment costs, and expected enforcement costs. However, the picture is different if we look at damage from emissions, since taxes induce less emission damage than permits. Therefore, the final ranking will depend on the relative weight given to emission damages compared to the other effects. As stated earlier, for our welfare analysis we considered the monitoring probability that ensures perfect compliance. A different result may arise if the only objective of the enforcement agency is to minimize aggregated emissions, as was explored by Macho-Stadler (2006). There are some other aspects that in practice do affect the welfare comparison and that are outside the analysis of the present paper. Differences in distributional consequences and differences in political acceptability of the instruments are some of them. The stringency of the tax and the TEPs system is subject to complicated political economy process for instance. The regulator may know that permit prices will fall during the course of a TEPs program. She may therefore make the TEP scheme tougher than she would have with a Tax scheme – to counteract.

One aspect not addressed in this paper is the effect of the rate of adoption on the optimal enforcement strategy. If the regulator wants to minimize enforcement, she/he could modify the parameters of the enforcement strategy in response to the adoption process, varying the probability of monitoring or the sanctions schemes. If firms could foresee this behavior, they could modify their initial adoption decisions, which in turn could affect social welfare and the incentives to comply with the regulation. In this sense, a hold-up problem arises, since the ex-post optimal behavior of the regulator is not consistent with the optimal incentives provided to firms ex-ante.

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APPENDIX A.

Table A. 1. Social welfare comparison by components.

Combination	*Damages from abatement*	*Abatement Costs*	*Investment Costs*	*Expected enforcement costs*
Scenario 1. Taxes $\lambda = 0$. Permits $\lambda = 0$				
Comparison $(t = P_{NA})$	$Taxes = Permits$	$Taxes = Permits$	$Taxes = Permits$	$Taxes = Permits$
Scenario 2. Taxes $\lambda = \alpha$. Taxes $\lambda = \alpha$				
Comparison $(t = P_{NA})$	$Taxes \succ Permits$	$Permits \succ Taxes$	$Permits \succ Taxes$	$Taxes = Permits$
Scenario 3. Taxes $\lambda = 1$. Permits $\lambda = 0$				
Comparison $(t = P_{NA})$	$Taxes \succ Permits$	$Permits \succ Taxes$	$Permits \succ Taxes$	$Taxes = Permits$
Scenario 4. Taxes $\lambda = \alpha$. Permits $\lambda = \alpha$				
Comparison $(t > P_{PA})$	$Taxes \succ Permits$	$Permits \succ Taxes$	$Taxes = Permits$	$Permits \succ Taxes$
Scenario 5. Taxes $\lambda = 1$. Permits $\lambda = \alpha$				
Comparison $(t > P_{PA})$	$Taxes \succ Permits$	$Permits \succ Taxes$	$Permits \succ Taxes$	$Permits \succ Taxes$
Scenario 6. Taxes $\lambda = 1$. Permits $\lambda = 1$				
Comparison $(t > P_{UA})$	$Taxes \succ Permits$	$Permits \succ Taxes$	$Taxes = Permits$	$Permits \succ Taxes$