Incentives for Green Technology Adoption, Imperfect Compliance, and Risk Aversion*

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Abstract

In this paper, we study the incentives to adopt environmentally friendly technologies as a response to different policy instruments, under imperfect compliance and risk aversion. Previous work has analyzed technology investment incentives and compliance issues under risk neutrality. However, the decision whether to exceed a regulation entails risks, since agents are exposed to a penalty with some probability. Also, there may be uncertainty regarding the impact of green technology adoption on firms' abatement costs. Therefore, preferences for risk matter. Under taxes, we find that adoption decisions are independent of risk preferences under perfect knowledge of future abatement costs, even if the enforcement policy is so weak that induces imperfect compliance. However, adoption incentives are altered by the degree of risk aversion in the case of emissions permits, and also under uncertainty about future abatement costs.

Keywords: Environmental policy; non-compliance; monitoring; technology adoption; risk aversion.

JEL Codes: K42, L51, Q28.

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1 Introduction

In this paper, we study firms' incentives to adopt environmentally friendly technologies as a response to different policy instruments, under imperfect compliance and risk aversion. Both the decisions whether to invest in green technology and whether to comply with regulations entail risks. On the one hand, there may be uncertainty regarding the impact of green technology adoption on firms' abatement costs. On the other hand, agents are exposed to a penalty with some probability if they exceed a regulation.

Up to our knowledge, the present study is the first to theoretically analyze adoption incentives as a response to environmental policies, under non-compliance and risk aversion. Previous work has focussed on technology adoption incentives and compliance issues under risk neutrality. The studies by Requate and Unold (2003) and Requate (2005) analyze technology adoption incentives in environmental policy, under perfect compliance and risk neutrality. Imperfect compliance in environmental policy (with risk neutral preferences) has been extensively studied in the literature. For example, Harford (1978), Montero (2002), and Macho-Stadler and Perez-Castrillo (2006) have explored the case of environmental taxes and subsidies, where non-compliance means that the amount of released pollution is larger than the declared amount. Keeler (1991), Stranlund and Dhanda (1999), Stranlund (2007), or Caffera and Chavez (2016) have analyzed the case of emission permits, where non-compliance refers to the cases where the amount of released pollution is larger than the amount of permit holding, see Stranlund (2017) for a recent survey of this literature. In the case of pollution limits or standards, non-compliance is associated with pollution released in excess of the maximum allowed limits, such as in Downing and

Watson (1974), Harford (1978), Jones (1989), or Arguedas (2008, 2013). The combination of technology adoption incentives and imperfect compliance under several policy instruments (taxes, permits and standards) were first analyzed by Arguedas et al. (2010), and Villegas and Coria (2010), in paralell works. Both studies assumed risk neutrality. The answer to the question whether there is any change in firms' incentives to adopt environmentally friendly technologies when compliance is an issue crucially depends on the environmental policy in place: (i) incentives to adopt remain unchanged under taxes/ subsidies; (ii) incentives to adopt are reduced only if widespread non-compliance induces a reduction in the permit price, under emission permits; and (iii) incentives to adopt can increase or decrease, under pollution standards. Finally, Malik (1990) and Stranlund (2008) combined imperfect compliance with risk averse preferences, but incentives for green technology adoption were not analyzed in those studies.

In this paper, we extend the results found in Arguedas et al. (2010), and Stranlund (2008), aiming to combine the features of adoption incentives and imperfect compliance with risk preferences. Our research question is whether the presence of risk aversion changes adoption incentives when compliance is an issue, as compared to the case of risk-neutrality. Linked to this question, we also ask ourselves if regulators should care about risk preferences when designing environmental and enforcement policies, especially if they are concerned about adoption incentives.

To answer these questions, we develop a basic model of technology adoption where firms are exposed to a pollution tax. The regulator cannot observe pollution levels. Hence, she monitors firms with some probability, and imposes sanctions if firms are found declaring amounts below released levels. Firms face risk averse preferences, and minimize expected disutility from overall costs, deciding on: (i) whether to adopt a new environmentally-friendly technology or to keep the status quo; (ii) the amount of released pollution; and (iii) the amount of declared pollution (or the amount of the violation).

We obtain some interesting, though preliminary, results. In the case where there is complete information about abatement costs related to the new technology, we find that optimal emissions and the decision whether to comply or not with the regulation are independent on the degree of risk aversion, but the degree of violation under risk aversion is lower than under risk neutrality. These results are in accordance with Stranlund (2008). When adding adoption incentives, the specific contribution of the present study, we find that adoption decisions are independent of risk preferences under perfect knowledge of future abatement costs, even if the enforcement policy is so weak that induces imperfect compliance. However, adoption incentives are altered by the degree of risk aversion when the implementation of the new technology entails some uncertainty regarding abatement costs.

Our results can be easily extended to the case of emission permits when abatement costs associated with the new technology are known. For a given permit price, pollution decisions are not afected by risk preferences. Non-compliance affects the permit price negatively, but the degree of violation decreases with the degree of risk aversion and, therefore, the amount of declared emissions (which constitutes the demand for permits) increases with the degree of risk aversion. Hence, while the induced permit price decreases as a result of non-compliance, the effect on the price is softened as long as the degree of risk aversion increases. As a result, incentives to adopt under non-compliance are not much affected in the case of emission permits, if combined with a sufficiently large degree of risk aversion.

The remainder of the paper is organized as follows. In the following section, we introduce the basic model under pollution taxes. In Section 3, we present some preliminary results. In Section 4, we present some extensions and directions for future work. Finally, we conclude in Section 5.

2 The Model

Following standard notation, we consider an industry with n (small) firms that emit a homogeneous pollutant. Firms are indexed by $i = 1, ...n$, and the pollution discharge of firm i is denoted as $e_i \in [0, e_i^{\max}]$. In the absence of regulation, firm i pollutes $e_i^{\max} > 0$. However, firm i can abate pollution by using its installed conventional pollution abatement technology, or by adopting a new, advanced abatement technology at a fixed cost I_i. The abatement technology of firm i is characterized by the abatement costs function $c_i^k(e_i)$, where $k = \{0, 1\}$ stands for the conventional and the new (cleaner) technology, respectively. Therefore, abatement costs $c_i^k(e_i)$ are firm i 's operational costs of using technology $k = \{0, 1\}$, while I_i stands for firm i's investment costs of installing the clean technology, $k = 1$. Regardless of the technology type, abatement costs are strictly decreasing and convex in the amount of pollution. The pairwise abatement costs comparison satisfies the usual assumptions $c_i^0(e_i) > c_i^1(e_i) > 0$ and $-c_i^{0\prime}(e_i) > -c_i^{1\prime}(e_i) > 0$, for all e_i.

We assume there is a regulation in place to control emissions. A regulator sets τ as the tax per unit of declared emissions.[1] Let r_i denote the amount of

[1] Later on, we adapt the model to consider alternative policy instruments.

reported or declared emissions by firm i. Assume that firm i can decide to be compliant (i.e., to report exactly the amount of released emissions, $r_i = e_i$), or to be non-compliant (i.e., to report an amount below actual emissions, $r_i < e_i$). Released emissions cannot be observed without monitoring. Since monitoring entails costs, firm i is monitored with some exogenous probability $\pi_i \in [0, 1]$. If the firm is monitored and found non-compliant, it faces a sanctioning cost, represented by $f_i(v_i)$, where $v_i = e_i - r_i > 0$. We assume $f_i'(v_i) > 0$, $f_i''(v_i) \geq 0$, and $f_i(0) = 0$.

We assume that firms face risk averse preferences. Firm i faces disutility D_i dependent on the final costs, such that $D_i'(\cdot) > 0$ and $D_i''(\cdot) \geq 0$.[2] Compliance behavior (i.e., $e_i = r_i$) entails no risk. In this case, total costs faced by the firm i are the sum of abatement costs, tax payments, and the cost of implementing technology k. In the event of non-compliance (i.e., $e_i > r_i$), the firm can be inspected and penalized with some exogenous probability π_i, facing the additional sanctioning costs. Under this alternative decision, the firm faces expected disutility for non-compliance.

The firms take their decisions in two stages. In the first stage, they decide whether to invest in the new technology or to keep the status quo. In the second stage, they decide on the amount of pollution and the amount of declared pollution. We solve the problem backwards. Results are presented in the following section.

[2] The case $D_i''(\cdot) = 0$ represents risk neutral preferences, and it is included in the analysis for completeness.

3 Results

In this section, we present the optimal decisions of the firms for a given environmental tax, τ. First, we solve the optimal decisions on actual emissions e_i and reported emissions r_i for a given technology choice k. Afterwards, we consider these optimal choices on the decision whether to adopt the green technology.

3.1 Optimal emissions and declared emissions

For a given technology k, and having produced emissions e_i^k, firm i's disutility for compliance is given by $D_i\left(c_i^k\left(e_i^k\right)+\tau e_i^k+I_i^k\right)$.[3] However, firm i's expected disutility for non-compliance is $\left(1-\pi_i\right)D_i\left(c_i^k\left(e_i^k\right)+\tau r_i^k+I_i^k\right)+\pi_i D_i\left(c_i^k\left(e_i^k\right)+\tau r_i^k+I_i^k+f_i\left(e_i^k-r_i^k\right)\right)$. To find firm i's optimal emissions and declared emissions, we solve the problem:

$$\begin{aligned} \min_{e_i^k, r_i^k} \quad & \left(1-\pi_i\right)D_i\left(c_i^k\left(e_i^k\right)+\tau r_i^k+I_i^k\right)+ \\ & +\pi_i D_i\left(c_i^k\left(e_i^k\right)+\tau r_i^k+I_i^k+f_i\left(e_i^k-r_i^k\right)\right), \\ s.t. \quad & r_i^k-e_i^k \leq 0. \end{aligned} \tag{1}$$

The following proposition summarizes the results.

Proposition 1 *For a given technology k, firm i's optimal emissions are implicitly obtained from the condition $c_i^{k\prime}\left(e_i^k\right)+\tau=0$. Firm i finds it optimal to declare released emissions $\left(e_i^k=r_i^k\right)$ if and only if condition $\tau \leq \pi_i f_i'(0)$ is met. In the alternative case, firm i does not comply $\left(e_i^k>r_i^k\right)$, and the degree of violation $v_i^k=e_i^k-r_i^k$ is implicitly obtained from the condition:*

$$\tau=\frac{D_i'\left(b_i^k\right)}{\left(1-\pi_i\right)D_i'\left(a_i^k\right)+\pi_i D_i'\left(b_i^k\right)}\pi_i f_i'\left(v_i^k\right). \tag{2}$$

[3] I_i^k stands for the investment cost associated with technology k. We only use this notation for presentation purposes, since we have assumed $I_i^0=0$ and $I_i^1=I_1>0$.

Proof. The first order conditions of problem (1) are the following:

$$(1-\pi_i) D_i' \left(a_i^k\right) c_i^{k\prime} \left(e_i^k\right) + \pi_i D_i' \left(b_i^k\right) \left(c_i^{k\prime} \left(e_i^k\right) + f_i' \left(v_i^k\right)\right) - \lambda = 0; \quad (3)$$

$$(1-\pi_i) D_i' \left(a_i^k\right) \tau + \pi_i D_i' \left(b_i^k\right) \left(\tau - f_i' \left(v_i^k\right)\right) + \lambda = 0; \quad (4)$$

$$\lambda \left(r_i^k - e_i^k\right) = 0;\ \lambda \geq 0;\ r_i^k \leq e_i^k; \quad (5)$$

where $a_i^k = c_i^k \left(e_i^k\right) + \tau r_i^k + I_i^k$, $b_i^k = c_i^k \left(e_i^k\right) + \tau r_i^k + I_i^k + f_i \left(v_i^k\right)$, $v_i^k = e_i^k - r_i^k$, and $\lambda \geq 0$ is the Kuhn Tucker multiplier of problem (1). Note that $a_i^k = b_i^k$ in the particular case where $v_i^k = e_i^k - r_i^k = 0$, since $f_i(0) = 0$. Otherwise, $a_i^k < b_i^k$. Combining conditions (3) and (4), we easily obtain:

$$\left[(1-\pi_i) D_i' \left(a_i^k\right) + \pi_i D_i' \left(b_i^k\right)\right] \left(c_i^{k\prime} \left(e_i^k\right) + \tau\right) = 0. \quad (6)$$

Since $(1-\pi_i) D_i' \left(a_i^k\right) + \pi_i D_i' \left(b_i^k\right) > 0$, condition (6) results in the familiar price equal to marginal cost condition:

$$c_i^{k\prime} \left(e_i^k\right) + \tau = 0 \quad (7)$$

Regarding declared emissions r_i^k, we now study the Kuhn-Tucker multiplier λ. Assume first that $\lambda \geq 0$, which means that $r_i^k = e_i^k$, by condition (5). Since in this case $a_i^k = b_i^k$, condition (4) reduces to:

$$D_i' \left(a_i^k\right) \left[(1-\pi_i) \tau + \pi_i \left(\tau - f_i' (0)\right)\right] \leq 0. \quad (8)$$

Since $D_i' \left(a_i^k\right) > 0$, condition (8) reduces to:

$$\tau \leq \pi_i f_i' (0). \quad (9)$$

We now consider $\lambda = 0$, which means that $r_i^k \leq e_i^k$, by condition (5). Since in this case $a_i^k \leq b_i^k$, condition (4) gives us the interior solution for r_i^k, as follows:

$$(1-\pi_i) D_i' \left(a_i^k\right) \tau + \pi_i D_i' \left(b_i^k\right) \left(\tau - f_i' \left(v_i^k\right)\right) = 0,$$

which results in condition (2). ■

These findings generalize the results in Stranlund (2008), who explores compliance in a permits' market model with risk averse firms, but without considering adoption incentives.[4] Also, the obtained condition for optimal emissions, $c_i^{k\prime}\left(e_i^k\right)+\tau=0$, is the usual marginal cost equal to price, and it is equivalent to that obtained under risk neutrality by Arguedas et al. (2010) or Villegas-Palacio and Coria (2010). Optimal emissions are only affected by abatement costs and the unit tax, and do not depend on either risk preferences or the fact that firms may be induced to not comply if the enforcement policy were lenient enough.

The condition that determines optimal compliance (that is, the condition under which it is optimal to report actual emissions, $r_i^k=e_i^k$), is $\tau\leq\pi_i f_i'(0)$. Otherwise the firm will prefer to declare lower emissions than those released. This is the traditional condition for the compliance decision commonly found in models that assume risk neutrality, such as Stranlund (2007) or Arguedas (2008), among others. The only thing that matters in the decision to comply is the relation between the unit tax (price of declaring an additional unit of emissions) and the marginal expected fine (price for not declaring that additional unit of emissions), so this decision is not link to risk preferences at all.

The optimality condition (2) for declared emissions under non-compliance when $\tau\geq\pi_i f_i'(0)$ differs from the condition under risk neutrality, which is $\tau=\pi_i f_i'\left(v_i^k\right)$, see Arguedas et al. (2010). Two features are worth mentioning in this case. The first feature is the fact that, everything else equal, the degree of violation under risk aversion is lower than under risk neutrality. To see

[4] Besides adoption incentives, a second difference in our analysis is the exogenous character of the pollution price in this first case that deals with taxes.

this, note that $r_i^k < e_i^k$ implies $b_i^k > a_i^k$, which means $\frac{D_i'\left(b_i^k\right)}{(1-\pi_i)D_i'\left(a_i^k\right)\tau+\pi_i D_i'\left(b_i^k\right)} > 1$, since $D_i''(\cdot) > 0$ under risk aversion. From condition (4), we then have $\tau > \pi_i f_i'\left(v_i^k\right)$ under risk aversion, while the equivalent condition under risk neutrality is $\tau = \pi_i f_i'\left(v_i^k\right)$. From the strict convexity of the expected penalty, we can then conclude that the degree of violation under risk aversion is lower.

The second feature is that the degree of violation under risk aversion does depend on the abatement cost function (or associated technology, $k = \{0, 1\}$), since this element is present in both a_i^k and b_i^k, and both terms are in turn present in condition (2). This property contrasts with the case of risk neutrality, where the degree of violation does not depend on technology choice. Hence, this feature may have implications for the adoption decision, as we study next.[5]

3.2 Adoption decision

We now consider firm i's adoption decision. Firm i is endowed with an abatement cost function $c_i^0\left(e_i^0\right)$. The firm chooses whether to keep this technology, or to adopt an environmentally superior technology, $c_i^1\left(e_i^1\right)$, such that $c_i^0(e) > c_i^1(e)$ and $c_i^{0\prime}(e) < c_i^{1\prime}(e)$, for every $e > 0$. If the firm decides to invest, it affords the investment cost $I_i > 0$.

As shown in Proposition 1, the decision whether to comply or not is crucially dependent on the fact that the unit tax is lower or larger than the marginal expected penalty. This particularly means that the specific choice of the technology does not affect this decision. Hence, irrespectively of the technology choice, the firm complies if condition (9) is met, $\tau \leq \pi_i f_i'(0)$, and does not comply

[5] More precisely, the abatement technology has an effect on the degree of violation as long as the degree of risk aversion is sufficiently large (that is, as long as the disutility function is sufficiently convex). The particular case of quadratic disutility is an exception, since the marginal disutility is constant and, therefore, independent of a_i^k and b_i^k. Only in that case (i.e., if the third derivative of the disutility function is negligible), we can ensure that the degree of violation is independent of technology choice.

otherwise. This is a remarkable result given its policy implications: inducing technology adoption (maybe by means of up-front subsidies) does not result in firms changing their behavior from non-compliance to compliance. This is also irrespective of risk preferences.[6]

Assume first that condition (9) is met. In this case, firm i complies under both the standard, $k = 0$, and the clean, $k = 1$, technologies. However, firm i finds it optimal to adopt the clean technology if and only if the disutility under the clean technology is lower than the disutility under the standard technology. That is, if and only if:

$$D_i \left(c_i^1 \left(e_i^1 \right) + \tau e_i^1 + I_i \right) \leq D_i \left(c_i^0 \left(e_i^0 \right) + \tau e_i^0 \right). \tag{10}$$

Since $D_i' > 0$, condition (10) reduces to:

$$c_i^1 \left(e_i^1 \right) + \tau e_i^1 + I_i \leq c_i^0 \left(e_i^0 \right) + \tau e_i^0, \tag{11}$$

and this is exactly the same condition that we find under risk neutrality. Under compliance, this means that firms that find it optimal to adopt the new technology under risk neutrality also find it optimal to do it if they faced risk averse preferences. The opposite is also true.

If we instead consider that condition (9) is not satisfied, firm i finds it optimal to not comply (under any of the two technologies). Therefore, firm i has incentives to adopt the clean technology if and only if the expected disutility for non-compliance under the clean technology is lower than the expected disutility

[6] This result may change if fines for non-compliance were dependant on the technology choice, since this feature may have some effect at the margin, see Arguedas (2013) for a discussion on this issue.

under the standard technology. That is, if and only if:

$$(1-\pi_i) D_i \left(c_i^1 \left(e_i^1\right) + \tau r_i^1 + I_i\right) + \pi_i D_i \left(c_i^1 \left(e_i^1\right) + \tau r_i^1 + I_i + f_i \left(e_i^1 - r_i^1\right)\right) \leq$$
$$(1-\pi_i) D_i \left(c_i^0 \left(e_i^0\right) + \tau r_i^0\right) + \pi_i D_i \left(c_i^0 \left(e_i^0\right) + \tau r_i^0 + f_i \left(e_i^0 - r_i^0\right)\right). \quad (12)$$

Clearly, this condition is different from condition (11), which therefore means that adoption incentives under compliance and non-compliance need not coincide. Next, we explore this issue.

We first analyze the case where at least $v_i^1 = v_i^0$, which corresponds to the situation of negligible third order derivative of the disutility function, as we have seen above (see footnote 5). Let us assume that condition (11) is met. We want to see how likely it is that condition (12) is also met. In this case, it is easy to see that investment incentives are aligned. Condition (12) can be rewritten as:

$$(1-\pi_i) \left[D_i \left(c_i^1 \left(e_i^1\right) + \tau r_i^1 + I_i\right) - D_i \left(c_i^0 \left(e_i^0\right) + \tau r_i^0\right)\right] \leq$$
$$\pi_i \left[D_i \left(c_i^0 \left(e_i^0\right) + \tau r_i^0 + f_i \left(e_i^0 - r_i^0\right)\right) - D_i \left(c_i^1 \left(e_i^1\right) + \tau r_i^1 + I_i + f_i \left(e_i^1 - r_i^1\right)\right)\right]. \quad (13)$$

If (11) holds, the left hand side of condition (13) is negative, since condition (11) is equivalent to $c_i^1 \left(e_i^1\right) + \tau r_i^1 + I_i \leq c_i^0 \left(e_i^0\right) + \tau r_i^0$ when $v_i^1 = v_i^0$ (that is, when $e_i^1 - r_i^1 = e_i^0 - r_i^0$), and $D_i' (\cdot) > 0$. For the same reason, the right hand side of condition (13) is positive. Hence, condition (13) is met when (11) holds. Using the same sort of arguments, it can also be shown that (13) is not met when (11) does not hold. As a result, for the specific case when $v_i^1 = v_i^0$, conditions (11) and (13) are equivalent. This means that investment incentives do not change in the presence of risk aversion under non-compliance, either. The result is then summarized as follows:

Proposition 2 *In the situations where the degree of violation does not depend on technology choice (particularly the case of risk neutrality, but also the case of risk aversion with negligible third order derivative for the disutility function), adoption decisions are independent of risk preferences or the compliance decision.*

However, things may change if $v_i^1 \neq v_i^0$. In fact, condition (11) is no longer equivalent to condition (13), which means that investment incentives may change under full and imperfect compliance in the case of risk aversion. Since there is also no way to see if one of the conditions is laxer than the other, our strategy now is to construct examples to see if we can give some light on the appropriate comparison between conditions (11) and (13).

Example 1 *We consider* $D(x) = x^{\rho_i+1}$*, with* $\rho_i > 1$*. This condition ensures that the degree of violation depends on technology choice, as we have seen above. Parameter* ρ_i *measures de degree of relative risk aversion of firm* i*. We assume* $c_i^0 = (100 - e_i)\, e_i$*,* $c_i^1 = (50 - e_i)\, e_i$*, and also* $\tau = 20$*.*

For the time being, we have run several simulations for several specifications of the adoption costs, the inspection probability and the fine for non-compliance. Specifically, we have considered three cases: (i) $I_i = 1000$, $\pi_i = 0.5$ and $f_i(v_i) = v_i^2$; (ii) $I_i = 2,375$, $\pi_i = 0.5$ and $f_i(v_i) = v_i^2$; (iii) $I_i = 2,375$, $\pi_i = 0.1$ and $f_i(v_i) = 5v_i^2$. For all the cases so far, we have not found any changes regarding adoption incentives when we change the parameter for relative risk aversion. In these three cases we find that firm i prefers to adopt for all parametrizations of the relative risk aversion coefficient considered ($\rho_i = 0, 1, ..., 6$). This means that, so far, we have not found any changes in adoption incentives when preferences for risk change. However, we still have work to do regarding the theoretical proof and/or a more detailed numerical analysis.

Since we do not have a definite conclusion regarding changes in adoption incentives linked to changes in preferences for risk, in the following section we work with alternative hypothesis to enrich the analysis.

4 Extensions

In this section, we consider two extensions of the basic model we have analyzed previously. The first is to assume an emissions permit market instead of a pollution tax. The main change is that the pollution price is now endogenous, and this has implications in terms of adoption incentives. The second is to consider uncertainty on the abatement costs associated with the new technology.

4.1 Adoption incentives in an emissions permit market

Now, we consider that the regulator sets an aggregate emission target $\overline{E}$ and then issues a number $S \leq \overline{E}$ of tradable permits, where p denotes the corresponding competitive permit market price and $s_i \geq 0$ is the number of permits held by firm i. For simplicity, we assume that initially the regulator allocates $\overline{s}_i \geq 0$ permits to firm i , while $s_i \geq 0$ denotes the number of permits held by firm i after trade has occurred, such that $\sum_i \overline{s}_i = \sum_i s_i = S$. Within this framework, a compliant firm pollutes no more than its permit holding, that is, $e_i \leq s_i$, whereas a non-compliant firm pollutes more than its final permit holding ($e_i > s_i$) and, therefore, the firm's violation amount is defined as $v_i = e_i - s_i > 0$.

In this context, firm i's decision variables are (i) whether to adopt the new technology or to keep the status quo, (ii) the amount of released pollution, and (iii) the amount of permit holding. As in the previous sections, the adoption decision is taken first, while the decisions on pollution and permit holding are taken at a later stage. The nature of the problem is similar to the previous one and therefore the two stage model is solved backwards.

To find firm i's optimal emissions and permit holding for a given technology k, we solve the following problem:

$$\begin{aligned}
\min_{e_i^k, s_i^k} \quad & (1-\pi_i) D_i \left(c_i^k \left(e_i^k\right) + p\left(s_i^k - \overline{s}_i^k\right) + I_i^k\right) \\
& + \pi_i D_i \left(c_i^k \left(e_i^k\right) + p\left(s_i^k - \overline{s}_i^k\right) + I_i^k + f_i\left(e_i^k - s_i^k\right)\right), \\
s.t. \quad & s_i^k - e_i^k \leq 0, \qquad (14)
\end{aligned}$$

where p is the equilibrium permit price, which is obtained from the market clearing condition $\sum_i s_i^k = S$, with s_i^k being the optimal permit holding of firm i.

We immediately see that the results presented in Proposition 1 can be recalled by simply interchanging τ for p. Therefore, all the properties there also apply in this context: (i) optimal emissions only depend on abatement costs and the permit price, but neither compliance issues nor risk preferences affect this decision; (ii) the decision whether to comply or not depends exclusively on the permit price and the expected marginal sanction, but not on risk preferences; and (iii) everything else equal, in the event of non-compliance, the degree of violation is lower under risk aversion than under risk neutrality.

Contrary to the case of pollution taxes, the price for permits is endogenously determined through the market clearing condition $\sum_i s_i^k = S$. The supply of permits is fixed, S, but the demand for permits depends on the degree of risk aversion. Since the degree of violation is decreasing in the degree of risk aversion, everything else equal, the demand for permits increases with the degree of risk aversion and, as a result, a larger demand for permits results in a larger equilibrium price. This feature is summarized in the following:

Proposition 3 *For given abatement costs, the equilibrium permits price increases with firms' degree of risk aversion.*

This is an interesting property that counteracts the negative effect of extended non-compliance on the permit price found in Arguedas et al. (2010). The final effect of non-compliance on the permit price is therefore softened when firms face risk averse preferences. As a result, adoption incentives do not change much under non-compliance, provided that firms are sufficiently risk averse.

4.2 Adoption incentives under uncertainty about future abatement costs

Going back to the case of pollution taxes, an alternative extension is to consider that abatement costs associated with the new technology are not fully known. This is not only more realistic, but it also helps us to enrich the results under risk aversion. Now, firms have two sources of risk that may affect preferences: (i) the risk of adopting a new technology with no clear picture of the new abatement costs; (ii) the risk of facing a penalty with some probability if they exceed a regulation.

To account for uncertainty on future abatement costs, we modify abatement costs associated with the adoption of the new technology, $c_i^1(e_i)$. For simplicity, we assume two possible specifications for these costs, $c_i^{1,1}(e_i)$ and $c_i^{1,2}(e_i)$. Firm i is not certain about the true abatement cost function, but at least know the likelihood of each possiblity, represented respectively by $(\alpha_i, 1-\alpha_i)$. Both cost functions satisfy the usual properties. In particular, both specifications entail lower abatement and marginal abatement costs than the one associated with the status quo.

For the time being, we are working with the following example to illustrate some initial findings.

Example 2 *We consider* $D(x) = x^{\rho_i+1}$. *We also assume* $c_i^0 = (100 - e_i)\, e_i$, $c_i^{1,1} = (75 - e_i)\, e_i$, $c_i^{1,2} = (25 - e_i)\, e_i$, *and* $\alpha_i = 0,5$. *We also consider* $\tau = 20$, $I_i = 1000$, $\pi_i = 0,5$ *and* $f_i(v_i) = v_i^2$.

Note that expected abatement costs under the new technology are equal to $(50 - e_i)\, e_i$, which is the same function we have used in the previous example. This easily help us to compare one case versus the other for alternative parameterizations for the degree of relative risk aversion ρ_i. Our preliminary findings in this example show that risk preferences now affect all the main choice variables, including emissions levels, declared emissions, and adoption incentives.

5 Conclusions

In this paper, we analyze firms' incentives to adopt environmentally friendly technologies as a response to pollution taxes and permits under imperfect compliance and risk aversion. To our knowledge, this paper is the first to theoretically address this relevant issue, since previous work has analyzed technology adoption incentives and compliance issues under risk neutrality. However, we consider that taking risk preferences into account is important because both the decisions whether to adopt greener technologies and to comply with regulations entail risks. On the one hand, there may be uncertainty regarding the impact of green technology adoption on firms' abatement costs. On the other hand, agents are exposed to a penalty with some probability if they exceed a regulation.

Under pollution taxes and full information about future abatement costs, our preliminary results suggest that optimal emissions and the decision whether to comply or not with the regulation are independent on the degree of risk aversion. However, the degree of violation under risk aversion is lower than under risk neutrality (similar to Stranlund, 2008). Additionally, adoption decisions seem to be independent of risk preferences, even if the enforcement policy is so weak that induces imperfect compliance.

Regarding emissions permits, pollution decisions are not affected by risk preferences either. The degree of violation decreases with the degree of risk aversion and, consequently, the amount of declared emissions (which constitutes the demand for permits) increases with the degree of risk aversion. Hence, the induced permit price increases with the degree of risk aversion, which counteracts the negative effect of extended non-compliance on the permit price found in Arguedas et al. (2010). The final effect of non-compliance on the permit price is therefore softened when firms face risk averse preferences. As a result, adoption incentives do not change much under non-compliance, provided that firms are sufficiently risk averse.

Our preliminary work shows that adoption incentives are altered by the degree of risk aversion if the implementation of the new technology entails some uncertainty regarding abatement costs. In this case we have two sources or risk (uncertainty about future abatement costs and the risk of being penalized with some probability in case of non-compliance). It may be worth exploring the combined effects of these two sources of risks for different degrees of risk aversion.

Besides exploring the case of uncertainty regarding the implementation of a new technology in more detail, we are also interested in deriving the implications of risk aversion in the case of pollution standards, to obtain a full picture of the impact of risk preferences on the different policy instruments.

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