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## Taxes, Permits, and the Diffusions of a New Technology

Jessica Coria



Environment for Development



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# Taxes, Permits, and the Diffusions of a New Technology

Jessica Coria

## Abstract

This study looks at the effects of the choice between taxes and permits on the pattern of adoption of a new (pollution) emissions abatement technology. It uses a dynamic setting, where the regulator observes the arrival and initial use of the technology and determines the optimal *ex-post* amount of emissions before firms start to adopt the technology.

In the model here, the adoption benefits and costs depend on the number of firms that are already using the technology. Thus, each firm decides the optimal date to adopt the technology, considering its benefits and costs, as well as the advantage they will gain over their rivals, producing a sequence of adoption that is “diffused” into the industry over time.

With this framework, the study shows that when the output demand is elastic, auctioned permits induce an earlier diffusion than taxes and thus provide the largest benefit to social welfare.

**Key Words:** Environmental policy, technological adoption, tradable permits, taxes

**JEL Classification Numbers:** L13, O33, Q53, Q55, Q58

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# Taxes, Permits, and the Diffusions of a New Technology

Jessica Coria\*

## Introduction

It has been well documented in the literature on technology adoption (see Geroski 2000; and Jaffe et al. 2002, for example) that one of the central features of technological diffusion is the apparently slow speed at which firms adopt new technologies. In fact, the time path of adoption typically follows an S-curve, where a slow take-off is followed by a period of relatively rapid adoption and then a slow down to satiation. If a new technology is a significant improvement over existing ones, it is important to ask why some firms adopt it earlier than others and which policies may help to accelerate this process. This is especially true in the environmental field, where the adverse impacts of current technologies could be reduced if more environmentally friendly technologies were adopted.

Considering that faster diffusion of environmentally friendly technologies could reduce the social costs of programs trying to improve environmental quality, it is worth asking how an environmental policy that implicitly or explicitly increases economic incentives to reduce emissions affects the diffusion of these technologies. Several theoretical models have tried to answer this question by comparing the incentives provided by different policy instruments. Existing models differ in three major dimensions.<sup>1</sup> First is a difference in the expected behavior of the regulator, which is assumed will act myopically or will engage in *ex-ante* or *ex-post* regulation. Second, the models differ in whether they include uncertainty regarding the arrival and value of the new technology. Finally, they differ in whether to pay attention to the output market.

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<sup>1</sup> Nelissen and Requate (2004) reviewed the theoretical developments on the progress of both pollution-reducing and resource-saving technologies.

With regard to this last dimension, Montero (2002a) is one of the few authors who has paid attention to imperfect competition in both the output and the permit market. He modeled emissions as a production input and evaluated the research and development (R&D) incentives to invest in abatement technologies when the regulator behaved myopically. In this setting, investment incentives came from a direct effect and a strategic effect (Tirole 1998, 323–36). If firms compete in quantities, research and development (R&D) will allow an investor to reduce its marginal cost of abatement. The direct effect is positive and accounts for the investor's abatement cost savings that does not affect the other firms' choice of output. Under a perfect competitive setting, this would be the only effect, but with imperfect competition, there are strategic effects since the investor's decision affects the ex post behavior and profits of its rivals.

Montero's (2002a) main result was that in the case of taxes, the investment profits consisted of just the direct effect, while in the case of permits, there were also strategic effects from both the output and the permit market. If the regulator is myopic and does not adjust the environmental policy in response to the advent of the new technology (neither reducing the tax nor decreasing the cap on emissions), the direct effect will be larger with taxes than with permits. The strategic effect from the output market results from the influence of one firm's R&D investment on the other firms' choice of output, and it is negative because the investment raises the competitors' output, which leads the firm to invest less. Finally, the strategic effect from the permit market results from the influence of the R&D investment on the permit equilibrium price. Since the permit price falls with R&D, this effect could be either positive or negative, depending on whether the firm is a buyer (positive) or a seller (negative) of permits. After accounting for all of these effects, Montero found that tradable permits offered fewer R&D incentives than taxes (2002a, 307).

The contribution of this paper is twofold. First, like Montero, I studied the impact of the choice of policy on technological adoption when firms engage in imperfect competition in the output market. However, I challenged his ranking by assuming a forward-looking regulator that committed to the ex post optimal environmental policy before firms began to adopt the technology. Second, unlike most of the other studies in this area, I took a dynamic approach, analyzing the impact of the choice of policy over the number of periods that elapsed until the new technology was "diffused" into the industry.

To take dynamics into account, I followed Reinganum (1981), who considered an industry composed of symmetric firms that engaged in Cournot competition in the output market. When a cost-reducing technology appears, each firm must decide when to adopt it, based in part upon the discounted cost of implementing it and in part upon the behavior of the rival firms. If a

firm adopts a technology before its rivals, it can expect to make substantial profits at the expense of the other firms. On the other hand, the discounted sum of purchase price and adjustment costs may decline if the adjustment period lengthens, as various quasi-fixed factors become available. Therefore, although waiting costs more in terms of foregone profits, it may save money on purchasing the new technology. Reinganum showed that diffusion, as opposed to immediate adoption, occurred because adoptions that yield lower incremental benefits are deferred until they are justified by lower adoption costs.

I adapted Reinganum's model in several ways. In my model, adoption increased profits since it allowed firms to reduce abatement costs. As current abatement costs are heterogeneous, firms can be ordered according to their adoption profits, from the firm with the highest current abatement cost to the firm with the lowest current abatement cost. Thus, the adoption profits decreased through the sequence because the current abatement cost came closer to the cost of the new technology. On the other hand, supply-side forces led the adoption costs to decrease as the number of firms using the new technology increased. Therefore, the firms with lower current abatement postponed the adoption until a larger number of firms adopted, offsetting the lower adoption profits with lower adoption costs.

My results support the use of auctioned permits over taxes, when output demand is elastic. As did Montero (2002a), I found that adoption benefits come from a direct effect and a strategic effect. Nevertheless, as the regulator responds to the advent of the new technology increasing the stringency of permits and reducing the stringency of taxes, adoption benefits from the direct effect will always be larger under permits. Therefore, the ranking between taxes and permits depends, ultimately, on the sign of the strategic effects. If the output demand is elastic, the strategic effects are positive and auctioned permits offer larger incentives to adopt than taxes. However, the cost of adoption decreases faster when a considerable percentage of firms have adopted, and the regulator speeds up the entire sequence of adoption by using auctioned permits. The reverse holds if the output demand is inelastic.

The paper has five sections. The next section shows the development of the adoption model. The second section analyzes how the choice of a policy instrument modifies the optimal date of adoption. In the third section, patterns of adoption are simulated under different policy instruments. The fifth section analyzes welfare implications, and the sixth section concludes.

## 1. The Model

Suppose that a stationary industry of  $n$  firms is producing a homogeneous good. The linear inverse demand function is given by:

$$P = P(Q) = a - b \sum_{i=1}^n q_i \quad (1)$$

$$a, b > 0 ,$$

where  $q_i$  denotes the level of production of firm  $i$ .

In addition to producing output, firms emit a homogeneous pollutant, and each unit of output generates a unit of emission  $e$  ( $\partial e_i / \partial q_i = 1$ ). To manage this emission, firms install an abatement technology. In accordance with most of the environmental technology adoption literature, I assumed that the total abatement cost for each firm can be described as  $c_i r_i^2$ , where  $r_i$  is the quantity of emissions that firm  $i$  reduces, or:

$$r_i = q_i - e_i . \quad (2)$$

There are no further production costs.

Current abatement costs are heterogeneous. Firms can be ranked according to an index of cost, and they are ordered, without loss of generality, from the firm with the highest index cost to the firm with the lowest cost; so  $c_1 > c_2 > \dots > c_i > \dots > c_n$ .<sup>2</sup>

Suppose a new technology becomes available and can be adopted by any at a cost  $K$ . This technology allows firms to reduce emissions at a lower total abatement cost  $c r_i^2$ , since  $c_1 > \dots > c_i > \dots > c_n > c$ , and no further technical advance is anticipated.<sup>3</sup>

It is assumed that, as the number of firms that adopt the new technology increases, more firms will enter the market to supply the new technology. This lowers the cost  $K$ . The cost

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<sup>2</sup> Notice that  $c_i$  corresponds just to an index of cost and not to total abatement costs. However, with taxes and emission permits, each firm equates its marginal abatement cost [ $2c_i r_i$ ] with the tax or the permit price, total abatement costs depends on the level of the tax or the permit price (identical for all firms) and on this index of cost.

<sup>3</sup> If firms anticipate that a better technology will arrive at an uncertain date, they must consider suspending the current adoption process in light of the expectation of future technological improvements. The suspension of the current process provides the firm with an option to purchase the future technology when it comes available. The value of the option to suspend must be equal to the expected net present value of the future technology. So, the profitability threshold required in order to adopt the current best technology increases, delaying the entire sequence of adoption.

decreases with the number of firms that have already adopted at a rate  $\theta_i$ , where  $\theta_i$  exhibits the usual properties  $\frac{\partial \theta_i}{\partial i} > 0$  and  $\frac{\partial^2 \theta_i}{\partial i^2} \leq 0$ .

The interaction between the firms and the regulator follows a certain pattern. The new technology arrives at the beginning of period 1. After noting its arrival, the regulator anticipates how many firms will optimally adopt the technology and announces a new allowed level of emissions. Let us assume that efficiency calls for universal adoption. Thus, the regulator sets the environmental policy such that the *ex post* amount of emissions is optimal according to the marginal cost of the new technology. At this point, firms start to adopt.

Let  $\pi_i^{NA}(m)$  be the rate of Cournot-Nash profit flow to firm  $i$ , when  $m$  firms have adopted the new technology and firm  $i$  belongs to the fraction that has not adopted yet. Let  $\pi_i^A(m)$  be the rate of Cournot-Nash profit flow to firm  $i$ , when  $m$  firms have adopted and firm  $i$  belongs to the fraction that has already adopted. It is assumed that  $\pi_i^{NA}(m)$  and  $\pi_i^A(m)$  are known with certainty by firms as the marginal cost of the new technology.

Let  $\tau_i$  be the date of adoption by firm  $i$ . Due to the decreasing ordering of the abatement costs, and for the same initial investment  $K$ , firm  $i$  benefits the most from technological adoption while firm  $n$  benefits the least. Then, we can order the adoption dates, such that  $\tau_1 \leq \tau_2 \leq \dots \leq \tau_{i-1} \leq \tau_i \leq \tau_{i+1} \leq \dots \leq \tau_n$ . Thus, the present value of firm  $i$ 's profits, net of the adoption costs when it adopts the new technology on date  $\tau_i$ , can be characterized as

$V^i(\tau_1, \dots, \tau_i, \dots, \tau_n)$ :

$$V^i(\tau_1, \dots, \tau_i, \dots, \tau_n) = \sum_{m=0}^{i-1} \int_{\tau_m}^{\tau_{m+1}} \pi_i^{NA} e^{-\delta t} dt + \sum_{m=i}^n \int_{\tau_m}^{\tau_{m+1}} \pi_i^A e^{-\delta t} dt - K e^{-(\delta+\theta_i)\tau_i}, \quad (3)$$

where  $\delta$  is the intertemporal discount rate.

The optimal date of adoption for each firm is found by maximizing  $V^i$  via the choice of  $\tau_i$  from the interval  $[\tau_{i-1}, \tau_{i+1}]$ .<sup>4</sup>

$$\frac{\partial V^i}{\partial \tau_i} = [\pi_i^{NA} - \pi_i^A] e^{-\delta \tau_i^*} + (\delta + \theta_i) K e^{-(\delta+\theta_i)\tau_i^*} = 0. \quad (4)$$

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<sup>4</sup> Since, at date  $\tau_i$ , there are  $i$  firms using the new technology,  $\pi_i^{NA}(m)$  and  $\pi_i^A(m)$  can simply be denoted as  $\pi_i^{NA}$  and  $\pi_i^A$ .

From equation (4), we observe that firm  $i$  will adopt the new technology when the costs of delaying adoption equal the benefits. The costs of delaying adoption of the technology correspond to the difference in the profit flows due to the lower marginal abatement cost, while the benefits of postponing adoption are equal to the opportunity cost of saving the initial investment. When both elements are equal, firm  $i$  adopts.

$$\tau_i^* = \frac{1}{\theta_i} \ln \left( \frac{(\delta + \theta_i)K}{\pi_i^A - \pi_i^{NA}} \right). \quad (5)$$

The sequence of adoption  $\tau_1 \leq \tau_2 \leq \dots \tau_{i-1} \leq \tau_i \leq \tau_{i+1} \leq \dots \leq \tau_n$  is a sub-game perfect equilibrium, if the change in the rate at which the adoption costs decreases  $\theta_i'$  is small (see appendix A).

The regulator can implement the environmental policy by means of emission taxes, auctioned permits, or freely allocated permits. Each policy produces a different value for the costs of delaying adoption and speeding up or delaying the diffusion of the new technology. The following section analyzes the behavior of the regulator and the costs of delaying adoption under each instrument.

## 2. The Behavior of the Regulator and the Adoption Incentives

Let us assume that total damage from the emissions is an increasing function of aggregate emissions  $E$  in the period  $\frac{\gamma E^2}{2}$  ( $\gamma > 0$ ), with a strictly convex emissions' marginal damage function equal to  $\gamma E$ . The regulator chooses the level of an environmental regulation so that the marginal aggregate cost of pollution control is equal to pollution's social marginal damage. Since the emissions' total damage function is strictly convex and since aggregate marginal abatement cost decreases because of adoption, efficiency requires that the allowed level of emissions falls in response to the advent of the new technology. Thus, the forward-looking regulator implements a tighter emissions level  $\bar{E}$  through emission taxes, auctioned-off emission permits, or freely allocated emission permits.  $\sigma_0$  and  $s_0$  are the tax and the permit price before the arrival of the new technology:  $\sigma$  is the tax after the one-time policy adjustment, and  $s(n)$  is the permit price after all firms have adopted the technology. For an emissions tax to set the new efficient level of emissions, the tax rate must be equal to marginal damage evaluated at the new efficient level of

emissions; that is,  $\sigma = \gamma \bar{E}$ . On the other hand, the total number of permits available is reduced (once) to  $\bar{E}$  as a response to the arrival of the new technology.<sup>5</sup>

I assumed that the regulator set policy *ex post*; that is, the regulator sets the level of the environmental policy, such that the *ex-post* level of emissions (after all firms from a social perspective have adopted) is optimal. Thus, the forward-looking regulator adjusts the tax rate and the cap, such that they result in the same optimal level of pollutants emitted over the long term—and  $\sigma_0$  and  $s_0$  coincide. The same happens with  $\sigma$  and  $s(n)$ . However, the decrease in the supply of permits increases the permit price in the short run, but this price falls gradually during the adoption sequence to the amount of the *ex-post* optimal tax  $\sigma$ , as adoption takes place.

### 2.1 The Adoption Incentives under Emission Taxes

In this section, I analyze the adoption incentives under each policy instrument. Let us assume that  $i$  firms have already adopted. Under tax regulation and Cournot competition, each firm looks for the output and the mix of abatement plus tax payment that maximizes profits. If the environmental authority has decided to charge a per unit fee equal to  $\sigma$ , the firms adopting the technology will maximize the following function:

$$\begin{aligned} \text{Max}_{e_j, q_j} \pi_j^A &= P(Q)q_j - c(q_j - e_j)^2 - \sigma e_j \\ j &= 1, 2, \dots, i, \end{aligned} \quad (6)$$

where the abatement cost corresponds to the cost of the new technology. Firms that have not already adopted face a higher abatement cost, since  $c_k > c$ :

$$\begin{aligned} \text{Max}_{e_k, q_k} \pi_k^{NA} &= P(Q)q_k - c_k(q_k - e_k)^2 - \sigma e_k \\ k &= (i+1), (i+2), \dots, n. \end{aligned} \quad (7)$$

The optimal level of emissions and output for each kind of firm is given by the first order conditions (FOC) for  $(e_j, q_j)$  and  $(e_k, q_k)$ .

$$2c(q_j - e_j) = \sigma, \quad (8)$$

$$P(Q) + P'(Q)q_j - 2c(q_j - e_j) = 0, \quad (9)$$

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<sup>5</sup> I assumed that environmental policy would be adjusted once and for all. Thus, the regulator observes the arrival of the new technology, anticipates that all firms will invest, and modifies the level of the environmental policy accordingly.

$$2c_k(q_k - e_k) = \sigma , \quad (10)$$

$$P(Q) + P'(Q)q_k - 2c_k(q_k - e_k) = 0 . \quad (11)$$

Equations (8) and (10) indicate that at the optimum, each firm faces a marginal abatement cost equal to the emission tax  $\sigma$ . Since firms that have already adopted the technology face a lower marginal abatement cost, they will reduce further emissions. Hence, technological adoption increases the optimal level of abatement.

Combining the FOC for  $(e_j, q_j)$  and  $(e_k, q_k)$ , we have:

$$P(Q) + P'(Q)q_j = \sigma \text{ and} \quad (12)$$

$$P(Q) + P'(Q)q_k = \sigma . \quad (13)$$

The term on the left-hand side in equations (12) and (13) is the marginal benefit of production, while the term on the right-hand side is the marginal abatement cost. At the optimum, each firm faces a benefit per unit of output equal to the marginal abatement cost. Since the marginal cost for both kinds of firms is constant at  $\sigma$ , adoption does not affect either adopters' or non-adopters' output.

In line with Montero (2002a), I separated the benefits of adoption  $\pi_j^A$  between a direct effect and a strategic effect. The direct effect does not account for the effect of adoption over the other firms' choice of output. However, in this case, there was no strategic effect from the output market, since adoption did not affect the rivals' output. Then, adoption benefits came solely from the direct effect because adopters reduced the abatement costs, which in turn re-optimized the mix of abatement plus tax payment.

$$\begin{aligned} (\pi_j^A)^{TAX} &= \left\{ P[Q(\sigma)]q_j(\sigma) - c[q_j(\sigma) - e_j^A(\sigma)]^2 - \sigma e_j^A(\sigma) \right\} \\ &\quad - \left\{ P[Q(\sigma)]q_j(\sigma) - c_j[q_j(\sigma) - e_j^{NA}(\sigma)]^2 - \sigma e_j^{NA}(\sigma) \right\} \\ &= c_j[q_j(\sigma) - e_j^{NA}(\sigma)]^2 - c[q_j(\sigma) - e_j^A(\sigma)]^2 + \sigma[e_j^{NA}(\sigma) - e_j^A(\sigma)]. \end{aligned} \quad (14)$$

Using the FOC for  $(e_j, q_j)$ , equation (14) can be re-written as:

$$(\pi_j^A)^{TAX} = \underbrace{\left[ \frac{\sigma^2}{4c} - \frac{\sigma^2}{4c_j} \right]}_{>0} . \quad (15)$$

Notice that the direct effect decreases through the sequence as the adopter's current abatement cost comes closer to the cost of the new technology.

## 2.2 The Adoption Incentives under Tradable Permits

Under tradable permits regulation, each firm looks for the output and the mix of abatement plus emission permits that maximize profits. Note that since grandfathered tradable permits and auctioned permits are closely related, the analysis can be merged into one. Let  $\varepsilon_j$  be the quantity of emissions permits received by firm  $j$ ,  $\varepsilon_k$  be the quantity of emissions permits received by firm  $k$ , and  $s(j)$  be the permit price after  $j$  firms have adopted. Thus, if permits are auctioned off,  $\varepsilon_j = \varepsilon_k = 0$ , while  $\varepsilon_j > 0$ ,  $\varepsilon_k > 0$  when permits are freely allocated.

Firms that adopt the technology solve:

$$\begin{aligned} \text{Max}_{q_j, e_j} \pi_j^A = P(Q)q_j - c(q_j - e_j)^2 - s(j)(e_j - \varepsilon_j), \\ j = 1, 2, \dots, i \end{aligned} \quad (16)$$

where the abatement cost corresponds to the cost of the new technology.

Firms that have not already adopted face a higher abatement cost, since  $c_k > c$ :

$$\begin{aligned} \text{Max}_{q_k, e_k} \pi_k^{NA} = P(Q)q_k - c_k(q_k - e_k)^2 - s(j)(e_k - \varepsilon_k) \\ k = (i+1), (i+2), \dots, n. \end{aligned} \quad (17)$$

The optimal level of emissions and output for each type of firm is given by the FOC for  $(e_j, q_j)$  and  $(e_k, q_k)$ :

$$2c(q_j - e_j) = s(j) \quad (18)$$

$$P(Q) + P'(Q)q_j - 2c(q_j - e_j) = 0 \quad (19)$$

$$2c_k(q_k - e_k) = s(j) \quad \text{and} \quad (20)$$

$$P(Q) + P'(Q)q_k - 2c_k(q_k - e_k) = 0 \quad (21)$$

Equations (18) and (20) indicate that at the optimum, each firm faces a marginal abatement cost equal to the permit price  $s(j)$ . Combining the FOC for  $(e_j, q_j)$  and  $(e_k, q_k)$ , we have:

$$P(Q) + P'(Q)q_j = s(j) \quad \text{and} \quad (22)$$

$$P(Q) + P'(Q)q_k = s(j) \quad (23)$$

The term on the left-hand side of equations (22) and (23) is the marginal benefit of production, while the term in the right-hand side is the marginal abatement cost. At the optimum, each firm faces a benefit per unit of output equal to the permit price  $s(j)$ .

It is easy to show that the emission permit price decreases with the number of firms that have already adopted according to the following function (see appendix B):

$$s^*(j) = \frac{\frac{n^*a}{b(n+1)} - \bar{E}}{j^* \frac{1}{2c} + \sum_{k=j+1}^n \frac{1}{2c_k} + \frac{n}{b(n+1)}} . \quad (24)$$

Notice that the permit price depends inversely on the number of firms that have already adopted. However, the permit price is larger when the output demand is larger ( $a \rightarrow \infty$ ) and more elastic ( $b \rightarrow 0$ ), and when current abatement costs and the cost of the new technology are larger.

Adoption benefits are given by  $(\pi_j^A)^{PERMITS}$ :

$$(\pi_j^A)^{PERMITS} = \left\{ P[Q(s(j))]q_j(s(j)) - c[q_j(s(j)) - e_j^A(s(j))]^2 - s(j)[e_j^A(s(j)) - \varepsilon_j] \right\} - \left\{ P[Q(s(j-1))]q_j(s(j-1)) - c_j[q_j(s(j-1)) - e_j^{NA}(s(j-1))]^2 - s(j-1)[e_j^{NA}(s(j-1)) - \varepsilon_j] \right\} . \quad (25)$$

Adoption benefits come from several sources. First, they come from the direct effect that gives account of the decrease in the costs when the adopters re-optimize the mix of abatement plus emission permits, but it does not account for the effect of adoption on the price of the permits and on the other firms' choice of output. We can assume that the permit price remains equal to  $s(j-1)$  after firm  $j$ 's adoption. Then, it is possible to identify the profits coming from the direct effect  $(\pi_j^A)^{DE}$  so:

$$\begin{aligned} (\pi_j^A)^{DE} &= \left\{ P[Q(s(j-1))]q_j(s(j-1)) - c[q_j(s(j-1)) - e_j^A(s(j-1))]^2 - s(j-1)[e_j^A(s(j-1)) - \varepsilon_j] \right\} \\ &\quad - \left\{ P[Q(s(j-1))]q_j(s(j-1)) - c_j[q_j(s(j-1)) - e_j^{NA}(s(j-1))]^2 - s(j-1)[e_j^{NA}(s(j-1)) - \varepsilon_j] \right\} \\ &= c_j[q_j(s(j-1)) - e_j^{NA}(s(j-1))]^2 - c[q_j(s(j-1)) - e_j^A(s(j-1))]^2 \\ &\quad + s(j-1)[e_j^{NA}(s(j-1)) - e_j^A(s(j-1))]. \end{aligned} \quad (26)$$

Using the FOC for  $(e_j)$ , equation (26) can be re-written as:

$$(\pi_j^A)^{DE} = \underbrace{\left[ \frac{(s(j-1))^2}{4c} - \frac{(s(j-1))^2}{4c_j} \right]}_{>0}. \quad (27)$$

Notice that the direct effect decreases through the sequence as the adopter's current abatement comes closer to the cost of the new technology and as the permit price falls gradually over time when adoption takes place.

The decrease in the permit price leads adopters to increase their emissions output or to buy and sell emission permits at a lower price and thus reduce abatement. This is the strategic effect from the permit market (SEP). If we assume that the other firms' choice of output remains equal to  $\overline{Q}_{-j}(s(j-1))$ , then, it is possible to identify the profits coming from the strategic effect from the permit market  $(\pi_j^A)^{SEP}$  so:

$$\begin{aligned} (\pi_j^A)^{SEP} = & \left\{ P \left[ \overline{Q}_{-j}(s(j-1)) + q_j(s(j)) \right] q_j(s(j)) - c \left[ q_j(s(j)) - e_j^A(s(j)) \right]^2 - s(j) \left[ e_j^A(s(j)) - \varepsilon_j \right] \right\} \\ & - \left\{ P \left[ \overline{Q}_{-j}(s(j-1)) \right] q_j(s(j-1)) - c \left[ q_j(s(j-1)) - e_j^A(s(j-1)) \right]^2 \right. \\ & \left. - s(j-1) \left[ e_j^A(s(j-1)) - \varepsilon_j \right] \right\}. \end{aligned} \quad (28)$$

Finally, the decrease in the permit price reduces the marginal abatement cost of the adopter's rivals, allowing them to increase their output as well. This negative strategic effect from the output market (SEO) reduces the adoption benefits because the lower output price allows adopters to increase their benefits by a smaller fraction than they would have in the absence of this effect.

$$\begin{aligned} (\pi_j^A)^{SEO} = & \left\{ P \left[ \overline{Q}_{-j}(s(j)) \right] q_j(s(j)) - P \left[ \overline{Q}_{-j}(s(j-1)) + q_j(s(j)) \right] q_j(s(j)) \right\} \\ = & \underbrace{\left\{ P \left[ \overline{Q}_{-j}(s(j)) \right] - P \left[ \overline{Q}_{-j}(s(j-1)) + q_j(s(j)) \right] \right\}}_{<0} q_j(s(j)). \end{aligned} \quad (29)$$

Using the FOC for the optimal level of  $(e_j, q_j)$ , the total strategic effect can be re-written as (see appendix C):

$$\begin{aligned}
(\pi_j^A)^{SEP} + (\pi_j^A)^{SEO} = & \frac{1}{b} \left\{ \underbrace{\left[ \frac{a-s(j)}{n+1} \right]^2 - \left[ \frac{a-s(j-1)}{n+1} \right]^2}_{>0} \right\} - \underbrace{\left[ \frac{(s(j-1))^2 - (s(j))^2}{4c} \right]}_{>0} \\
& - \underbrace{[s(j-1) - s(j)]}_{>0} \varepsilon_j.
\end{aligned} \quad (30)$$

The first term on the right-hand side of equation (30) represents the net benefits of increasing the output: the larger the market price elasticity ( $b \rightarrow 0$ ), the larger the benefits of increasing the output. The second term represents the decrease in savings from the abatement costs via increased permits purchases rather than increased abatement. The larger the decrease in the permit price, the larger the decrease in the abatement costs' savings. The third term represents the capital losses resulting from the lower price of freely allocated permits. Thus, if the number of freely allocated permits is larger, the capital losses are greater.

Finally, notice that the market price elasticity also affects the total strategic affect by modifying the level of the permit price. Here, if the market price elasticity is greater, then the permit price is higher.

From equation (30), it is straightforward that auctioned permits offer larger incentives to adopt than freely allocated permits, since the total strategic effect decreases when permits are freely allocated. When there are a larger number of freely allocated permits, then there is a greater difference between the adoption incentives from auctioned and freely allocated permits. If permits are allocated in proportion to historical emissions, older firms in the sequence receive more permits. Therefore, the difference between the adoption incentives provided by auctioned and freely allocated permits is larger for those firms.

Note that the permit price falls more gradually as the adopter's current abatement comes closer to the cost of the new technology. This smaller permit price variation reduces the decrease in the savings and the capital losses of the abatement. Therefore, if the total strategic effect is negative, one would expect it to increase throughout the sequence of adoption. On the other hand, if the total strategic effect is positive, one would expect it to decrease throughout the sequence of adoption.

Combining equations (27) and (30), we get the total adoption benefits under permits  $(\pi_j^A)^{PERMITS}$  :

$$(31)$$

$$(\pi_j^A)^{PERMITS} = \frac{1}{b} \left\{ \left[ \frac{a-s(j)}{n+1} \right]^2 - \left[ \frac{a-s(j-1)}{n+1} \right]^2 \right\} + \left[ \frac{(s(j))^2}{4c} - \frac{(s(j-1))^2}{4c_j} \right] - [s(j-1) - s(j)] \varepsilon_j$$

Again, total adoption profits depend on the number of permits freely allocated to a firm, on the permit price variation, and on the market price elasticity. Notice that the market price elasticity affects the adoption benefits by two means. First, it modifies the benefits of increasing output; and second, it modifies the level of the permit price, since as the market price elasticity increases, so does the permit price.

### 2.3 Taxes versus Permits

Suppose we compare the direct effect under taxes and permits. By regulatory design,  $s(j-1)$  is higher than  $\sigma$ . Then, if we compare equations (15) and (27), we see that the direct effect is larger under permits. This results runs counter Montero (2002a), who found that direct effects were lower under permits. The key to his result was the myopic behavior of the regulator. Under Montero's framework, the tax remained the same, while the permit price fell because of adoption. Thus, one sees more abatement with taxes and therefore profits coming from adoption. On the other hand, if the regulator is forward looking, the optimal tax is lower than under a myopic regulator, which weakens the incentive to adopt. Nevertheless, with permits, the cap is set tighter, which increases the permit price in the short run. The permit prices gradually drops over time, to the *ex post* optimal tax level, as more firms adopt the technology.

Subtracting equation (15) from equation (31),  $(\pi_j^A)^{PERMITS} - (\pi_j^A)^{TAX}$  produces this:

$$\begin{aligned} (\pi_j^A)^{PERMITS} - (\pi_j^A)^{TAX} &= \frac{1}{b} \left\{ \left[ \frac{a-s(j)}{n+1} \right]^2 - \left[ \frac{a-s(j-1)}{n+1} \right]^2 \right\} \\ &\quad + \left[ \frac{(s(j))^2 - \sigma^2}{4c} \right] - \left[ \frac{(s(j-1))^2 - \sigma^2}{4c_j} \right] - [s(j-1) - s(j)] \varepsilon_j. \end{aligned} \tag{32}$$

#### Proposition 1

With Cournot competition in the output market and a forward-looking regulator, the number of periods that elapses until all firms adopt the new technology with emission taxes is greater, smaller, or the same than the number of periods that elapses until all firms adopt the new technology under freely-allocated permits.

**Proof:** Let us compute the adoption benefits for the last firm in the sequence. By regulatory design,  $s(n)$  coincides with  $\sigma$ . Then, equation (32) becomes:

$$(\pi_n^A)^{PERMITS} - (\pi_n^A)^{TAX} = \frac{1}{b} \left\{ \left[ \frac{a - \sigma(b)}{n+1} \right]^2 - \left[ \frac{a - s(n-1, b)}{n+1} \right]^2 \right\} - \left\{ \frac{[s(n-1, b)]^2 - [\sigma(b)]^2}{4c_n} \right\} - [s(n-1, b) - \sigma(b)] \varepsilon_n. \quad (33)$$

The comparison between taxes and freely allocated tradable permits depends ultimately on the market price elasticity. If the output demand is more elastic ( $b \rightarrow 0$ ), then the benefits of increasing the output offset the decrease in the savings and the capital losses of the abatement. In this case, permits provide more incentive to adopt the new emission-reducing technology than taxes. On the other hand, if output demand is more inelastic ( $b \rightarrow \infty$ ), then taxes are likely to be a greater incentive to adopt than freely-allocated permits, since the benefits of increasing the output do not offset the *decrease in the savings and the capital losses of the abatement*.

**Corollary:** There is a critical value of the slope of the inverse demand function  $b^*$  determining the ranking between taxes and freely allocated tradable permits. If value of the slope of the inverse demand function is smaller than  $b^*$ , then freely-allocated permits induce an earlier technological diffusion. On the other hand, if value of the slope of the inverse demand function is larger than  $b^*$ , then taxes induce an earlier technological diffusion.

## Proposition 2

Under Cournot competition in the output market and a forward-looking regulator, the number of periods that elapses until all firms adopt the new technology under emission taxes is larger, smaller, or the same than number of periods that elapses until all firms adopt the new technology under auctioned permits.

**Proof:** Let us compute the adoption benefits for the last firm in the sequence. By regulatory design,  $s_n$  coincides with  $\sigma$  and since firm  $n$  does not receive any permits,  $\varepsilon_n = 0$ . Then, (33) becomes:

$$(\pi_n^A)^{PERMITS} - (\pi_n^A)^{TAX} = \frac{1}{b} \left\{ \left[ \frac{a - \sigma(b)}{n+1} \right]^2 - \left[ \frac{a - s(n-1, b)}{n+1} \right]^2 \right\} - \left[ \frac{[s(n-1, b)]^2 - [\sigma(b)]^2}{4c_n} \right] \quad (34)$$

The comparison between taxes and freely allocated tradable permits depends ultimately on the market price elasticity. If the output demand is more elastic ( $b \rightarrow 0$ ), the first term on the

right-hand side of (34) offsets the second term and auctioned permits offer larger incentives to adopt than taxes. On the other side, if the output demand is more inelastic ( $b \rightarrow \infty$ ), (34) becomes negative and taxes offer larger incentives to adopt than auctioned permits. Then, if the output demand is more elastic ( $b \rightarrow 0$ ), auctioned permits induce an earlier technological diffusion than taxes.

**Corollary:** There is a critical value of the slope of the inverse demand function  $b^{**}$  determining the ranking between taxes and auctioned tradable permits. If the value of the slope of the inverse demand function is smaller than  $b^{**}$ , then auctioned permits induce an earlier technological diffusion. On the other side, if the value of the slope of the inverse demand function is larger than  $b^*$ , taxes induce an earlier technological diffusion.

### Proposition 3

Under Cournot competition in the output market and a forward-looking regulator, the number of periods that elapses until all firms adopt the new technology under auctioned permits is smaller than number of periods that elapses until all firms adopt the new technology under freely allocated permits.

**Proof:** Let us compute the difference in adoption benefits under auctioned permits  $\pi^{AP}$  and freely allocated permits  $\pi^{FAP}$  for the last firm in the sequence:

$$(\pi_n^A)^{AP} - (\pi_n^A)^{FAP} = [s(n-1, b) - \sigma(b)] \varepsilon_n. \quad (35)$$

Since  $s(n-1, b) > \sigma(b)$  and  $\varepsilon_n > 0$ , adoption benefits are larger under auctioned permits. Then, auctioned permits induce an earlier technological diffusion than freely allocated permits.

**Corollary:** The critical value of the slope of the inverse demand function  $b^*$  determining the ranking between taxes and freely allocated tradable permits is lower than the critical value of the slope of the inverse demand function  $b^{**}$  determining the ranking between taxes and auctioned tradable permits. Thus, auctioned tradable permits induce an earlier technological diffusion than taxes and freely allocated permits when  $b \in [b^*, b^{**}]$ .

In order to illustrate previous propositions, next section presents some numerical simulations that give account of the magnitude of the direct effect and strategic effects.

### 3. Simulations

In this section, I analyze the impacts of the choice of policy instruments over the diffusion of the new technology. For that purpose, I undertake a numerical simulation to analyze

how many periods elapse until all firms adopt the new technology under taxes and permits. The parameters are chosen to have direct and strategic effects of similar magnitude.

As did Montero (2002a), I present the results for two demand curves: an “inelastic” demand and an “elastic” demand. Let  $P(Q) = 300 - 3.5Q$  be the “inelastic demand” curve and let  $P(Q) = 300 - 0.2Q$  be the “elastic demand” curve.

I assume the industry composed of  $n = 5$  firms. The current marginal abatement costs  $c_i$  range between 12 and 14 uniformly. The marginal cost of the new technology is equal to  $c = 10$ . The marginal environmental damage is equal to  $E$  ( $\gamma = 1$ ).

The rate of discount is equal to 6 percent, while the rate of learning ranges between 3.8 percent and 3.96 percent. The investment required to bring the technology in use is equal to US\$ 5000.

Table 1 below shows the results for the “inelastic demand” case. Before the arrival of the new technology, the regulator allows 60 units to be emitted. After that, the allowed level of emissions is capped at 50, which is achieved by setting an emission tax  $\sigma = 124$ , freely allocating or auctioning off a total number of permits  $\bar{E} = 60$ . I assume that if permits are freely allocated, firms receive permits in proportion to their level of emissions before the arrival of the new technology. Thus, older firms in the sequence receive more permits.

As is shown in table 1, the direct effect is larger under permits. As discussed earlier, the regulator increases the stringency of permits in response to the arrival of the new technology, while the reverse holds for the emission tax. The increase in the permit price leads to an increase in the adopters’ amount of abatement, and thus the direct effect, while the reverse, holds for the emission tax.

As the output demand is more inelastic, the total strategic effect is negative. Throughout the sequence of adoption, the adopters’ current abatement cost comes closer to the marginal abatement cost of the new technology, and the permit price falls more slowly. Thereby, the direct effect becomes smaller since the abatement does not increase much in response to adoption. On the other hand, the total strategic effects become less negative because newer firms in the sequence receive fewer permits (and therefore capital losses are smaller) and because the permit price falls more slowly.

**Table 1 Inelastic Demand Case ( $b = 3.5$ )**

Firm i	1	2	3	4	5
<b>Uniform emission tax</b>					
Total effect	58.29	56.31	54.38	52.27	50.19
Date of adoption	56.00	56.40	56.90	57.40	57.90
<b>Freely allocated permits</b>					
Direct effect	70.75	65.46	60.60	56.11	51.95
Total strategic effect	-17.50	-15.72	-14.14	-12.74	-11.48
Total effect	53.25	49.74	56.54	43.37	40.47
Date of adoption	58.40	59.70	60.90	62.20	63.40
<b>Auctioned tradable permits</b>					
Direct effect	70.75	65.46	60.60	56.11	51.95
Total strategic effect	-8.06	-7.07	-6.22	-5.47	-4.82
Total effect	62.69	58.39	54.38	50.64	47.13
Date of adoption	54.10	55.50	56.90	58.20	59.50

As the total strategic effect offsets the direct effect for the last firms in the sequence of adoption, the number of periods that elapses until all firms adopt the new technology is larger under permits. In this numerical example, it takes the industry 58 periods to adopt the new technology if an emission tax is used. However, if auctioned permits are used, diffusion takes more than 60 periods, while under an emission tax this period is extended to more than 55 years.

Table 2 below shows the results for the “elastic demand” case. The *ex ante* amount of emissions is equal to 1000, while *ex post* efficiency allows 930 units to be emitted, which is achieved by setting an emission tax  $\sigma = 213$ , freely allocating, or auctioning off a total number of permits  $\bar{E} = 930$ .

Again, the direct effect is larger under permits. However, in contrast to the “inelastic” demand case, the total strategic effect is positive under auctioned permits. Thus, auctioned permits produce the earliest diffusion, followed by taxes and freely allocated permits.

**Table 2 Elastic Demand ( $b = 0.2$ )**

<b>Firm i</b>	<b>1</b>	<b>2</b>	<b>3</b>	<b>4</b>	<b>5</b>
<b><i>Uniform emission tax</i></b>					
Total effect	321.83	292.03	259.94	225.28	187.73
Date of adoption	11.10	13.60	16.50	21.10	24.60
<b><i>Freely allocated permits</i></b>					
Direct effect	330.32	297.78	263.49	227.16	188.44
Total strategic effect	-35.23	-31.75	-27.55	-23.52	-19.32
Total effect	295.09	266.33	235.94	203.64	169.13
Date of adoption	13.30	16.00	15.50	19.20	27.30
<b><i>Auctioned tradable permits</i></b>					
Direct effect	330.32	297.78	263.49	227.16	188.44
Total strategic effect	9.10	8.35	7.50	6.55	5.49
Total effect	339.42	306.13	270.99	233.71	193.94
Date of adoption	9.70	12.40	15.50	19.20	23.80

It can be seen that in the “elastic demand case,” firms adopt earlier regardless of the policy instrument. In fact, it takes a much shorter period for policy instruments to encourage the diffusion of the new technology. The reason is the greater stringency of the policies. In the Cournot game without any regulation, the level of output depends inversely on the price elasticity. Then, if the output demand is more elastic, the initial level of emissions is higher, as is the required stringency of the environmental policies. The greater stringency of the policies increases the adoption benefits and speeds up the sequence of adoption.

The timing of adoption also depends strongly on the marginal abatement cost of the new technology and the current abatement costs’ heterogeneity. If the reduction in the marginal abatement cost is substantial, we should see earlier adoption. The same result would be obtained if sources were less heterogeneous. In this case, adoption profits are quite similar among firms, as is the optimal date of adoption.

#### **4. Total Welfare and the Timing of Adoption**

In the previous sections, I simulated the pattern of adoption produced by taxes, auctioned permits, and freely allocated permits. However, determining which instrument is optimal

requires identifying the social welfare associated with each pattern. Social welfare can be written as the discounted sum of consumer surplus plus firms profits (exclusive of taxes or profits from permit trades<sup>6</sup>) minus emission damages and investment costs. Let  $Q(i)$  and  $E(i)$  be the aggregate output and aggregate emissions when  $i$  firms are using the new technology and  $(n-i)$  continue using current technologies. Given the demand curve, the consumer surplus  $CS(i)$  is equal to:

$$CS(i) = \frac{b}{2} * (Q(i))^2 . \quad (34)$$

Total emissions' damage is equal to  $\frac{\gamma}{2} E^2(i)$ . Therefore, if  $i$  firms are using the new technology, social welfare is given by  $W(i)$ :

$$W(i) = \left[ \frac{b}{2} * (Q(i))^2 - \frac{\gamma}{2} E^2(i) + \sum_{m=1}^i \pi_m^A + \sum_{m=i+1}^n \pi_m^{NA} - Ke^{-\theta_i \tau_i} \right] * e^{-\delta \tau_i} . \quad (35)$$

Table 3 shows consumer surplus, environmental damages, profits, investment costs, and social welfare for the “inelastic demand case.”

By regulatory design, each instrument induces the optimal *ex post* amount of emissions once technological diffusion is completed, but also the same *ex post* amount of output since the abatement cost is the only production cost.

Since the optimal tax  $\sigma$  is reduced, firms increase the output immediately after the policy adjustment. Permits, instead, lead firms to increase the output gradually towards the *ex post* optimal level. Thus, taxes produce the largest consumer surplus throughout the sequence of adoption.

With permits, environmental damages stay the same throughout the sequence of adoption since emissions are capped at the *ex post* optimal level before adoption starts. With taxes, adoption leads firms to reduce emissions gradually towards the *ex post* level. Therefore, taxes produce the largest environmental damage. Since the output demand is inelastic, profits are larger under taxes because the strategic effects offset the direct effects.

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<sup>6</sup> Incomes from permit transactions or tax payment are not included, since these represent only transfers among firms and the government.

After accounting for consumer surplus, environmental damage, profits, investment costs, and the timing of adoption, the results indicate that emission taxes produce the largest social welfare, followed by auctioned permits and freely allocated permits. Table 4 shows consumer surplus, environmental damages, profits, investment costs, and social welfare for the “elastic demand case.”

Again, output and emissions are greater under taxes. Taxes, then, produce the largest consumer surplus and environmental damage throughout the sequence of adoption. Since the output demand is elastic, strategic effects are positive under auctioned permits. Therefore, they produce the largest profits, the earliest diffusion, and the largest social welfare. Emission taxes and freely allocated permits follow them.

**Table 3 Social Welfare and Inelastic Demand ( $b = 3.5$ )**

<b>Firm i</b>	<b>1</b>	<b>2</b>	<b>3</b>	<b>4</b>	<b>5</b>
<b><i>Uniform emission tax</i></b>					
Consumer surplus	3590.5	3590.5	3590.5	3590.5	3590.5
Environmental damage	236.3	214.5	194.5	176.2	159.4
Firm's profits	5231.6	5171.3	5113.0	5056.7	5002.3
Total investment costs	595.4	573.3	549.8	527.0	504.9
Discounted welfare	278	270	262	254	246
<b><i>Freely allocated permits</i></b>					
Consumer surplus	3274.1	3361.0	3442.5	3518.9	3590.5
Environmental damage	159.4	159.4	159.4	159.4	159.4
Firm's profits	4925.4	4882.6	49880.4	4908.2	4902.0
Total investment costs	543.5	505.1	470.7	436.6	406.1
Discounted welfare	225.5	210.8	199.1	187.5	176.6
<b><i>Auctioned tradable permits</i></b>					
Consumer surplus	3274.1	3361.0	3442.5	3518.9	3590.4
Environmental damage	159.4	159.4	159.4	159.4	159.4
Firm's profits	4925.4	4882.6	4880.4	411	4902.0
Total investment costs	640	593	550	511	474
Discounted welfare	290	169	251	236	220

In sum, the numerical simulation suggest that if firms engage in imperfect competition on the output market, a forward looking regulator speeds up the sequence of adoption by the choice of auctioned permits if the output demand is more elastic.

**Table 4 Social Welfare and Elastic Demand ( $b = 0.2$ )**

Firm i	1	2	3	4	5
<b>Uniform emission tax</b>					
Consumer surplus	13363.9	13363.9	13363.9	13363.9	13363.9
Environmental damage	51710.8	50829.7	50051.8	49382.5	48828.1
Firm's profits	78918.7	78567.1	78243.0	77948.4	77685.6
Total investment costs	3279.3	2966.0	2635.9	2273.9	1887.5
Discounted welfare	19159	16863	14461	11873	9218
<b>Freely allocated permits</b>					
Consumer surplus	12738.1	12927.2	13095.7	13241.9	13363.9
Environmental damage	48828.1	48828.1	48828.1	48828.1	48828.1
Firm's profits	76836.3	76638.4	76806.7	77219.6	77310.1
Total investment costs	3016.3	2704.8	2392.3	2053.6	1696.1
Discounted welfare	16987.1	14562.4	12371.2	10138.3	7803.8
<b>Auctioned tradable permits</b>					
Consumer surplus	12738.1	12927.2	13095.7	13241.9	13363.9
Environmental damage	48828.1	48828.1	48828.1	48828.1	48828.1
Firm's profits	76836.3	76638.4	76806.7	77219.6	77310.1
Total investment costs	3459	3106	2740	2356	1948
Discounted welfare	20936	17949	15166	12438	9582

## 5. Conclusions

This paper explores how the choice between taxes and permits affects the pattern of adoption of an environmentally friendly technology when firms engage in imperfect competition on the output market and the regulator commits to the optimal *ex post* amount of emissions. The study concludes that when the output demand is more elastic, the regulator speeds up technological diffusion by using auctioned permits instead of emission taxes or freely allocated permits.

This question has been previously addressed by Montero (2002a), where he generated a different ranking supporting the use of taxes over auctioned permits. The key to Montero's result is the myopic behavior of the regulator—that is, the regulator does not adjust the environmental policy and neither reduces the tax nor decreases the industry-wide cap in response to the availability of a new technology. Under such a framework, the tax remains the same, while the permit price falls due to adoption. Hence, there is more abatement with taxes and too much profit with adoption when compared to tradable permits.

The assumption of a myopic regulator is used frequently in technology adoption literature. However, if the regulator observes the arrival of a new technology, this assumption is not longer plausible since the regulator chooses policy optimally with respect to the available technologies to minimize the social cost of pollution control. If, in response to the advent of a new technology, the regulator commits to the ex post optimal environmental policy, the ranking is reversed. Therefore, it is clear that the influence of regulation on technological adoption is complex and depends not only on the design and instrument choice but also on the timing of the regulatory interventions. This issue should be explored further, since few if any industries fit in cases where a regulator either acts myopically or engages in ex ante or ex post regulation. Instead, regulatory adjustments can be costly and regulator must offset the benefits and costs of changing policies before implementing policy adjustments.

Another contribution of this paper introduces a dynamic setting in which to compare the rate of diffusion produced by different policy instruments. Here, firms adopt sequentially, and the regulator can alter the number of the periods that elapses until the new technology is diffused over the industry by the choice of policy. Even though the introduction of dynamics does not affect the results very much, it allows one to compare how long it takes each policy to reach the optimal situation and what happens throughout the trajectory.

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