UNIVERSITY OF GOTHENBURG
SCHOOL OF BUSINESS, ECONOMICS AND LAW

WORKING PAPERS IN ECONOMICS

No 442

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April, 2010

ISSN 1403-2473 (print)
ISSN 1403-2465 (online)

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Taxes, Permits and Costly Policy Response to Technological Change*

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Abstract

In this paper we analyze the effects of the choice of price (taxes) versus quantity (tradable permits) instruments on the policy response to technological change. We show that if policy responses incur transactional and political adjustment costs, environmental targets are less likely to be adjusted under tradable permits than under emission taxes. This implies that the total level of abatement over time might remain unchanged under tradable permits while it will increase under emission taxes.

Keywords: Environmental Taxes, Tradable Permits, Technology Adoption, Policy Adjustment, Regulatory Costs

*The authors are very grateful to Juan Pablo Montero, Katrin Millock, Jiegen Wei, Fredrik Carlsson and Olof Johansson-Stenman for helpful comments. Research funding from Mistra's Climate Policy Research Program (CLIPORE) and Adlerbertska is gratefully acknowledged.

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JEL codes: H82, O32, O33, Q52, Q55, Q58

1 Introduction

Continued R&D and adoption of cleaner technologies are key requirements for sustainable development in the long run. Nevertheless, society will not benefit much from technological progress if the policy architecture is not flexible enough to allow for updating of environmental targets when cleaner technologies become available [1]. Since the choice of policy instrument influences firms' decision to adopt new technologies that reduce abatement costs and the environmental policy targets are conditioned on industry-wide aggregate abatement costs [2], the incentives to adopt new technology provided by different policies have important implications with respect to the need for policy adjustment. In this paper we analyze the effects of the choice of price (taxes) versus quantity (tradable permits) instruments on the optimal policy response to technological change. It is shown that the social losses of allowing for an inefficient level of emissions as well as the decision to adjust the stringency of environmental policies depend not only on the policy instrument in place but also on transactional and/or political adjustments costs.

There are many studies analyzing the links between environmental policy and technology adoption.[1] However, to our knowledge, the effect of the choice of policy instruments on the policy response to technology adoption has not yet been directly addressed. Most studies model the regulation-investment game as a two-stage game, where the regulator is assumed to either act myopically (e.g., [7], [14], and [11]) or

[1] See [18] for a review of the literature on incentives provided by environmental policy instruments for adoption of advanced abatement technology.

engage in ex-ante or ex-post regulation (e.g., [3], [12], [8], and [17]). The incentives provided by price (taxes) and quantity (tradable permits) policies are then compared. If the regulator makes long-term commitments to policy levels and does not adjust the level of the policy in response to arrival of new technology, taxes provide stronger incentives for firms to adopt new technologies than do permits. Instead, if the regulator anticipates new technologies and adjusts the policy levels, taxes and permits will induce first-best outcomes if firms move first, whereas only permits will induce the first-best outcome if the regulator moves first ([17]).

In practice, transactional and political costs may prevent or delay the regulator from implementing her preferred policy or updating such policies in response to new market conditions ([4], [15], [9], [6], and [13]). Transactional and administrative adjustment costs arise since contracts are costly to write and enforce. Policy updating might require costly studies and/or much time spent instructing firms and monitoring and enforcement officers. Political costs of adjustment arise from contrasting the preferences of environmentalists and industry when these groups try to influence the policy outcome through lobbying.

The regulator may therefore respond to the advent of the new technology after a certain (endogenously given) lapse of time and/or adjusting the policy to a low extent. Thus, the links between policy adjustments and technology adoption seem to be two-directional: (1) costly policy adjustment might influence the decision to adjust policy intruments and/or the level of the adjusted policies, which influences firms' incentives to further technology adoption in the industry, and (2) the availability of a new technology that reduces abatement costs might influence the regulator's decision to adjust the policy level.

The aim of this paper is to compare emission taxes and tradable permits in terms of these links. We develop a model where the regulator maximizes social welfare subject to transactional and/or political costs that may prevent updating of environmental targets. Between policy reviews, firms face two decisions: the choice of abatement level and the choice of adopting a new technology that reduces the costs of compliance with environmental regulation. The latter takes the form of either emission taxes or auctioned tradable permits. We characterize firms' solutions and the resulting dilemmas for the regulator.

As soon as some firms (having the lowest investment cost) begin adopting the new technology, the stringency of the policy (which is based on the aggregate abatement costs corresponding to the current abatement technology) is no longer efficient. The regulator must now decide whether to adjust the policy, and if so by how much, taking into account (i) the lower aggregate abatement cost, (ii) the social losses of allowing for an inefficient level of emissions, (iii) the policy adjustment costs, and (iv) the policy effects on further adoption among firms. We identify the magnitude of these pros and cons as well as the thresholds at which the policy adjustment costs outweigh the welfare gain under taxes and permits.

We conclude that if a policy update implies fixed transactional costs, the regulator will be more prone to adjust the environmental target under emission taxes than under auctioned permits. The result is explained by inefficient investment behavior under taxes; firms overinvest since the tax is set at a more demanding level and the regulator can induce larger welfare gains by adjusting the tax level and hence influence investment incentives.

Also in the case of political costs, the regulator is more prone to adjust the environmental target under emission taxes than under permits. However, in this case, the result is explained by the fact that the cap on emissions becomes more stringent as aggregate abatement costs are reduced while the optimal tax becomes more lax. In the presence of powerful lobbying by industry that can skew the policy adjustment process to benefit its economic interests, the reduced stringency of taxes makes adjustment less costly and more likely, while the reverse holds in the case of the emissions cap.

Our model is simplified in a number of aspects to keep the analysis tractable. For example, we analyze a flow rather than a stock pollutant. Also, we assume an industry comprising a continuum of firms. Therefore, single firms cannot influence the level of the policy through their adoption decisions. Finally, we focus on a discrete technological improvement and a once and for all policy adjustment. In spite of these simplifications, the analysis provides a useful starting point for assessing the economic incentives for updating environmental policies in response to technology adoption under different environmental policies.

The paper is organized as follows. The next section introduces the technology adoption model. Section 3 analyzes the effects of introducing policy adjustment costs. Section 4 compares the effects of policy adjustment on welfare and derive propositions about the optimal timing of policy adjustments under taxes and tradable permits. Section 5 concludes the paper.

2 The Model

Consider a competitive industry consisting of a continuum of firms of mass 1. Let Q be the aggregate level of abatement in the industry and $q_i \in [0, 1]$ abatement in a single firm i. Emissions from each firm is $1 - q_i$; i.e., without any abatement, each firm emits one unit of a homogeneous pollutant. Before the new technology becomes available, firms' abatement cost functions are homogeneous[2] with total abatement costs equal to:

$$\digamma q_i + cq_i^2 \quad \digamma > 0, c > 0 \quad \forall i \tag{1}$$

Firms are subject to the regulator's policy instrument, which could take the form of Pigovian taxes or auctioned tradable permits. Each firm selects a level of abatement to minimize the sum of abatement costs and payments for non-reduced emissions according to the following problem:

$$\min_{q_i} \mu_i = \left\{ \digamma q_i + cq_i^2 + x(1 - q_i) \right\} \quad , \tag{2}$$

where x denotes the "equilibrium permit price" of emissions and the last term in (2) is payments for non-reduced emissions $(1 - q_i)$. Therefore, the first-order condition (FOC) for the optimal level of abatement is given by:

$$\digamma + 2cq_i = x \quad \forall i. \tag{3}$$

That is, firms reduce emissions until the marginal abatement cost equals the price of emissions.

Let us now consider the optimal level of the regulation in place before the arrival of the new technology. The regulator's social welfare W equals abatement benefit less abatement costs, adoption costs, and the cost of adjusting the policy. Let us

[2]To keep the analysis mathematically tractable and simple, we assume that firms are homogeneous in terms of initial abatement costs. Nevertheless, our results still hold in the case of heterogeneous abatement. For example, following [5], we could have assumed that firms current abatement costs are heterogeneous and that firms can be ordered according to their adoption savings from the firm with the highest to the firm with the lowest current abatement cost. Therefore, the arbitrage condition that states that for the marginal adopter the adoption savings offsets the adoption costs still holds. In such a setting, and as shown later, adopters will increase their abatement effort due to the availability of the new technology and will reduce their demands for emissions.

assume that the total abatement benefit function is given by $B(Q)$, with $B'(Q) > 0$ and $B''(Q) < 0$. Then, given (1), the aggregate abatement cost corresponding to the current abatement technology is given by $C(Q) = FQ + cQ^2$, and social welfare is given by:

$$W = B(Q) - FQ - cQ^2. \tag{4}$$

Differentiating (4) with respect to Q, we obtain the optimal aggregate level of abatement in place before the arrival of the new technology:

$$\overline{Q}_0 = \frac{B'(\overline{Q}_0) - F}{2c}, \tag{5}$$

where $\overline{Q}_0 > 0$. From (3) and (5) follows that the optimal tax τ required to induce such a level of abatement is given by the marginal damage:

$$\tau_0 = B'(\overline{Q}_0). \tag{6}$$

By analogy, the permit price that clears the market before the arrival of the new technology is given by:

$$p_0 = B'(\overline{Q}_0). \tag{7}$$

The optimal cap on emissions $\bar{\epsilon}_0^*$ is given by $\left[1 - \overline{Q}_0\right]$. Note that the permit price is a positive function of the stringency of the cap on emissions. The more stringent the cap, due to a greater marginal benefit in (7), the higher the equilibrium permit price p_0.

2.1 Rate of Adoption with Different Policy Instruments

When the new technology becomes available, each firm independently decides whether to invest in and install the new technology. Adopting the new technology requires a fixed investment cost k_i for firm i, where $k_i \sim U(\underline{k}, \overline{k})$[3], and shifts the firm's abatement cost function in (1) downwards by $\mathit{\Gamma} q_i$. Hence, the new abatement cost function for adopting firms becomes cq_i^2. Let μ_{Bi} and μ_{Ai} denote firm i's total costs before and after technological adoption, respectively, such that the cost saving from adopting is $\mu_{Bi} - \mu_{Ai}$. Any firm whose cost saving offsets its adoption cost will adopt the new technology. In the continuum of firms, the marginal adopter is then identified by the arbitrage condition:

$$\mu_{NAi} - \mu_{Ai} = \widehat{k_i} \in [\underline{k}, \overline{k}], \tag{8}$$

i.e., the total cost saving of adopt (A) compared to no-adopt (NA) at least outweighs the adoption cost for adopters. Hence, the rate of firms $\lambda \in [0, 1]$ adopting the new technology is defined by the integral:

$$\begin{aligned} \lambda &\equiv \int_{\underline{k}}^{\widehat{k_i}} f(k_i)dk = F(\widehat{k_i}) = F(\mu_{NAi} - \mu_{Ai}) = \frac{\mu_{NAi} - \mu_{Ai} - \underline{k}}{\overline{k} - \underline{k}}, \\ &= \psi(\mu_{NAi} - \mu_{Ai}) - \frac{\underline{k}}{\overline{k} - \underline{k}} \in [0, 1]. \end{aligned} \tag{9}$$

where the RHS follows from the definition of the uniform cumulative distribution to $k_i \sim U(\underline{k}, \overline{k})$ and $\psi = \frac{1}{\overline{k} - \underline{k}} \leq 1$. For simplicity, we assume that $\frac{\underline{k}}{\overline{k} - \underline{k}} \approx 0$.

[3]The assumption that adoption costs differ among firms is not new in the literature analyzing the effects of the choice of policy instruments on the rate of adoption of new technologies. See for example [16]. On the other hand, [19] point out that although a majority of the theoretical and empirical literature on technological adoption concentrates on the demand side alone, supply-side forces might be very important in explaining patterns of adoption in practice. Thus, for example, costs of acquiring new technology might vary among firms due to firm characteristics - e.g., location or output, or to competition among suppliers of capital goods.

Note that the rate of adoption $\lambda \in [0,1]$ is endogenous to the policymaker's choice of policy instrument, the stringency of the environmental policy, and the firms' own optimal responses to the choice of policy instrument and its stringency. Hence, the rate of adoption, which by (9) is a fraction of the cost saving from adoption $\Delta\mu_i$, is:

$$\lambda \equiv \psi \Delta\mu_i \equiv \psi \left[\min_{q_{NAi}} \mu_{NAi} - \min_{q_{Ai}} \mu_{Ai} \right], \tag{10}$$

where the RHS is the marginal adopter's optimization problems without and with adoption of technology:

$$\min_{q_{NAi}} \mu_{NAi} = \left\{ \digamma q_{NAi} + c q_{NAi}^2 + x(1 - q_{NAi}) \right\}, \tag{11}$$

$$\min_{q_{Ai}} \mu_{Ai} = \left\{ c q_{Ai}^2 + x(1 - q_{Ai}) \right\}. \tag{12}$$

It is sufficient to keep track of the marginal adopter's optimal choices of abatement in order to derive the rate of adoption. Thus, the subscript i is hereinafter omitted. The first-order conditions (FOC) of (11) and (12) are then:

$$\digamma + 2cq_{NA} = x, \tag{13}$$

$$2cq_A = x. \tag{14}$$

That is, firms reduce emissions until the marginal abatement cost equals the price of emissions, and adopters' levels of abatement are increased due to the availability of the new technology.

If the policymaker chooses regulation by a tax (T), the "price" x of emissions represents the tax τ. Substituting τ in (13) and (14), the rate of adoption in (10) is given by:

$$\lambda_m^T \equiv \psi \Delta \mu_m^T = \psi \digamma \left[\frac{\tau_m}{2c} - \frac{\digamma}{4c} \right] \quad m = F, E, \tag{15}$$

where m refers to the policy adjustment cost scenario that corresponds to the two different structures: fixed transactional adjustment cost (F) and endogenous political adjustment cost (E), which will be discussed in Section 3. Note that the rate of adoption depends positively on the stringency of the tax policy τ_m, and it is positive if $\tau_m > \digamma/2$. The larger the emission tax, the larger the rate of adoption.

If the industry instead is regulated by auctioned permits (P), the "price" of emissions represents the endogenous equilibrium market price p. Substituting p into (13) and (14), the rate of adoption in (10) is given by:

$$\lambda_m^P \equiv \psi \Delta \mu_m^P = \psi \digamma \left[\frac{p(\overline{Q}_m)}{2c} - \frac{\digamma}{4c} \right] \quad m = F, E. \tag{16}$$

Market clearing on the permit market requires that the policy-prescribed level $\overline{Q}_m$ equals aggregate demand by adopting and non-adopting firms:

$$\overline{Q}_m = \lambda_m^P q_A(p) + [1 - \lambda_m^P] q_{NA}(p). \tag{17}$$

Substituting (16) into (17) and solving for the price function, adjusted for the diffusion of the new technology in the industry, yield:

$$p(\overline{Q}_m) = \alpha \overline{Q}_m + \beta, \tag{18}$$

where $\alpha = \left[\frac{8c^2}{4c + 2\psi \digamma^2} \right]$ and $\beta = \left[\frac{4\digamma c + \psi \digamma^3}{4c + 2\psi \digamma^2} \right]$. Still, the endogenous permit price is a positive function of the stringency of the cap on emissions $\overline{Q}_m$.

As discussed in the introduction, several researchers have found that the incentive to adopt new technologies is greater under taxes than under tradable permits when the regulator is myopic and she does not adjust the level of the policy in response to the advent of the new technology. The superiority of taxes is due to the fact that the emissions price is fixed under the tax regime while it falls under the tradable permit regime as the cost-reducing technology diffuses into the industry. This creates a wedge between the two instruments and between the rates of adoption they induce. Indeed, substituting the cap (5) into (18) yields the equilibrium permit price that would hold if the stringency of the cap on emissions is not adjusted:

$$p(\overline{Q}_0) = \frac{4cB'(\overline{Q}_0) + \psi \digamma^3}{4c + 2\psi \digamma^2}. \tag{19}$$

Note that $p(\overline{Q}_0)$ in equation (19) is smaller than τ_0 if $p(\overline{Q}_0) > \digamma/2$; that is, $p(\overline{Q}_0) < \tau_0$ if $\lambda_m^P > 0$. On the other hand, $Q_0^T > \overline{Q}_0$.[4]

3 Policy Adjustment Subject to Costs

After the arrival of the new technology, adopting firms will adjust the abatement level and the regulator should increase the policy stringency for the policy to remain efficient. However, in practice, there are several types of constraints, such as transactional, administrative, and political constraints, characterizing the regulatory process and preventing the regulator from implementing or updating policies [13]. For example, policy updating might require costly studies and/or much time spent

[4]The aggregate level of abatement Q can be written as $Q = \alpha x - \beta$, where x denotes the price of emissions, $\alpha = \left[\frac{8c^2}{4c+2\psi\digamma^2}\right]$ and $\beta = \left[\frac{4\digamma c+\psi\digamma^3}{4c+2\psi\digamma^2}\right]$. Since $\tau_0 > p(\overline{Q}_0)$, it is straightforward that $Q_0^T > \overline{Q}_0$.

instructing firms and monitoring and enforcement officers. Regulators might also be constrained by codes, administrative procedures, and laws that must be changed in order to update policies. All together, these costs incur a fixed cost on adjusting the policy level.

Another important constraint is lobbying by those who are affected by the externality and those who are subject to the policy instruments. Environmentalists lobby for policies that lower emissions while firms seek to minimize the costs of compliance (see [4], [15], and [6]). Lobbying might affect the costs of adjusting the policy and therefore the extent of the policy adjustment when the regulator seeks a policy that minimizes opposition (or maximizes political support in the form of votes or campaign contributions; e.g.,[15], [9] ,and [6]).[5] If she reduces the stringency of the policy, she minimizes the opposition (or gains political support) from firms, but loses support from environmentalists. The reverse will hold in the case of increased stringency. Therefore, the regulator faces a trade-off. If both environmentalists and industry have the power to skew the policy adjustment process, the final cost of adjustment and policy outcome will depend on the relative political lobbying power of each group.

In this section, we analyze how a policy adjustment affects the rate of adoption under taxes and permits under two exclusive and different cost structures and two different scenarios in each case. We consider the case of an exogenous and fixed transactional cost $z_F > 0$ and an endogenous and asymmetric political cost of adjustment $z_E(Q_E - Q_0) \geq 0$ that depends on the increased (decreased) stringency of the policy

[5]Environmentalists and firms might prefer different types of instruments. For example, environmentalists might prefer command and control policies instead of market-based approaches while the reverse holds for firms. However, since we focus on market-based approaches, our analysis omits such differences.

according to the functions:

$$z_E(Q_E - Q_0) = \begin{cases} \varphi_1(Q_E - Q_0) \geq 0 \text{ if } Q_E - Q_0 > 0 \\ \varphi_2(Q_E - Q_0) \geq 0 \text{ if } Q_E - Q_0 < 0 \end{cases}, \tag{20}$$

where $\varphi_1'(Q_E - Q_0) \geq 0$, $\varphi_2'(Q_E - Q_0) \geq 0$, $\varphi_1''(Q_E - Q_0) \geq 0$, and $\varphi_2''(Q_E - Q_0) \geq 0$. We consider two cases. The first case is when firms exercise a dominant pressure on policy by spending large amounts of money to skew the policy-making processes to benefit their economic interests. The cost of increased policy stringency is then larger than the cost of reducing it, i.e., $\varphi_1(Q_E - Q_0) > \varphi_2(Q_E - Q_0)$. Secondly, when environmentalists exercise a dominant pressure on the regulator to increase the stringency of environmental policies, we have $\varphi_1(Q_E - Q_0) < \varphi_2(Q_E - Q_0)$.

Let $\hat{z}_F$ and $\hat{z}_E$ denote the thresholds at which the adjustment costs outweigh the welfare gain of policy adjustment. In Section 4 we will identify these endogenous thresholds under taxes and permits, respectively. For the moment, let us say that if the adjustment costs are major (i.e., $z_F > \hat{z}_F$ and $z_E > \hat{z}_E$), the policy level will remain as before the arrival of the new technology; that is, $\tau_0 = B_Q(\overline{Q}_0)$ and $p(\overline{Q}_0) = \frac{4cB_Q(\overline{Q}_0)+\psi F^3}{4c+2\psi F^2} < \tau_0$. As mentioned previously, in such a case, taxes induce a larger rate of adoption than do auctioned permits, as well as a higher level of abatement.

On the other hand, if the adjustment costs are minor (i.e., $z_F < \hat{z}_F$ and $z_E < \hat{z}_E$), the policy level will be adjusted.

The social welfare, when a fraction λ of firms have adopted the new technology and when the adjustment of the policy incurs fixed transactional costs z_F and political costs z_E, is given by:[6]

$$\begin{aligned} W &= B(\lambda_m q_A + [1-\lambda_m]\, q_{NA}) - \lambda_m c q_A^2 \\ &\quad - [1-\lambda_m]\left[c q_{NA}^2 + \digamma q_{NA}\right] - \frac{\lambda_m^2}{2} \\ &\quad - z_F - z_E(\lambda_m q_A + [1-\lambda_m]\, q_{NA} - Q_0) \\ z_F &= 0 \quad \veebar \quad z_E = 0 \end{aligned} \tag{21}$$

In the following two sections, we calculate the level of the policy that maximizes social welfare in equation (21) given the two cost-exclusive scenarios: fixed transactional cost (F) $z_F < \hat{z}_F$ and $z_E = 0$ and endogenous political costs that vary with the extent of policy adjustment $z_E < \hat{z}_E$ and $z_F = 0$ in (21). We also compare the rates of adoption under taxes and permits in these cases.

3.1 Minor Fixed Transactional Adjustment Costs

Substituting the optimal level of abatement by non-adopters (13) and adopters (14) and the rate of adoption with the tax (15) into the welfare function (21), differentiating with respect to τ, and rearranging yields the optimal level of the tax (see Appendix A.1.1.):

$$\tau_F = \frac{[4c + 2\psi\digamma^2]\, B'(Q_F^T) - \digamma^3\,[\psi - \psi^2]}{4c + 2\psi^2\digamma^2}. \tag{22}$$

Thus, in response to adoption of the new technology by a fraction λ_F^T of firms, the regulator sets the emission tax τ_F.

The optimal aggregate abatement under a permit regime is obtained by substitut-

[6]The aggregate investment cost function $\frac{\lambda_m^2}{2}$ in (21) follows from $k_i \sim U(\underline{k}, \overline{k})$.

ing the optimal level of abatement by non-adopters (13) and adopters (14) and the rate of adoption with permits (15) into the welfare function (21) and differentiating with respect to aggregate abatement (see Appendix A.1.2.):

$$\overline{Q}_F = \frac{\left[4c + 2\psi F^2\right] B'(\overline{Q}_F) - F^3 \left[\psi - \psi^2\right]}{\alpha \left[4c + 2\psi^2 F^2\right]} - \frac{\beta}{\alpha}. \tag{23}$$

Substituting (23) into equation (18), we obtain the equilibrium permit price after the policy adjustment:

$$p(\overline{Q}_F) = \frac{\left[4c + 2\psi F^2\right] B'(\overline{Q}_F) - F^3 \left[\psi - \psi^2\right]}{4c + 2\psi^2 F^2}. \tag{24}$$

Thus, the emission tax and the permit price coincide once the policy is adjusted.

Let us start with two straightforward results, i.e., when the costs are minor and do not prevent a policy level adjustment.

Proposition 1 *If the abatement benefit function is concave, the adjusted tax τ_F is lower than τ_0. On the other hand, the permit price that emerges after the cap on emissions is adjusted, $p(\overline{Q}_F)$ coincides with the tax τ_F and is lower than $p(\overline{Q}_0)$.*

Proof. See Appendix A.2. ■

Proposition 2 *When the fixed transactional adjustment cost is minor, i.e., it does not offset the gain of adjusting the policy, the regulator adjusts the level of the policy instruments and the rate of adoption under emission taxes is the same as that under auctioned permits.*

Proof. Since the emission tax and the permit price after the policy adjustment coincide, it is straightforward to state that taxes induce the same rate of adoption as auctioned permits. ■

In line with the literature (see [12] and [17]), these results indicate that the emission tax cannot induce too little technological change but can induce too much. This problem arises from the fact that the tax does not discriminate across units of abatement according to the benefit they produce, but is set equal to the benefit caused by the marginal unit of abatement, and this tax rate is applied to every unit of abatement. This means that when the abatement benefit function is strictly concave, the total tax payment exceeds the total benefit achieved. In assessing the private net profit of adopting a cleaner technology, the single firm thinks in terms of reduced tax payments. Yet what matters from a social perspective is the increased welfare due to increased abatement. Since the reduction in tax payments exceeds the abatement benefits, firms' incentive is distorted in favor of adoption of cleaner technology. The optimal policy response implies a reduction in the tax level such that social and private adoption benefits are in line.

In the case of permits, if the regulator does not adjust the supply of permits, the private net profit to any firm from adopting the new technology is decreasing in the number of firms using that technology, and this in turn allows an equilibrium to exist in which some firms adopt while others find it unprofitable to do so. Hence, by reducing the supply of permits, the regulator stimulates further adoption among firms.

Propositions 1 and 2 imply that the adjustment will lead to a reduced price of emissions both under taxes and under permits. On the other hand, the optimal level of abatement is increased under permits and reduced under taxes, although in both cases it is higher than the initial level of abatement $\overline{Q}_0$. Hence, there is an asymmetry in the way the optimal stringency of price and quantity policies evolves due to technological change; technological improvement implies more demanding caps on emissions and reduced emissions prices. As we describe in Section 3.2, this asymmetry might have some implications in terms of the optimal level of the adjusted policies if variations in policy stringency affect the extent of the adjustment costs.

3.2 Minor Political Adjustment Costs

Let us first consider the political cost structure case when $z_E < \hat{z}_E$ and $z_F = 0$ in (21). Substituting the optimal level of abatement by non-adopters (14) and adopters (13), the rate of adoption with the tax (15), and the aggregate levels of abatement Q_E^T and Q_0^T into (21) and differentiating with respect to the tax, we obtain (see Appendix A.3.1.):

$$\tau_E = \frac{[4c + 2\psi\digamma^2]\left[B'(Q_E^T) - \varphi_2'(Q_E^T - Q_0^T)\right] - \digamma^3\left[\psi - \psi^2\right]}{4c + 2\psi^2\digamma^2}. \tag{25}$$

By analogy, substituting the optimal levels of abatement by non-adopters (13) and adopters (14), the optimal rate of adoption with permits (15) into the welfare function (21), and differentiating with respect to the level of aggregate abatement, we obtain (see appendix A.3.2.):

$$\overline{Q}_E = \frac{[4c + 2\psi\digamma^2]\left[B'(\overline{Q}_E) - \varphi_1'(\overline{Q}_E - \overline{Q}_0)\right] - \digamma^3\left[\psi - \psi^2\right]}{\alpha\left[4c + 2\psi^2\digamma^2\right]} - \frac{\beta}{\alpha}. \tag{26}$$

Substituting (26) into equation (18), we obtain the equilibrium permit price after the policy adjustment:

$$p(\overline{Q}_E) = \frac{[4c + 2\psi\digamma^2]\left[B'(\overline{Q}_E) - \varphi_1'(\overline{Q}_E - \overline{Q}_0)\right] - \digamma^3\left[\psi - \psi^2\right]}{4c + 2\psi^2\digamma^2}. \tag{27}$$

Proposition 3 *If the endogenous political adjustment cost is minor, i.e., it does not* *offset the gain of adjusting the policy, the rate of adoption under emission taxes might be higher, lower, or the same as the rate of adoption under auctioned permits:*

(i) If the marginal cost of increasing the policy stringency is greater than the marginal cost of reducing it, the emission tax τ_E *is higher than the permit price* $p(\overline{Q}_E)$ *and the rate of adoption is therefore higher under taxes.*

(ii) If the marginal cost of reducing the policy stringency is greater than the marginal cost of increasing it, the emission tax τ_E *is lower than the permit price* $p(\overline{Q}_E)$ *and the rate of adoption is therefore lower under taxes.*

(iii) Finally, if the marginal cost of increasing the policy stringency is equal to the marginal cost of reducing it, the emission tax τ_E *and the permit price* $p(\overline{Q}_E)$ *coincide and so do the rates of adoption.*

Proof. Note that since $Q_E^T < Q_0^T$ and $\overline{Q}_E > \overline{Q}_0$, it follows that $z_E'(Q_E^T - Q_0^T) = \varphi_2'(Q_E^T - Q_0^T)$ and $z_E'(\overline{Q}_E - \overline{Q}_0) = \varphi_1'(\overline{Q}_E - \overline{Q}_0)$.

(i) If $\varphi_1'(\overline{Q}_E - \overline{Q}_0) > \varphi_2'(Q_E^T - Q_0^T)$, the emission tax τ_E is higher than the permit price $p(\overline{Q}_E)$ and the rate of adoption is therefore higher under taxes.

(ii) If $\varphi_1'(\overline{Q}_E - \overline{Q}_0) < \varphi_2'(Q_E^T - Q_0^T)$, the emission tax τ_E is lower than the permit price $p(\overline{Q}_E)$ and the rate of adoption is therefore lower under taxes.

(iii) Finally, if $\varphi_1'(\overline{Q}_E - \overline{Q}_0) = \varphi_2'(Q_E^T - Q_0^T)$, the emission tax τ_E and the permit price $p(\overline{Q}_E)$ coincide and so do the rates of adoption. ∎

Proposition 4 *If the endogenous political adjustment cost does not offset the gain of adjusting the policy, the regulator adjusts the policy instruments. However, the adjusted policies are less stringent than the policies that would have been set in the absence of adjustment costs.*

Proof. Let us compare the optimal level of abatement in equations (23) and (26). Since $\varphi_1'(\overline{Q}_E - \overline{Q}_0) \geq 0$ and $\varphi_2'(Q_E^T - Q_0^T) \geq$, it follows that $\tau_E \leq \tau_F$ and $\overline{Q}_E \leq \overline{Q}_F$. Hence, the contrasting preferences of environmentalists and firms result in a reduced stringency of the policies selected, and through this process they affect the rate of adoption, the aggregate level of abatement, and the welfare gains of policy adjustment.

Proposition 4 also implies that due to political lobbying, the adjusted policies will deviate from the policies that minimize environmental damages, independently of the relative political power of each group. Nevertheless, if the industry is more powerful, the cost of adjusting quantity policies is higher and so is the deviation under this instrument. ■

4 Welfare Comparison and Cost Thresholds

Whether the regulator adjusts the policy or not depends on whether the gain from adjusting outweighs the fixed transactional costs. In this section, we compare the effects of the policy adjustment on welfare and calculate the endogenous adjustment cost thresholds $\hat{z}_F$ and $\hat{z}_E$ under emission taxes and auctioned permits.

4.1 Welfare Comparison with Transactional Costs

Let us calculate the threshold $\hat{z}_F$ under emission taxes and tradable permits. For simplicity, let us assume that the total abatement benefit function is given by $B(Q) = aQ - bQ^2$, such that $B'(Q) > 0$ and $B''(Q) < 0$.

4.1.1 Emission Taxes

The level of welfare with minor fixed transactional cost (F) is given by W_F^T while the level of welfare without policy adjustment is given by W_0^T:

$$\begin{aligned} W_F^T &= B(Q_F^T) - \left[cq_{NA}^2 + F q_{NA}\right] + \lambda_F^T \left[c(q_{NA}^2 - q_A^2) + F q_{NA}\right] - \frac{(\lambda_F^T)^2}{2}, \quad (28) \\ &= aQ_F^T - b\left[Q_F^T\right]^2 - \tau_F^2 \left[\frac{2c + \psi^2 F^2}{8c^2}\right] - \frac{\tau_F F^3 \left[\psi - \psi^2\right]}{8c^2} - g - z_F^T, \quad (29) \\ W_0^T &= aQ_0^T - b\left[Q_0^T\right]^2 - \tau_0^2 \left[\frac{2c + \psi^2 F^2}{8c^2}\right] - \frac{\tau_0 F^3 \left[\psi - \psi^2\right]}{8c^2} - g, \quad (30) \end{aligned}$$

where $g = \frac{F^4}{32c^2}\left[\psi^2 - 2\psi\right] - \frac{F^2}{4c^2}$. Thus, the gain in welfare due to the policy adjustment ΔW_F^T is positive[7] and given by:

$$\begin{aligned} \Delta W_F^T &= W_F^T - W_0^T = a\left[Q_F^T - Q_0^T\right] + b\left[\left[Q_0^T\right]^2 - \left[Q_F^T\right]^2\right] \quad (31) \\ &\quad + \left[\tau_0^2 - \tau_F^2\right] \frac{\left[2c + \psi^2 F^2\right]}{8c^2} + \left[\tau_0 - \tau_F\right] \frac{F^3 \left[\psi - \psi^2\right]}{8c^2} - z_F^T. \end{aligned}$$

The maximum adjustment cost z_F^T that makes the adjustment socially optimal with emission taxes is given by:

$$\begin{aligned} \widehat{z}_F^T &= a\left[Q_F^T - Q_0^T\right] + b\left[\left[Q_0^T\right]^2 - \left[Q_F^T\right]^2\right] \quad (32) \\ &\quad + \left[\tau_0^2 - \tau_F^2\right] \left[\frac{2c + \psi^2 F^2}{8c^2}\right] + \left[\tau_0 - \tau_F\right] \frac{F^3 \left[\psi - \psi^2\right]}{8c^2}. \end{aligned}$$

[7] As shown in Appendix A.1., τ_F is a maximum.

Substituting the aggregate levels of abatement with and without adjustment, Q_F^T and Q_0^T as functions of the taxes, we obtain:

$$\widehat{z}_F^T = [\tau_0 - \tau_F]\left[\frac{[\tau_0 + \tau_F]\,[2c + \psi^2 F^2 + \varkappa] + F^3\,[\psi - \psi^2] - \upsilon}{8c^2}\right]. \tag{33}$$

4.1.2 Auctioned Permits

The welfare level with minor transactional cost (F) is given by W_F^P while the welfare level without policy adjustment is given by W_0^P :

$$W_F^P = a\overline{Q}_F - b\left[\overline{Q}_F\right]^2 - p^2(\overline{Q}_F)\left[\frac{2c + \psi^2 F^2}{8c^2}\right] - \frac{p(\overline{Q}_F)F^3\,[\psi - \psi^2]}{8c^2} - g - z_F^P, \tag{34}$$

$$W_0^P = a\overline{Q}_0 - b\left[\overline{Q}_0\right]^2 - p^2(\overline{Q}_0)\left[\frac{2c + \psi^2 F^2}{8c^2}\right] - \frac{p(\overline{Q}_0)F^3\,[\psi - \psi^2]}{8c^2} - g. \tag{35}$$

Thus, the welfare gain due to the policy adjustment is positive and given by ΔW_F^P.

$$\begin{aligned}\Delta W_F^P &= W_F^P - W_0^P = a\left[\overline{Q}_F - \overline{Q}_0\right] + b\left[\left[\overline{Q}_0\right]^2 - \left[\overline{Q}_F\right]^2\right] \\ &\quad + \left[p^2(\overline{Q}_0) - p^2(\overline{Q}_F)\right]\left[\frac{2c + \psi^2 F^2}{8c^2}\right] + \left[p(\overline{Q}_0) - p(\overline{Q}_F)\right]\frac{F^3\,[\psi - \psi^2]}{8c^2} - z_F^P.\end{aligned} \tag{36}$$

The maximum adjustment cost z_F^P that makes the adjustment socially optimal with auctioned permits is given by:

$$\begin{aligned}\widehat{z}_F^P &= a\left[\overline{Q}_F - \overline{Q}_0\right] + b\left[\left[\overline{Q}_0\right]^2 - \left[\overline{Q}_F\right]^2\right] \\ &\quad + \left[p^2(\overline{Q}_0) - p^2(\overline{Q}_F)\right]\left[\frac{2c + \psi^2 F^2}{8c^2}\right] + \left[p(\overline{Q}_0) - p(\overline{Q}_F)\right]\frac{F^3\,[\psi - \psi^2]}{8c^2}.\end{aligned} \tag{37}$$

Substituting the aggregate levels of abatement with and without adjustment, $\overline{Q}_F$ and $\overline{Q}_0$ as functions of the permit prices, we obtain :

$$\widehat{z}_F^P = \left[p(\overline{Q}_0) - p(\overline{Q}_F)\right] \left[\frac{\left[p(\overline{Q}_0) + p(\overline{Q}_F)\right] \left[2c + \psi^2 F^2 + \varkappa\right] + F^3 \left[\psi - \psi^2\right] - \upsilon}{8c^2} \right]. \quad (38)$$

Proposition 5 *If the adjustment of the policy implies a fixed cost z_F, the adjustment cost threshold at which the adjustment costs outweigh the gain of policy adjustment is higher under emission taxes than under auctioned permits, i.e., $\widehat{z}_F^T > \widehat{z}_F^P$. Therefore, the regulator is more likely to adjust the policy under emission taxes.*

Proof. Since $\tau_0 - \tau_F > p(\overline{Q}_0) - p(\overline{Q}_F)$ and $\tau_0 + \tau_F > p(\overline{Q}_0) + p(\overline{Q}_F)$, we have $\widehat{z}_F^T > \widehat{z}_F^P$. Since $\widehat{z}_F^T > \widehat{z}_F^P$, the tax adjustment is more likely to enhance social welfare than the emission cap adjustment. Moreover, the regulator is more likely to adjust the level of the tax than the cap on emissions in response to the availability of the new technology. ■

As discussed before, this result arises from the fact that it is not enough that policy instruments create incentives for technological change; they must create the *right* incentives, in the sense that they also induce technology adoption decisions that correctly balance the benefits and costs of alternative technologies. As in this model, investments are costly and positively correlated to the stringency of the policy, the regulator enhances social welfare by reducing the stringency of the tax. In the case of permits, welfare is enhanced due to the increased abatement. However, since the abatement benefit function is strictly concave, the social welfare is increased to a larger extent when the regulator adjusts the tax under a tax regime.

4.2 Welfare Comparison with Political Adjustment Costs

We identify and compare the endogenous threshold $\hat{z}_E$ under emission taxes and tradable permits.

4.2.1 Emission Taxes

The level of welfare with minor endogenous political adjustment cost (E) is given by W_E^T while the level of welfare without policy adjustment is given by W_0^T:

$$\begin{aligned} W_E^T &= aQ_E^T - b\left[Q_E^T\right]^2 - \left[cq_{NA}^2 + Fq_{NA}\right] \\ &\quad +\lambda_E^T\left[c(q_{NA}^2 - q_A^2) + Fq_{NA}\right] - \frac{(\lambda_E^T)^2}{2} - z_E^T\left[Q_E^T - Q_0^T\right], \quad (39) \\ &= aQ_E^T(\tau_E) - b\left[Q_E^T\right]^2 - \tau_E^2\left[\frac{2c + \psi^2 F^2}{8c^2}\right] \quad (40) \\ &\quad - \frac{\tau_E F^3\left[\psi - \psi^2\right]}{8c^2} - g - z_E^T(Q_E^T - Q_0^T), \\ W_0^T &= aQ_0^T - b\left[Q_0^T\right]^2 - \tau_0^2\left[\frac{2c + \psi^2 F^2}{8c^2}\right] - \frac{\tau_0 F^3\left[\psi - \psi^2\right]}{8c^2} - g. \quad (41) \end{aligned}$$

Thus, the welfare gain due to the policy adjustment is positive and given by ΔW_E^T:

$$\begin{aligned} \Delta W_E^T &= W_E^T - W_0^T = a\left[Q_E^T - Q_0^T\right] + b\left[\left[Q_0^T\right]^2 - \left[Q_E^T\right]^2\right] \quad (42) \\ &\quad + \left[\tau_0^2 - \tau_E^2\right]\frac{\left[2c + \psi^2 F^2\right]}{8c^2} + \left[\tau_0 - \tau_E\right]\frac{F^3\left[\psi - \psi^2\right]}{8c^2} - z_E^T(Q_E^T - Q_0^T). \end{aligned}$$

Since $Q_E^T < Q_0^T$, $z_E^T(Q_E^T - Q_0^T) = \varphi_2(Q_E^T - Q_0^T)$. Therefore, the gain in welfare due to the policy adjustment is given by:

$$\Delta W_E^T = [\tau_0 - \tau_E]\left[\frac{[\tau_0 + \tau_E]\,[2c + \psi^2 F^2 + \varkappa] + F^3\,[\psi - \psi^2] - \upsilon}{8c^2}\right] - \varphi_2(Q_E^T - Q_0^T). \tag{43}$$

4.2.2 Auctioned Permits

The level of welfare with minor endogenous adjustment cost (E) is given by W_E^P while the level of welfare without policy adjustment is given by W_0^P:

$$\begin{aligned} W_E^P &= a\overline{Q}_E - b\left[\overline{Q}_E\right]^2 - p^2(\overline{Q}_E)\left[\frac{2c + \psi^2 F^2}{8c^2}\right] \\ &\quad - \frac{p(\overline{Q}_E) F^3\,[\psi - \psi^2]}{8c^2} - g - z_E(\overline{Q}_E - \overline{Q}_0), \end{aligned} \tag{44}$$

$$W_0^P = a\overline{Q}_0 - b\left[\overline{Q}_0\right]^2 - p^2(\overline{Q}_0)\left[\frac{2c + \psi^2 F^2}{8c^2}\right] - \frac{p(\overline{Q}_0) F^3\,[\psi - \psi^2]}{8c^2} - g. \tag{45}$$

Thus, the welfare gain due to the policy adjustment is positive and given by ΔW_E^P :

$$\begin{aligned} \Delta W_E^P &= W_E^P - W_0^P = a\left[\overline{Q}_E - \overline{Q}_0\right] + b\left[\left[\overline{Q}_0\right]^2 - \left[\overline{Q}_E\right]^2\right] \\ &\quad + \left[p^2(\overline{Q}_0) - p^2(\overline{Q}_E)\right]\left[\frac{2c + \psi^2 F^2}{8c^2}\right] + \\ &\quad \left[p(\overline{Q}_0) - p(\overline{Q}_E)\right]\frac{F^3\,[\psi - \psi^2]}{8c^2} - z_E^P(\overline{Q}_E - \overline{Q}_0). \end{aligned} \tag{46}$$

Substituting the aggregate levels of abatement with and without adjustment, $\overline{Q}_E$ and $\overline{Q}_0$ as functions of the permit prices, we obtain :

$$\begin{aligned}\Delta W_E^P &= \left[p(\overline{Q}_0) - p(\overline{Q}_E)\right] \left[\frac{\left[p(\overline{Q}_0) + p(\overline{Q}_E)\right] [2c + \psi^2 F^2 + \varkappa]}{8c^2}\right] \\ &\quad + \left[p(\overline{Q}_0) - p(\overline{Q}_E)\right] \left[\frac{F^3 [\psi - \psi^2] - \upsilon}{8c^2}\right] - z_E^P(\overline{Q}_E - \overline{Q}_0).\end{aligned} \tag{47}$$

Since $\overline{Q}_E < \overline{Q}_0$, $z_E^P(\overline{Q}_E - \overline{Q}_0) = \varphi_1(\overline{Q}_E - \overline{Q}_0)$. Therefore, the gain in welfare due to the policy adjustment is given by:

$$\begin{aligned}\Delta W_E^P &= \left[p(\overline{Q}_0) - p(\overline{Q}_E)\right] \left[\frac{\left[p(\overline{Q}_0) + p(\overline{Q}_E)\right] [2c + \psi^2 F^2 + \varkappa]}{8c^2}\right] \\ &\quad + \left[p(\overline{Q}_0) - p(\overline{Q}_E)\right] \left[\frac{F^3 [\psi - \psi^2] - \upsilon}{8c^2}\right] - \varphi_1(\overline{Q}_E - \overline{Q}_0).\end{aligned} \tag{48}$$

Proposition 6 *(i) If the political cost of increasing the policy stringency is greater than the political cost of reducing it (firms dominate lobbying), the regulator is more likely to adjust the policy under emission taxes than under auctioned permits.*

(ii) The regulator might still be more likely to adjust the policy under emission taxes even when the political cost of reducing stringency is greater than the political cost of increasing it (environmentalists dominate lobbying) as long as the political costs are not large.

Proof. If $\varphi_1(\overline{Q}_E - \overline{Q}_0) > \varphi_2(Q_E^T - Q_0^T)$ and $\varphi_1'(\overline{Q}_E - \overline{Q}_0) > \varphi_2'(Q_E^T - Q_0^T)$, then $\tau_E > p(\overline{Q}_E)$ and $\tau_0 + \tau_E > p(\overline{Q}_0) + p(\overline{Q}_E)$. It is straightforward to see that if $\tau_0 - \tau_E > p(\overline{Q}_0) - p(\overline{Q}_E)$, the welfare gains of adjusting the policy are larger under taxes, i.e., $\Delta W_E^T > \Delta W_E^P$, and so is the likelihood of adjusting the policy.

On the other hand, if $\varphi_1(\overline{Q}_E - \overline{Q}_0) < \varphi_2(Q_E^T - Q_0^T)$ and $\varphi_1'(\overline{Q}_E - \overline{Q}_0) < \varphi_2'(Q_E^T - Q_0^T)$, then $\tau_E < p(\overline{Q}_E)$ and $\tau_0 - \tau_E > p(\overline{Q}_0) - p(\overline{Q}_E)$. Thus, it is straightforward to see that if $\tau_0 + \tau_E > p(\overline{Q}_0) + p(\overline{Q}_E)$, the net gains of the updated level of abatement (excluding adjustment costs) are larger under taxes. Hence, the welfare comparison will depend on the extent of the adjustment costs. If $\varphi_1(\overline{Q}_E - \overline{Q}_0)$ and $\varphi_2(Q_E^T - Q_0^T)$ are small, ΔW_E^T might be still larger than ΔW_E^P, and so might the likelihood of adjusting the taxes. ■

Thus, if the costs of updating policies depend on the stringency of the adjustment, ex-post price and quantity policies are no longer equivalent in terms of abatement, adoption incentives and extent of the policy adjustment. If firm lobbying is powerful enough to skew the policy update toward a reduced stringency, policy adjustment is more likely to occur under taxes.

5 Conclusions and Further Research

An important consideration in the choice of pollution control instruments is the incentive for regulated firms to adopt new abatement technologies. The adoption of these technologies holds the key to long-term consumption growth with limited accompanying emissions. Market-based instruments are becoming increasingly popular in practice due in part to their dynamic incentives. By attaching an explicit price to emissions, these policy instruments create an ongoing incentive for firms to continually invest in technologies that reduce their emission volumes. However, if more efficient technologies become available and diffused in among firms, the price on emissions should be revised. In this paper, we have shown that the welfare gains from updating environmental targets in response to availability of cleaner technologies are larger under taxes. As a result, for given constraints that make updating costly in the policymaking process, environmental targets are more likely to be adjusted under a tax regime.

The results above might have some implications in terms of the variations in the aggregate level of abatement over time. Indeed, since policy adjustment is more likely to occur under taxes, taxes and auctioned permits will induce different paths of abatement. Although such an analysis exceeds the scope of our two-stage model and should be studied in a dynamic setting, it is intuitive that aggregate abatement under taxes will increase over time to a larger extent than under permits as new technologies are diffused into the industries. The reasons for this are threefold. First, in the absence of policy adjustments, aggregate abatement is higher under a tax regime. Second, even when the regulator adjusts the policy levels, the aggregate abatement is still higher under a tax regime if industry lobbying is powerful enough to skew the policy update toward a reduced stringency. In this case, abatement under permits will be even lower. Finally, policy adjustment is less likely to occur under permits and thus the cap on emissions will be more likely to remain unchanged.

Nevertheless, under the assumptions of our model, higher level of abatement does not imply a higher level of welfare. As discussed previously, if the abatement benefit function is strictly concave and the abatement cost function (as well as investment costs) is convex, there is less welfare under taxes when the policies remain unchanged. It is this reduced welfare (and therefore larger welfare gain from adjustment) that triggers the policy update when transactional and political adjustment costs are introduced.

Although some previous studies have investigated the impacts of political lobbying on the choice of environmental policy instruments, the results on transactional and political adjustment costs in Section 4 highlight the potential consequences of the asymmetric response of price and quantity policies the availability of new technologies. It is not enough that policy instruments create incentives for technological change; they must create the right incentives. Through taxes, the actual stringency of the regulation will decrease with technological progress. Through permits, it will increase.

When the political costs of updating policies depend on the stringency of the adjustment, ex-post price and quantity policies are no longer equivalent in terms of abatement, adoption incentives and the extent of policy adjustment. Although, the final price of emissions should coincide under both regimes, the political process of updating environmental targets (and improving environmental quality) might become more demanding with quantity policies.

A Appendix

A.1 Appendix

The social welfare, when a fraction λ of firms have adopted the new technology and there is a fixed transactional cost of adjustment z_F, is given by:

$$\begin{aligned} W &= B(\lambda q_A + [1-\lambda]\, q_{NA}) - \left\{\lambda c q_A^2 - [1-\lambda] \left[c q_{NA}^2 + \digamma q_{NA}\right]\right\} \\ &\quad -\frac{\lambda^2}{2} - z_F. \end{aligned} \tag{49}$$

Where the first term on the RHS of (49) takes account of the abatement benefits $B(Q)$, the second term (in parentheses) the aggregate abatement costs $CT(Q)$, and the third term the investment costs $CI(\lambda)$.

A.1.1 Taxes

Let us calculate the optimal adjusted tax. The optimal levels of abatement for adopters and non-adopters are given by:

$$q_A^T = \frac{\tau}{2c}, \tag{50}$$

$$q_{NA}^T = \frac{\tau - F}{2c}. \tag{51}$$

The rate of adoption with taxes is:

$$\lambda^T = \psi F \left[\frac{\tau}{2c} - \frac{F}{4c} \right]. \tag{52}$$

Substituting (50), (51), and (52) in the function of abatement benefits and differentiating with respect to τ, we obtain:

$$\frac{\partial B(Q)}{\partial \tau} = \left[\frac{4c + 2\psi F^2}{8c^2} \right] B'(Q_F). \tag{53}$$

On the other hand, substituting (50), (51), and (52) in the function of aggregate abatement costs and differentiating with respect to τ, we obtain:

$$\frac{\partial CT(Q)}{\partial \tau} = \frac{4c\tau + \psi F^3}{8c^2}. \tag{54}$$

Finally, substituting (52) in the investment function and differentiating with respect to τ, we obtain:

$$\frac{\partial CI(\lambda)}{\partial \tau} = \frac{2\psi^2 F^2 \tau - \psi^2 F^3}{8c^2}. \tag{55}$$

The level of abatement with the optimal tax τ_F is such that the marginal benefit of abatement offsets the marginal cost of abatement and investment.

$$\tau_F = \frac{\left[4c + 2\psi F^2\right] B'(Q_F) - F^3\left[\psi - \psi^2\right]}{4c + 2\psi^2 F^2}. \tag{56}$$

From equation (56) is clear that $\frac{\partial W(\tau_F)^2}{\partial^2 \tau_F} < 0$; that is, welfare is maximized by the tax τ_F.

A.1.2 Auctioned Permits

Let us now consider the case of tradable emission permits. The permit price is given by:

$$p = \alpha Q + \beta. \tag{57}$$

Where $\alpha = \frac{8c^2}{4c+2\psi F^2}$ and $\beta = \frac{4Fc+\psi F^3}{4c+2\psi F^2}$. The optimal levels of abatement for adopters and non-adopters are given by

$$q_A^P = \frac{p}{2c} = \frac{\alpha Q + \beta}{2c}, \tag{58}$$

$$q_{NA}^P = \frac{p - F}{2c} = \frac{\alpha Q + \beta - F}{2c}. \tag{59}$$

The rate of adoption with permits is given by λ^P:

$$\lambda^P = \psi F\left[\frac{\alpha Q + \beta}{2c} - \frac{F}{4c}\right]. \tag{60}$$

Substituting (58), (59), and (60) in (49) and differentiating with respect to Q, we obtain the optimal cap on emissions $\overline{Q}_F$. The level of abatement with the cap $\overline{Q}_F$ is such that the marginal benefit of abatement offsets the marginal cost of abatement and investment.

$$\overline{Q}_F = \frac{[4c + 2\psi F^2]\, B'(\overline{Q}_F) - F^3\, [\psi - \psi^2]}{\alpha\, [4c + 2\psi^2 F^2]} - \frac{\beta}{\alpha}. \tag{61}$$

Substituting (61) into (57) we obtain:

$$p(\overline{Q}_F) = \frac{[4c + 2\psi F^2]\, B'(\overline{Q}_F) - F^3\, [\psi - \psi^2]}{4c + 2\psi^2 F^2}. \tag{62}$$

Thus, the emission tax and the permit price coincide after the policy is adjusted and so do the rates of adoption.

A.2 Appendix

We compare the level of emissions tax and permit price once the regulator has adjusted the prices.

A.2.1 Taxes

Adoption is socially optimal if and only if the total costs of a given abatement target are reduced due to the availability of the new technology. This implies that at the optimum, the sum of the marginal abatement costs and the marginal investment costs in (53) and (54) must be lower than the marginal abatement costs without technology in equation (1), which yields the following condition:

$$\tau_F < \frac{4c\tau_0 - F^3\, [\psi - \psi^2]}{4c + 2\psi^2 F^2}. \tag{63}$$

On the other hand, $\tau_0 = B'(\overline{Q}_0)$ while the tax τ_F is given by:

$$\tau_F = \frac{\left[4c + 2\psi \digamma^2\right] B'(Q_F^T) - \digamma^3 \left[\psi - \psi^2\right]}{4c + 2\psi^2 \digamma^2}. \tag{64}$$

It is straightforward that $\tau_0 > \tau_F$ if $4cB'(\overline{Q}_0) > \left[4c + 2\psi \digamma^2\right] B'(Q_F^T)$, i.e., if the abatement benefits are decreasing with the level of abatement.

As known in the literature, note that if the marginal benefit function is linear, the optimal tax rate is independent of the technologies used. Since the tax payments by a firm are exactly equal to the damage caused by its emissions, it follows that the private net profit and social benefit from cleaner technology adoption coincide such that the tax before and after the adjustment coincides. Note as well that the regulatory problem is somewhat more complicated if the abatement benefit function is convex (and assuming that a well-defined problem exists). In particular, if partial adoption of the new technology is optimal, then the corresponding first-best tax rate is never time consistent. If an announced fixed tax rate induces adoption of the new technology by any firm, then it will induce universal adoption when firms are ex ante identical.

A.2.2 Auctioned Permits

As in the case of the tax, adoption is socially optimal if and only if the total costs of a given abatement target are reduced due to adoption. This implies that at the optimum, the sum of the marginal abatement costs and the marginal investment costs in (53) and (54) must be lower than the marginal abatement costs without technology in equation (1), which yields the following condition:

$$p(\overline{Q}_F) < \frac{4cp_0 - \digamma^3 \left[\psi - \psi^2\right]}{4c + 2\psi^2 \digamma^2}. \tag{65}$$

Since $p_0 = B'(\overline{Q}_0)$ and since the abatement benefits are decreasing with the level of abatement, it follows that $4cB'(\overline{Q}_0) > \left[4c + 2\psi \digamma^2\right] B'(Q_F)$. If the regulator does not adjust the cap on emissions, the permit price is given by:

$$p(\overline{Q}_0) = \frac{4cB'(\overline{Q}_0) + \psi \digamma^3}{4c + 2\psi \digamma^2}. \tag{66}$$

Let us assume that $p(\overline{Q}_0) > p(\overline{Q}_F)$. Then, it holds that:

$$2p(\overline{Q}_0) - \digamma > 2p(\overline{Q}_F) - \digamma. \tag{67}$$

Substituting $p(\overline{Q}_0)$ and $p(\overline{Q}_F)$ in equation (67), it follows that:

$$\frac{4cB'(\overline{Q}_0) - 2c\digamma}{2c + \psi \digamma^2} > \frac{\left[4c + 2\psi \digamma^2\right] B'(\overline{Q}_F) - 2c\digamma}{2c + \psi^2 \digamma^2} - \frac{\psi \digamma^2}{2c + \psi^2 \digamma^2}. \tag{68}$$

Equation (68) holds since $4cB'(\overline{Q}_0) > \left[4c + 2\psi \digamma^2\right] B'(\overline{Q}_F)$ and $0 < \psi \leq 1$.

A.3 Appendix

The social welfare, when a fraction λ of firms have adopted the new technology and when the adjustment cost is endogenous to the increased stringency of the policy, is given by the function $W(\lambda, Q_E - Q_0)$:

$$\begin{aligned} W &= B(\lambda q_A + [1-\lambda]\, q_{NA}) - \lambda c q_A^2 - [1-\lambda]\left[c q_{NA}^2 + F q_{NA}\right] \\ &\quad - \frac{\lambda^2}{2} - z_E\left(\lambda q_A + [1-\lambda]\, q_{NA} - Q_0\right). \end{aligned} \tag{69}$$

Where:

$$z_E(Q_E - Q_0) = \begin{cases} \varphi_1(Q_E - Q_0) \geq 0 \text{ if } Q_E - Q_0 > 0 \\ \varphi_2(Q_E - Q_0) \geq 0 \text{ if } Q_E - Q_0 < 0 \end{cases}, \tag{70}$$

from (20). Equivalently, we can express equation (69) as:

$$\begin{aligned} W &= \{B(\lambda q_A + [1-\lambda]\, q_{NA}) - z_E\left(\lambda q_A + [1-\lambda]\, q_{NA} - Q_0\right)\} \\ &\quad - \lambda c q_A^2 - [1-\lambda]\left[c q_{NA}^2 + F q_{NA}\right] - \frac{\lambda^2}{2}. \end{aligned} \tag{71}$$

Where the first term on the RHS of equation (69) takes account of the abatement benefits (net of adjustment costs) $BN(Q)$, the second term (in parentheses) the aggregate abatement costs $CT(Q)$, and the third term the investment costs $CI(\lambda)$.

A.3.1 Taxes

Let us calculate the optimal adjusted tax: The optimal levels of abatement for adopters and non-adopters are given by:

$$q_A^T = \frac{\tau}{2c}, \tag{72}$$

$$q_{NA}^T = \frac{\tau - F}{2c}. \tag{73}$$

The rate of adoption with taxes is:

$$\lambda^T = \psi \left[\frac{\tau F}{2c} - \frac{F^2}{4c} \right]. \tag{74}$$

The total abatement with taxes before the adjustment is given by:

$$Q^T(\tau_0) = \frac{\psi F^2}{2c} \left[\frac{B_Q(\overline{Q}_0)}{2c} - \frac{F}{4c} \right]. \tag{75}$$

Substituting (72), (73), (74), and (75) into the function of abatement benefits $BN(Q)$ and differentiating with respect to τ, we obtain:

$$\frac{\partial BN(Q)}{\partial \tau} = \left[\frac{4c + 2\psi F^2}{8c^2} \right] \left[B'(Q_E^T) - z_E'(Q_E^T - Q_0^T) \right]. \tag{76}$$

On the other hand, substituting (72), (73), and (74) into the function of aggregate abatement costs and differentiating with respect to τ, we obtain:

$$\frac{\partial CT(Q)}{\partial \tau} = \frac{4c\tau + \psi F^3}{8c^2}. \tag{77}$$

Finally, substituting (74) into the investment function and differentiating with respect to τ, we obtain:

$$\frac{\partial CI(\lambda)}{\partial \tau} = \frac{2\psi^2 F^2 \tau - \psi^2 F^3}{8c^2}. \tag{78}$$

The level of abatement with the optimal tax τ_E is such that the marginal benefit of abatement (net of adjustment costs) offsets the marginal cost of abatement and investment.

$$\tau_E = \frac{[4c + 2\psi F^2] \left[B'(Q_E) - z_E'(Q_E^T - Q_0^T) \right] + [\psi^2 - \psi] F^3}{4c + 2\psi^2 F^2}. \tag{79}$$

From equation (79), it is clear that $\frac{\partial W(\tau_E)^2}{\partial^2 \tau_E} < 0$; that is, welfare is maximized by the tax τ_E. Finally, since $Q_E^T < Q_0^T$, $z_E'(Q_E^T - Q_0^T) = \varphi_2'(Q_E^T - Q_0^T)$. Then:

$$\tau_E = \frac{\left[4c + 2\psi F^2\right]\left[B'(Q_E) - \varphi_2'(Q_E^T - Q_0^T)\right] + \left[\psi^2 - \psi\right] F^3}{4c + 2\psi^2 F^2}. \tag{80}$$

A.3.2 Auctioned Permits

Let us consider now the case of tradable emission permits. The permit price is given by:

$$p(Q) = \alpha Q + \beta, \tag{81}$$

with $\alpha = \frac{8c^2}{4c+2\psi F^2}$ and $\beta = \frac{4Fc+\psi F^3}{4c+2\psi F^2}$. The optimal levels of abatement for adopters and non-adopters are given by

$$q_A^P = \frac{p}{2c} = \frac{\alpha Q + \beta}{2c}, \tag{82}$$

$$q_{NA}^P = \frac{p - F}{2c} = \frac{\alpha Q + \beta - F}{2c}. \tag{83}$$

While the rate of adoption with permits is:

$$\lambda^P = \psi F \left[\frac{\alpha Q + \beta}{2c} - \frac{F}{4c}\right]. \tag{84}$$

and the total abatement with taxes before the adjustment is given by:

$$\overline{Q}_0 = \frac{B_Q(\overline{Q}_0) - F}{2c}. \tag{85}$$

Substituting (82), (83), (84), and (85) in (71) and differentiating with respect to Q, we obtain the optimal adjustment on the aggregate level of abatement with permits

Q_E

$$\overline{Q}_E = \frac{\left[B_Q(\overline{Q}_E) - z'_E(\overline{Q}_E - \overline{Q}_0)\right]\left[4c + 2\psi F^2\right] + \left[\psi^2 - \psi\right] F^3}{\alpha\left[4c + 2\psi^2 F^2\right]} - \frac{\beta}{\alpha}. \tag{86}$$

Substituting (86) into (81), we obtain:

$$p_E(\overline{Q}_E) = \frac{\left[B_Q(\overline{Q}_E) - z'_E(\overline{Q}_E - \overline{Q}_0)\right]\left[4c + 2\psi F^2\right] + \left[\psi^2 - \psi\right] F^3}{4c + 2\psi^2 F^2}. \tag{87}$$

Notice that since $\overline{Q}_E > \overline{Q}_0$, $z'_E(\overline{Q}_E - \overline{Q}_0) = \varphi'_1(\overline{Q}_E - \overline{Q}_0)$. Then:

$$p_E(\overline{Q}_E) = \frac{\left[B_Q(\overline{Q}_E) - \varphi'_1(\overline{Q}_E - \overline{Q}_0)\right]\left[4c + 2\psi F^2\right] + \left[\psi^2 - \psi\right] F^3}{4c + 2\psi^2 F^2}. \tag{88}$$

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