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The Role of Abatement Technologies for Allocating Free Allowances*

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October 2011

Abstract

The issue of how to allocate pollution permits is critical for the political sustainability of any cap-and-trade system. Under the objective of offsetting firms' losses resulting from the environmental regulation, we argue that the criteria for allocating free allowances must account for the type of abatement technology: industries that use process integrated technologies should receive some free allowances, whereas those using end-of-pipe abatement should not. In the long run, we analyze the interaction between the environmental policy and the evolution of the market structure. In particular, a reserve of pollution permits for new entrants may be justified when the industry uses a process integrated abatement technology.

JEL Classification: L13, Q53, Q58.
Key words: Cap-and-trade system, profit-neutral allocations, abatement technologies.

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1 Introduction

An issue common to the implementation of any permits market concerns the distribution of allowances amongst firms. Despite the active debate that has occurred since the introduction of the European Union Emissions Trading System (EU ETS), the problem is still not settled and the decisions taken for the third phase (2013-2020) clearly fail to reach consensus. As far as incumbents are concerned, the debate relates to the allocation method, and more specifically to the optimal share between free allowances and other types of allowances (sold through auction or at the market price for instance). Focusing on potential new entrants, an additional question arises as to whether some allowances should be set aside to accommodate entry. Our paper helps clarifying the pros and cons associated to the distribution of free allowances in a context where firms have various abatement possibilities and enjoy some market power, as is typical of industries subject to the EU ETS.

The ETS assigns a monetary value to pollution and thus increases the opportunity cost of production. Industrial lobbies then claim that the ETS increases final prices and reduces firms' profits. This negative effect is all the stronger that industries face international competition. Industrial lobbies then conclude that firms must be granted free allowances in order to compensate for this loss of profitability.

Economists, on the other hand, have argued that as long as allowances are grandfathered,[1] which has been the case in the EU ETS since 2005, they are only a lump-sum transfer from the regulator to the firms. Therefore, free allowances do not affect firms' price or quantity decisions in the short run, for they have no effect on marginal incentives. However, free allowances do increase firms' profits which induces entry and affects the market structure in the long run. In a similar vein, free allowances can help local firms facing strong international competition.

In this paper, we show that the effect of free allowances on competition on final markets is more complex than the conventional wisdom. We highlight three effects of the ETS. First, when firms are granted free allowances, they enjoy an opportunity profit that corresponds to the market value of free allowances. This opportunity profit increases with the price of permits.

Second, and perhaps most importantly, even without free allowances, the ETS creates an opportunity profit of pollution abatement, that is firms find it profitable to reduce their emissions. Following Requate (2005), two types of technologies are considered. In the case of end-of-pipe abatement, which includes capture and storage systems, pollution filters and clean development mechanisms, this opportunity profit is positive and fully disconnected from product-market decisions (i.e., price or quantity). In the case of process integrated technology (which implies shifting to a cleaner technology

[1] The reasoning continues to hold if allowances are auctionned off rather than grandfathered.

or reducing the energy intensity of production), however, this opportunity profit is related to the characteristics of the final product market. In our framework, it turns out that when firms use process integrated abatement the opportunity profit of pollution abatement is fully dissipated by the competitive forces on the final product market.

Finally, the ETS increases firms' marginal cost of production. Under imperfect competition, this third effect can increase profits. Intuitively, if the demand is sufficiently inelastic, firms pass through most of the permits price to consumers without reducing much the demand for their products. This yields an increase in firms' gross revenues, which may more than compensate the increase in costs.[2]

We illustrate these effects in several standard competition frameworks and show that the industry profit is increasing (respectively, decreasing) with the permits price under end-of-pipe (respectively, process integrated) abatement technology. Our model thus predicts that the impact of an ETS on industrial profitability should be quantitatively and qualitatively different according to the type of the abatement technologies used. As a policy implication, the criteria for allocating free allowances must depend on the abatement technologies.

Our results provide some theoretical support to several empirical studies which find that some industries have benefited from the market for permits (Sijm, Neuhoff and Chen, 2006; Grubb and Neuhoff, 2006). It also supports the amendment to the Directive 2003/87/EC that implemented the EU ETS, according to which electricity production will no longer enjoy free allowances from 2013 on.[3] Finally, Demailly and Quirion (2008) find that, despite the international competition faced by the European steel industry, granting for free about 50% of the permits would be enough to compensate the firms' losses due to the environmental regulation.

A second contribution concerns the policy towards entry. The EU plans to set aside 5% of all the European emission permits for new entrants, and to grant part of this amount for free. Besides, this reserve shall be used first and foremost for innovative projects, which includes capture and storage systems as well as the use of renewable energy technologies. Our analysis argues that the allocation of permits to entrants should be contingent on the type of abatement technology.

In the presence of large entry barriers, entry should be facilitated only when firms use process integrated technologies. When firms use end-of-pipe abatement, the environmental regulation should become more severe as more firms enter the market: the

[2]This effect bears an analogy with Seade (1985) and Kimmel (1992) who analyze the impact of cost shocks in an oligopoly. However they both consider a Cournot setting whereas we focus on a Bertrand framework.

[3]Directive of the European Parliament and of the Council amending Directive 2003/87/EC so as to improve and extend the greenhouse gas emission allowance trading scheme of the Community (2009/29/EC).

regulator should then use a preemption right to buy permits on the market so as to reduce the pollution cap.[4]

In a contemporaneous work, Hepburn et al. (2010) study the impact of a small tax on an imperfectly competitive industry using a process integrated technology to abate pollution. They find, as we do, that the industry may benefit from the environmental regulation. By considering a more specific model, we do not need to restrict attention to a small permits price. Moreover, we tackle other issues, such as the policy towards entry for instance, and discuss the role of several abatement technologies and of various competitive environments.

The structure of the article is a follows. Section 2 describes our model. In Section 3, we determine the level of profit-neutral allowances that should be grandfathered to firms, depending on their abatement technology. In Section 4, we determine the regulator's optimal policy towards entry. Section 5 studies several extensions. Importantly, we show that our results extend qualitatively to other forms of competition or demand functions. Section 6 concludes.

2 The Model

Consumers. We consider the standard Hotelling-Salop model in which a mass m of consumers is uniformly distributed on the unit circle. Each consumer decides whether to consume the good. There are n firms symmetrically located on the circle. Consumers have a unit transport cost t, which can be interpreted either as a differentiation factor, or as the inverse of the intensity of competition on the market.

Consumers have a unit demand for the good and their gross valuation is denoted by v.[5] Thus, the consumer located at a distance q_i from firm i gets a net utility $v - p_i - tq_i$ if he buys from that firm, where p_i is firm i's price. He gets 0 if he does not buy from any firm. Each consumer buys from the firm that brings him the highest net utility level. Consumers' surplus at a symmetric equilibrium in which all firms set the same price p is given by: $CS = 2nm \int_0^{\frac{1}{2n}} (v - p - tx)\, dx$.

Product market. All firms face the same fixed cost of production F and the same constant marginal cost, normalized to 0 without loss of generality.[6] Since firms are

[4]Ellerman (2008) considers a model with perfect competition in the product market and shows that granting new entrants free allowances leads to excess capacity and to more output, although the effect on emissions is ambiguous. Focusing on the French NAP, Godard (2005) argues that the best way to induce new entrants to choose the most environmentally-friendly technology is to have new firms buy all their allowances in the market.

[5]We assume that v is large enough so that all consumers decide to buy one unit at equilibrium.

[6]Indeed, in this model prices can be interpreted as prices net of marginal costs.

located symmetrically, the distance between two firms is $1/n$, and the mass of consumers at each point is m. Thus, firm i faces a demand given by:[7]

$$q_i(p) = m\left(\frac{1}{n} - \frac{2p_i - p_{i-1} - p_{i+1}}{2t}\right),$$

where p_{i-1} and p_{i+1} are the prices set by the two firms adjacent to firm i, and p is the vector of prices.[8]

Pollution and abatement technologies. When firm i produces a quantity q_i, it emits an amount $\bar{\alpha}q_i$ of pollution, where $\bar{\alpha} > 0$ is an exogenous polluting factor linked to the production technology. We consider two different ways for firms to abate their pollution: end-of-pipe technology and process integrated technology.

If firm i uses an end-of-pipe technology, then in order to reduce its emissions from the baseline level $\bar{\alpha}q_i$ to a given target e_i, that is, in order to abate pollution by an amount of $x_i = \bar{\alpha}q_i - e_i$, the firm has to bear a cost $\gamma x_i^2/2$, where $\gamma \geq 0$. Note that this type of technology does not modify the production process and, therefore, does not modify the polluting factor $\bar{\alpha}$.

The second abatement technology we focus on is process integrated, which alters the production process in a more environmentaly-friendly way, and therefore reduces the polluting factor. If firm i invests y_i at a cost $\frac{\beta}{2}y_i^2$, where $\beta \geq 0$, then its polluting factor becomes $\alpha(y_i) = \bar{\alpha} - y_i$.[9]

We assume in the following that all firms on the market use the same abatement technology, which is either end-of-pipe abatement or process integrated.

Environmental regulation and free allowances. We are interested in two possible criteria that can be used by a regulator to give free allowances. First, in Section 3, we do not consider that the regulator has any environmental concerns: its only purpose is to ensure that firms do not lose profits following the introduction of the environmental regulation, which is exogenous. Second, in Section 4, we consider that the regulator maximizes social welfare defined as the sum of firms' profits, consumers' surplus, and the environmental damage caused by pollution. The regulator has environmental as well as industrial concerns, and the social cost is represented by a damage function

[7] See Tirole (1988).

[8] We use the convention that $p_0 = p_n$.

[9] In the usual specification of process integrated technology, the abatement cost depends on total abatement (in this case $y_i q_i$, see Requate, 2005), which allows to define the marginal abatement curve associated with the abatement function. However, it seems realistic to assume that the cost of switching to a cleaner technology is an investment cost that does not depend on output but only on the difference between the initial and final pollution factors y_i. Besides, it is possible to show that our results hold qualitatively with that specification.

$D(e)$, where $e = (e_1, \cdots, e_n)$ is the vector of the firms' pollution emissions. Since we are mostly interested in global warming, the damage function is additive and given by $D(e) = \lambda \sum_i e_i$, where $\lambda \geq 0$ describes the social cost associated to the total amount of pollution.

In order to maximize social welfare, the regulator can use three tools: the choice of a global emission target E, the granting of free allowances $(\varepsilon_1, ..., \varepsilon_n)$, and a permits market in order to promote efficiency in abatement decisions. The first tool amounts to imposing the following constraint on the industry: $\sum_i e_i \leq E$. Assumption 1 ensures that the analysis focuses on the interesting cases, in which the total industry abatement is always positive:[10]

Assumption 1. *$E < \bar{a}m$.*

A firm must own a permit for each unit of pollution it emits. The regulator gives free allowances to the firms. For simplicity, we assume that all firms receive the same level of initial allowances ε, with $n\varepsilon \leq E$. A market for permits allows firms to buy or sell permits, depending on their needs. Competition on this market is perfect. The price of permits is denoted by σ.

We denote by π_i the profit of firm i, and by $RR = \sigma \sum_i (e_i - \varepsilon)$ the regulator's revenue from selling permits to the industry. Social welfare is then given by $W = CS + \sum_{i=1}^{n} \pi_i - \lambda D(e) + RR$.

Timing of the game. The timing is as follows:

1. Firms decide whether to enter the market. Firms that enter are located symmetrically on the circle. Every firm is granted ε free allowances.

2. The market for permits opens.

3. Firms simultaneously choose their price on the product market, abatement levels and positions on the market for permits.

We look for the symmetric subgame-perfect equilibrium of that game.

3 Profit-Neutral Allowances

We first determine what the level of profit-neutral allowances is for each type of abatement for a given market structure. In other words, we consider that the number of

[10] In this model, all consumers will buy one unit at equilibrium. Therefore, the total equilibrium output is always equal to m. Thus, when firms do not abate pollution, they always emit a pollution $\bar{a}m$. Assumption 1 therefore implies that the global emission target must be lower than the firms' maximum possible emission level.

firms is exogenous (and equal to n), and determine how many allowances must be given for free to a firm so that its profit is not harmed by the environmental regulation.

In order to answer this question, we first need to consider the case in which firms are not subject to any regulation. Clearly, when it does not face any regulation, firm i has no reason whatsoever to make an effort to pollute less. As a consequence, whatever the type of abatement used by firms, each firm emits exactly the amount of pollution associated to its output. At the symmetric equilibrium, all firms set the same price $p^{\varnothing} = \frac{t}{n}$ and the resulting individual output is $q^{\varnothing} = \frac{m}{n}$. Firm i's profit is then $\pi^{\varnothing} = t\frac{m}{n^2}$.

3.1 End-of-pipe abatement

When the emission cap is E and firms use end-of-pipe abatement, the final profit of firm i is:

$$\pi_i = (p_i - \sigma\bar{\alpha})q_i(p) - \gamma\frac{x_i^2}{2} + \sigma x_i + \sigma\varepsilon. \tag{1}$$

Firms' price and abatement choices. We start with the analysis of firms' strategies in terms of prices and emission levels for a given price on the market for permits. Firm i maximizes its profit π_i given by equation (1). The necessary first-order conditions are:[11]

$$q_i + (p_i - \sigma\bar{\alpha})\frac{\partial q_i}{\partial p_i} = 0, \tag{2}$$

$$\gamma x_i = \sigma. \tag{3}$$

At the symmetric equilibrium, the price is $p^*_{EP} = \frac{t}{n} + \sigma\bar{\alpha}$ and the resulting output sold by a firm is $q^*_{EP} = \frac{m}{n}$. Thus, the firm's equilibrium price increases with the price of permits σ. The intuition may be explained as follows. Increasing the price of permits amounts to increasing the firms' marginal cost, which makes them increase their prices on the product market. Besides, since the profit is separable in p_i and x_i, this holds whatever the abatement level: equation (3) states that the marginal cost of abatement equals its marginal benefit, which is given by the permits price; importantly, the level of abatement is independent of the product market characteristics.

To understand the previous results, consider the case in which no abatement technology is available ($x_i = 0$, $\forall i$). In this situation, firm i chooses p_i that maximizes $(p_i - \sigma\bar{\alpha})q_i(p)$. It is then obvious that introducing a positive exogenous permit price increases the marginal cost of all firms by an amount $\sigma\bar{\alpha}$. In our framework, faced with such a symmetric shock, firms react by increasing their price up to $p^*_{EP} = p^{\varnothing} + \sigma\bar{\alpha}$.

Consider now that firms can choose an abatement level $x_i > 0$. The product price

[11] Sufficient second-order conditions are always satisfied and hence omitted in the following.

they choose then is the same as when $x_i = 0$, that is p^*_{EP}, because as illustrated by equation (1) the profit is separable in p_i and x_i. More precisely, we can decompose the profit into three parts:

- a "product market profit given the baseline pollution": $(p_i - \sigma\bar{\alpha})q_i(p)$;
- an "abatement opportunity profit": $\sigma x_i - \gamma x_i^2/2$;
- the gain due to free allowances $\sigma\varepsilon$.

The firm thus chooses its price to maximize the first element while it chooses its abatement in order to maximize the second element.[12] The third part is simply a transfer from the regulator to the firm, over which the latter has no control.

At the symmetric equilibrium, all firms abate $x^*_{EP} = \frac{\sigma}{\gamma}$.[13] This choice is the result of a trade-off between the abatement cost on the one hand, and the monetary value of the abatement effort on the other hand. As a consequence, for a given price of permits σ, aggregate emissions are decreasing in n. Indeed, the equilibrium aggregate output is $\sum_i q^*_{EP} = m$, and is thus constant with the number of firms n on the market. Meanwhile, each firm abates $x^*_{EP} = \frac{\sigma}{\gamma}$, which implies that the equilibrium aggregate abatement level is $n\frac{\sigma}{\gamma}$, which is increasing in n. As a consequence, the total pollution level $\sum_i(\bar{\alpha}q^*_{EP} - x^*_{EP})$ is decreasing in n. This implies that industry concentration not only harms consumers' surplus, since it increases prices, but also increases environmental damages.

Lemma 1. *Without free allowances, when firms use end-of-pipe abatement, their profits increase with the price of permits σ.*

Proof. The equilibrium profit is $\pi^*_{EP} = \pi_i(p^*_{EP}, x^*_{EP})$, with $p^*_{EP}(\sigma) = \frac{t}{n} + \bar{\alpha}\sigma$ and $x^*_{EP} = \frac{\sigma}{\gamma}$. Therefore, a firm's equilibrium profit is equal to:

$$\pi^*_{EP}(\sigma) = t\frac{m}{n^2} + \frac{\sigma^2}{2\gamma} + \sigma\varepsilon = \pi^{\varnothing} + \frac{\sigma^2}{2\gamma} + \sigma\varepsilon.$$

and thus increasing in σ and higher than $\pi^{\varnothing}$. □

The profit firms earn on the product market is never harmed by the regulation: $(p^* - \bar{\alpha}\sigma)q_i(p^*) = p^{\varnothing}q_i(p^{\varnothing})$. Moreover, their opportunity profit $\sigma x_i - \frac{\gamma x_i^2}{2}$ is strictly positive when $x_i = x^*_{EP}$. Therefore, firms always gain in the regulated case with respect to the case with no regulation.

[12] Note that this is true because the abatement cost only depends on the abatement level x_i and not directly on the firm's output q_i.

[13] This is true as long as the price of a permit is low enough, that is lower than $\tilde{\sigma} = \frac{m\gamma\bar{\alpha}}{n}$. When σ gets higher than this threshold, firms prefer not to buy any permit and abate all their pollution ($x^*_{EP} = 0$). We will see that when the price of permits is endogenous, it is always lower than $\tilde{\sigma}$ at equilibrium.

Opening of the market for permits. On the market for permits, the aggregate demand for permits is equal to the total amount of permits firms need and have not been granted for free, that is, $n(e^*_{EP} - \varepsilon)$, where $e^*_{EP} = \bar{\alpha} q^*_{EP} - x^*_{EP}$. The total supply is the amount of permits that the social planner is ready to sell, that is, $E - n\varepsilon$. Thus, the perfectly competitive permits market clears when supply equals demand, or $n(e^*_{EP} - \varepsilon) = E - n\varepsilon$. The resulting equilibrium price for permits is then $\sigma^*_{EP} = \frac{\gamma(\bar{\alpha}m - E)}{n}$.

The equilibrium price of permits σ^*_{EP} is thus decreasing in the number of firms on the market. The reason for this result is that the aggregate demand for permits is $ne^*_{EP} = \bar{\alpha}m - n\sigma$, and is thus decreasing in n, while the aggregate supply is constant and equal to E. Besides, σ^*_{EP} only depends on the social planner's emission objective, and not on the amount of free allowances. Indeed, since the total amount of permits available must remain equal to the cap E, if the regulator gives ε free allowances to each firm on the market, then its supply on the permits market is reduced by $n\varepsilon$.

The equilibrium product market price and abatement level are respectively $p^*_{EP} = \frac{t}{n} + \frac{\bar{\alpha}\gamma(\bar{\alpha}m - E)}{n}$ and $x^*_{EP} = \frac{\bar{\alpha}m - E}{n}$. The resulting individual output is still $q^*_{EP} = \frac{m}{n}$. Firm i's profit can then be written:

$$\pi^*_{EP}(\sigma^*_{EP}) = t\frac{m}{n^2} + \frac{\gamma(\bar{\alpha}m - E)^2}{2n^2} + \frac{\gamma(\bar{\alpha}m - E)}{n}\varepsilon.$$

Since the equilibrium permits price is decreasing in E, Lemma 1 implies that the more severe the constraint on emissions, the higher firms' equilibrium profits: firms always benefit from the introduction of an environmental regulation.

Profit-neutral allowances. We now determine the amount of profit-neutral allowances in the end-of-pipe abatement case. The profit of a firm that is granted ε free allowances is $\pi_{EP}(E, \varepsilon) = \pi^*_{EP}(\sigma^*_{EP})$. Profit-neutral allowances are such that firms' profits remain constant after the introduction of the environmental regulation:

$$\pi_{EP}(E, \varepsilon^{PNA}_{EP}) = \pi^{\varnothing} \Leftrightarrow \varepsilon^{PNA}_{EP} = -\frac{\bar{\alpha}m - E}{2n^2} < 0.$$

Proposition 1. *With end-of-pipe abatement technologies, free allowances should not be given on the ground of profit neutrality.*

This result comes from two effects. First, without free allowances, firms profits increase with σ. Second, free allowances only represent a transfer from the regulator to the firm, and hence have no impact on the firms' strategic decisions. In this setting, if the regulator wanted to reach profit-neutrality, it should tax firms.

3.2 Process integrated technology

We now consider the case where the only technology available to curb emissions is process integrated technology. Firm i wants to maximize the following profit:

$$\pi_i = q_i(p)\left[p_i - \alpha(y_i)\sigma\right] - \frac{\beta}{2}y_i^2 + \sigma\varepsilon.$$

Firms' price and abatement choices. As in the end-of-pipe abatement case, the three terms of the sum represent respectively the product market profit, the cost of reducing emissions and the gain due to free allowances. However in this case, the profit is not separable in p_i and y_i. Therefore, the gains from abatement now directly affect the product market profit. With end-of-pipe abatement, a firm gains from abatement by selling more permits on the permits market, hence increasing its abatement opportunity profit without altering the product market profit. Meanwhile, with process integrated technologies, a firm gains from abatement by reducing its perceived marginal cost of production ($\alpha(y_i)$), which affects the firm's product market profit, and hence its behaviour on this market. We describe this effect with the necessary and sufficient first order conditions:

$$q_i + \left[p_i - \alpha(y_i)\sigma\right]\frac{\partial q_i}{\partial p_i} = 0, \tag{4}$$

$$\beta y_i = q_i\sigma. \tag{5}$$

At the symmetric equilibrium,[14] the final price and abatement levels are respectively $p_I^*(\sigma) = \frac{t}{n} + \alpha(y_I^*(\sigma))\sigma$ and $y_I^* = \frac{m\sigma}{\beta n}$. The resulting output sold by each firm is again $q_I^* = \frac{m}{n}$. Thus, the firm's equilibrium price increases with the price of permits σ. The intuition mirrors that of the end-of-pipe abatement case.

Abatement increases with the permits price, for as σ increases, the marginal gain of abatement and the marginal loss from buying permits both increase. Abatement decreases with the size of the industry. Indeed, when the number of firms on the market increases, a firm's individual output decreases, since the aggregate output is always m. As a consequence, the marginal gain to abate decreases with n. It results that the polluting factor and aggregate emissions increase with the number of firms and decrease with the permits price. Indeed, aggregate emissions are given by $nq_I^*\alpha(y_I^*) = m\alpha(y_I^*) = m\left[\bar{\alpha} - \frac{m\sigma}{n}\right]$.

Lemma 2. *Without free allowances, when firms use process integrated technologies to*

[14] We consider the interior solution, which is the unique solution under our assumptions. Note however that this solution holds provided that the second order conditions are satisfied, which is true as long as the emission cap is high enough ($E > \max\{0, \bar{\alpha}m - \frac{m^2}{n}\sqrt{\frac{2t}{\beta}})\}$.

abate pollution, their profits decrease with the price of permits σ.

Proof. If firms receive no free allowances (that is $\varepsilon = 0$), the equilibrium profit is: $\pi_I^*(\sigma) = \frac{tm}{n^2} - \frac{1}{2\beta}\left(\frac{m\sigma}{n}\right)^2$, which is decreasing in the price of permits. □

Competition induces firms to abate in order to reduce their marginal cost. Equation (5) means that firm i chooses an abatement level such that the marginal cost of abatement equals the marginal gain in terms of reduction of its perceived marginal cost $\alpha(y_i)\sigma$. For given prices set by its competitors, firm i's abatement allows it to reduce its price and gain market shares. However, at the symmetric equilibrium, all firms abate the same amount so that competition on the product market becomes fiercer. Any reduction of the perceived marginal cost is fully passed through to consumers by all firms at equilibrium. Therefore, each firm's market share remains $\frac{1}{n}$, and the symmetric abatement decisions do not affect the product market profit. Meanwhile, the cost of abatement increases with the permits price. Finally, the profit without free allowances decreases with σ.

Opening of the market for permits. On the market for permits, the aggregate demand for permits is equal to the total amount of permits firms need and have not been granted for free, that is, $n(e_I^* - \varepsilon)$, where $e_I^* = \alpha(y_I^*)q_I^*$. The total supply is $E - n\varepsilon$ again. Thus, the perfectly competitive permits market clears when supply equals demand, or $n(e_I^* - \varepsilon) = E - n\varepsilon$. The resulting equilibrium price for permits is then: $\sigma_I^* = \frac{n\beta}{m}\left(\bar{\alpha} - \frac{E}{m}\right)$. It is increasing in the number of firms on the market, for the aggregate demand for permits is increasing in n and decreasing in σ whereas the supply of permits E is constant.

Besides, the equilibrium abatement depends neither on the number of firms nor on the cost of process integrated technologies: $y_I^* = \bar{\alpha} - \frac{E}{m}$. It is decreasing in the global cap of emissions E. Indeed, setting a cap E amounts to imposing the total level of pollution in the industry. Now, the aggregate pollution on the final market is given by $\sum_i \alpha(y_i)q_i$. Since firms are symmetric and all choose the same abatement $y_I^*(\sigma)$, this aggregate level of pollution is equal to $\alpha(y_I^*)\sum_i q_i^*$. Since the aggregate output $\sum_i q_i^*$ is always equal to m, the equilibrium aggregate level of pollution is $\alpha(y_I^*)m = (\bar{\alpha} - y_I^*)m$ regardless of the number of firms n. The equilibrium abatement is thus fully specified by the following equation: $m(\bar{\alpha} - y_I^*) = E$. Note that in this case, the regulator could reach the same result with command-and-control instruments.

The equilibrium price and individual output are respectively $p_I^* = \frac{t}{n} + \frac{\beta n E}{m^2}\left(\bar{\alpha} - \frac{E}{m}\right)$ and $q_I^* = \frac{m}{n}$. Firm i's equilibrium profit can be written:

$$\pi_I^*(\sigma_I^*) = \frac{tm}{n^2} - \frac{\beta}{2}\left[\bar{\alpha} - \frac{E}{m}\right]^2 + \frac{n\beta}{m}\left(\bar{\alpha} - \frac{E}{m}\right)\varepsilon. \qquad (6)$$

Therefore, without free allowances, the more severe the environmental constraint imposed by the regulator (i.e. the lower E), the lower firms' equilibrium profits.

Profit-neutral allowances. We now determine the profit-neutral allowances in the case of process integrated technology. As in the case of end-of-pipe abatement, when firm i is granted free allowances, its equilibrium profit is $\pi_I(E, \varepsilon) = \pi_I^*(\sigma_I^*)$. Profit-neutral allowances ε_I^{PNA} are such that the profit remains constant after the introduction of the environmental regulation, that is:

$$\pi_I(E, \varepsilon_I^{PNA}) = \pi^{\varnothing} \Leftrightarrow \varepsilon_I^{PNA} = \frac{\bar{\alpha}m - E}{2n} > 0.$$

Proposition 2. *With process integrated technology, free allowances must always be given on the ground of profit neutrality. The ratio of free allowances is* $\frac{\bar{\alpha}m}{2E} - \frac{1}{2}$.

Proof. The total amount of permits is E and the total amount of free allowances is $n\varepsilon_I^{PNA}$, hence the ratio: $\frac{n\varepsilon_I^{PNA}}{E}$. $\square$

The total amount of free allowances is thus independent of the number of firms. Because of the form of profits, profit-neutral allowances increase when the mass of consumers m increases and when the regulation becomes more severe. However, it should be noted that for the ratio of free allowances to be 100%, the cap E must be equal to $\frac{\bar{\alpha}m}{3}$, which implies reducing emissions by 67%. If the regulator wants to reduce emissions by 20% (respectively 30%),[15] then the ratio of free allowances is 12.5% (resp. 21.5%).

3.3 Both technologies are available

We now consider that both abatement technologies are available. In other words, each firm on the market can use end-of-pipe abatement and process integrated technology simultaneously. We want to determine if free allowances must be given on the ground of profit neutrality in such a case. We can write firm i's final profit as follows:

$$\pi_i = q_i(p)(p_i - \alpha(y_i)\sigma) - \frac{\beta}{2}y_i^2 + x_i\sigma - \gamma\frac{x_i^2}{2} + \sigma\varepsilon.$$

First taking the price of permits as given, we find that at equilibrium, $x_{EPI}^* = x_{EP}^*$ and $y_{EPI}^* = y_I^*$. As in both previous sections, the equilibrium price is equal to $p_{EPI}^* =$

[15] The EU has committed to "a reduction of at least 20% in greenhouse gases (GHG) by 2020 – rising to 30% if there is an international agreement committing other developed countries to comparable emission reductions and economically more advanced developing countries to contributing adequately according to their responsibilities and respective capabilities." See Directive 2009/29/CE of april 2009.

$\frac{t}{n} + \alpha(y^*_{EPI})\sigma$. As a consequence, firm i's equilibrium profit may be written as follows:

$$\pi^*_{EPI}(\sigma) = \frac{tm}{n^2} + \left(\frac{1}{\gamma} - \frac{m^2}{\beta n^2}\right)\frac{\sigma^2}{2} + \sigma\varepsilon.$$

Because of the form of end-of-pipe abatement, the profit of a firm is separable in y_i and x_i. As a result, the effect of the regulation on the firm's profits is the sum of the profit-increasing effect of end-of-pipe abatement, measured by $\frac{\sigma^2}{2\gamma}$, and the profit-decreasing effect of process integrated abatement, measured by $\frac{m^2\sigma^2}{2\beta n^2}$. The effect of the regulation on profits depends on which effect offsets the other: profits decrease with σ if and only if $\frac{m^2}{\beta n^2} \geq \frac{1}{\gamma}$. Only in this case should free allowances be given to the firms on the ground of profit-neutrality.

Most industries use abatement technologies that neither completely belong to the end-of-pipe abatement type nor to the process integrated type. However, with this last analysis, we show that it is possible to rank each industry amongst one of the two families. Therefore, what is important for the regulator is to determine each sector's dominant technology.

4 Policy towards entry

In the former section, we have shown that the regulator's policy towards incumbents must be contingent on the type of abatement technology they use. Firms should thus be granted free allowances on the ground of profit-neutrality when they use process integrated technology, but not if they use end-of-pipe abatement.

In this section, we focus on the policy of the regulator towards entry, and show that the environmental policy must adapt to entry. Besides, as for incumbents, the adjustment of the policy to entry is contingent on the type of abatement technology used by the industry. Nevertheless, in the case of entry, the regulator adapts its policy by changing the cap of pollution rather than the level of free allowances. Indeed, we show in Appendix A.2 that the regulator should never give firms free allowances in order to increase social welfare, for the standard result obtained in the Salop model holds: there are always too many firms at the free-entry equilibrium, as compared to the optimal market structure.

In order to emphasize the effect of entry on the regulator's decisions, we focus on the path that leads to the free-entry equilibrium rather than on the equilibrium itself.

Proposition 3. *The regulator's optimal policy towards entry is contingent on the abatement technology available to the industry. As the number of firms on the market increases, the regulator:*

- *reduces the cap of permits available to the industry with end-of-pipe abatement,*

- *increases the cap of permits available to the industry with process integrated technology.*

Proof. See appendix A.2. □

Proposition 3 results from the fact that an increase of the number of firms does not have the same effect on the marginal cost of reducing emissions when firms use end-of-pipe abatement and when they use process integrated technology. Indeed, in both cases, firms have an incentive to reduce pollution emissions as the price of pollution permits increases: both x^*_{EP} and y^*_I are increasing in σ. On the contrary, we have shown in Section 3 that the price of permits σ is affected differently by an increase of the number of firms, depending on the type of abatement technology used by the industry.

Consider first the case of end-of-pipe abatement. As a firm always abates the same amount of pollution regardless of the number of firms on the market, the aggregate demand for permits decreases with n. Therefore, the equilibrium price of permits σ^*_{EP} decreases with n too. As a result, for a given cap of permits E, the marginal abatement cost for society decreases as more firms enter the market. Since the marginal gain of polluting less is always λ, the optimal cap of permits E^{opt}_{EP} is decreasing in n: when a firm enters the market, the regulator wants to set a more severe environmental regulation.

In the case of process integrated technology, we find the opposite result. As the number of firms increases, a firm's marginal gain to abate pollution decreases, which increases the aggregate demand for permits. Therefore, the equilibrium price of permits σ^*_{EP} increases with n, and for a given cap of permits E, the marginal abatement cost for society increases with n too. As a consequence, the optimal cap of permits E^{opt}_I increases with n: the more firms on the market, the lighter the burden the regulator wants to impose on firms.

From Proposition 3, we can point out an important feature of the optimal environmental regulation. Although free allowances are irrelevant, the environmental regulation must adapt to entry by adjusting the total emission target. Moreover, this necessary adjustment is contingent on the type of abatement technology available to the firms. Indeed, in the case of end-of-pipe abatement, the regulator should reduce the cap of permits when firms enter. In order to do so, it may buy permits to incumbents with a preemption right and give free allowances to entrants. On the contrary, in the case of process integrated technology, the regulator should increase the number of permits available when the number of firms increases. The regulator then foresees a reserve of permits available to potential entrants, hence increasing official caps of emissions in the event of entry.

Finally, it should be noted that this result is consistent with the conclusions we reached as regards the regulator's policy towards incumbents in Section 3. Indeed, whether it considers its policy towards entrants or incumbents, the regulator should always have a more lenient attitude towards industries that use process integrated technology than end-of-pipe abatement. In the case of incumbents, such discrimination involves granting free allowances to the latter but not to the former. In the case of entrants, it involves relaxing the emission constraint for the latter and intensifying this constraint on the former when firms enter the market.

5 Extensions

In this section, we discuss three assumptions of our model. First, we consider a more general demand function and show that the profit-increasing effect of permits in the case of end-of-pipe abatement remains. Second, we allow firms to choose their abatement technology prior to the market game. Finally, we consider that end-of-pipe abatement is cooperative: this affects our results on profit-neutral allowances and on the environmental regulation.

5.1 General demand function

We first test the robustness of the profit increasing effect of the environmental regulation. We assume that the price of permits σ is exogenous. We consider that two firms, denoted by 1 and 2, compete in price to sell differentiated goods. The demand for good i is denoted by $q_i(p_1, p_2)$, where p_i is the price set by firm i on the final market. It is such that $\frac{\partial q_i}{\partial p_i} < 0$ and $\frac{\partial q_i}{\partial p_j} > 0$. Besides, we respectively denote the direct- and cross-price elasticities by $\eta_{ii} = \frac{p_i}{q_i}\frac{\partial q_i}{\partial p_i} < 0$ and $\eta_{ij} = \frac{p_j}{q_i}\frac{\partial q_i}{\partial p_j} > 0$. As in the model described in Section 2, if firm i produces a quantity q_i, it emits a pollution $\bar{\alpha} q_i$. We study the effect of σ on profits first in the case of end-of-pipe abatement and then in the case of process integrated technology. In each case, we denote by π^* the equilibrium profit.

End-of-pipe abatement. We first assume that each firm uses end-of-pipe abatement to reduce pollution by x_i, which then costs $\gamma x_i^2/2$. The problem of firm i is thus:

$$\max_{p_i, x_i} \pi_i = (p_i - \bar{\alpha}\sigma) q_i(p_1, p_2) - \gamma \frac{x_i^2}{2} + \sigma x_i.$$

As previously, we decompose the total profit into two parts: the product market profit given the baseline pollution and the abatement opportunity profit. As in the simpler model described in Section 2, these two parts are separable here. On the one hand, the effect of the permits price on the abatement opportunity profit is unchanged as compared to our former analysis: The abatement opportunity profit is thus equal to $\frac{\sigma^2}{2\gamma}$ and increases with the price of permits. This part does not depend on the firm's production.

On the other hand, contrary to the case where total demand is inelastic, the product market profit varies with marginal cost, and thus with the permits price. This effect is standard in the industrial organization literature. An increase of the permits price increases the price on the final market and reduces total output (as well as individual output, since firms are symmetric), which in most cases reduces the firms' revenue. However, Seade (1985) and Vives (2000) show in the case of Cournot competition that under some conditions, even this part of the firm's profit may increase following an increase of the permits price. As the following equation shows, in the case of price competition, the effect of σ on the product market profit depends both on the direct- and on the cross-price elasticities η_{ii} and η_{ij}, and on the pass-through, that is the part of the cost increase that is passed to consumers through the increase of the final price: $pt = \frac{\frac{\partial p^*}{\partial \sigma}}{\alpha}$. The variation of π^*_{EP} with respect to σ is given by:

$$\frac{\partial \pi^*_{EP}}{\partial \sigma} = q_i(p^*_{EP}, p^*_{EP}) \left(1 - \frac{\sigma \bar{\alpha}}{p^*_{EP}}\right) \bar{\alpha} \left(pt\eta_{ij} + \eta_{ii}\right) + \frac{\sigma}{\gamma}. \tag{7}$$

The effect of the permits price on the total profit thus depends on the trade-off between these two effects, one of which is always positive, while the other is ambiguous.

Proposition 4. *Industries that use an end-of-pipe abatement technology suffer less from the introduction of a cap-and-trade regulation than industries that have access to no abatement technology. In particular, when firms use end-of-pipe abatement, profits are all the more likely to increase with σ that:*

- *the direct-price elasticity of demand is low enough relative to the cross-price elasticity of demand,*

- *the pass-through pt is high enough.*

Proof. See Appendix A.3. □

It should be noted that this result holds with a more general end-of-pipe abatement function such that the cost $A(.)$ of abating satisfies the following standard conditions: $A' > 0$, $A'' > 0$, $A(0) = 0$, $A'(0) = 0$.

We illustrate this result with a standard linear demand function. We assume that $q_i(p_1, p_2) = 1 - p_i + \gamma p_j$, where $\gamma \in [0, 1]$ is the differentiation parameter. The higher γ, the closer substitutes the two goods. Then, it is immediate that when σ increases, profits can only increase because of the possibility to abate. Indeed, the pass-through $pt = \frac{1}{2-\gamma}$ is unsurprisingly lower than 1. Besides, as $\frac{\partial q_i}{\partial p_i} = -1$ and $\frac{\partial q_i}{\partial p_j} = \gamma < 1$, both firms set the same final price and $q_i(p^*_{EP}, p^*_{EP}) = q_j(p^*_{EP}, p^*_{EP})$, we always have

$\eta_{ii} + \eta_{ij} < 0$. Therefore, the left-hand term of equation (7) is negative for all values of σ. Finally, we observe two opposite effects: The first one is the decrease of the product-market profit. The second one is the increase of the abatement opportunity profit. If we consider those two effects simultaneously, we find a condition on σ such that beyond a given value of the permits price, profits increase with σ. The threshold permits price is given in Appendix A.4.

Process integrated technology. We now assume that firms can use process integrated technology and reduce their polluting factor by y_i at cost $\frac{\beta y_i^2}{2}$. The problem of firm i is thus:

$$\max_{p_i, y_i} \pi_i = (p_i - \sigma\bar{\alpha})\, q_i(p_1, p_2) - \beta \frac{y_i^2}{2} + \sigma y_i q_i(p_1, p_2).$$

Note that in this case, the separation of the profit between the product market profit and the abatement opportunity profit is artificial, as abatement and output decisions are interdependent. Nevertheless, this allows us to compare the two technologies more thoroughly.

In the case of process integrated abatement, the setting of the final price depends on the level of abatement y_i, which has two contradictory effects.

On the one hand, this tends to tighten the conditions for the product market profit as well as total profit to be increasing in σ. Indeed, following an increase of σ, the final price is likely to increase more when firms use end-of-pipe abatement than when they use process integrated abatement, for in the latter case, an increase of σ induces firms to abate more. This reduces their marginal cost and eventually induces them to increase their final price less than they would with end-of-pipe abatement. This first effect goes against the profit increasing effect.

On the other hand, an increase of σ has less impact in the case of process integrated abatement than in the case of end-of-pipe abatement, for firms can limit the increase of their marginal cost of production through abatement. This, on the contrary, tends to ease the constraint for a profit increase following an increase of σ.

The effect of σ on total profit is given by the following equation:[16]

$$\frac{\partial \pi_I^*}{\partial \sigma} = q_i(p_I^*, p_I^*) \left(1 - \frac{(\bar{\alpha} - y^*)\sigma}{p_I^*}\right) (\bar{\alpha} - y^*)(pt\eta_{ij} + \eta_{ii}). \tag{8}$$

Proposition 5. *When firms use process integrated abatement, profit increase with σ if and only if $pt\eta_{ij} + \eta_{ii} > 0$.*

[16]See Appendix A.3 for the complete analysis.

Proof. Given equation (8) and since $q_i(p^*, p^*) > 0$, $p_I^* > \bar{\alpha} - y^*$ and $y^* \in [0, \bar{\alpha}]$, it is immediate that $\frac{\partial \pi_I^*}{\partial \sigma} > 0$ if and only if $pt\eta_{ij} + \eta_{ii} > 0$. □

Comparing (7) and (8), one can note the two essential differences between the two technologies: First, when firms use process integrated abatement, a firm could individually benefit from the permits market by lowering its final price and hence increase its demand; however, as all firms in the market behave symmetrically, this benefit is offset by increased competition. On the contrary, in the case of end-of-pipe abatement, the benefit of the permits market is equal to $\frac{\sigma}{\gamma}$ and independent of competition on the product market. Second, as firms perceive a lower cost increase in the case of process integrated abatement, they increase their price less when σ increases. This affects elasticities, final demand and the pass-through.

Considering now linear demand, we find that it is never the case that the profit of firms increases with σ when they use process integrated abatement. This result is developed in Appendix A.4.

Finally, qualitatively similar conclusions obtain under Cournot competition (the proof is available from the authors upon request).

5.2 Endogenous choice of abatement technology

Until now, we have assumed that abatement technologies are given to the firms and that all firms in the same industry use the same abatement technology. We show here that allowing firms to choose their technology prior to setting their price and abatement level confirms our results regarding the granting of free allowances.[17]

It is generally argued that process integrated abatement is better than end-of-pipe abatement from an environmental point of view (see Frondel, Horbach and Rennings, 2007). Indeed, process integrated abatement avoids the emission of pollution at the source and induces long term changes in the production process, whereas end-of-pipe abatement only deals with pollution ex post in order to satisfy environmental requirements in the short run. In this section, we assume that firms can choose their own abatement technology before the price competition stage and that the regulator wants firms to choose process integrated abatement over end-of-pipe abatement.

We consider a Hotelling framework where two firms are located at the extremities of a segment of length 1. The demand faced by firm i is $q_i(p_1, p_2) = \frac{p_j - p_i + t}{2t}$ $(j \neq i)$, where t is the unit transport cost. The timing is as follows: First each firm chooses either

[17] Montero (2002) studies the effect of the environmental regulation on the incentives of firms to invest in environmental R&D. This section is related to his work in that we study incentives to invest in a specific abatement technology when there is imperfect competition on the product market. However, we consider one type of instrument and two types of technologies, whereas Montero (2002) considers different instruments and their effect on one type of technology (end-of-pipe abatement).

end-of-pipe or process integrated abatement. Second, firms compete on the final market and set their abatement levels simultaneously. Third, the market for permits clears. The cost function and pollution abatement associated with each abatement technology are unchanged with regards to the model presented in Section 2.

Proposition 6. *Assume that firms are granted no free allowances. Then:*

- *there always exists an equilibrium where the two firms choose end-of-pipe abatement;*

- *if end-of-pipe abatement is expensive enough relative to process integrated abatement (i.e., if $\beta < \left(\sqrt{\frac{5}{6}} - \frac{3}{4}\right)\gamma$)), then there exists an equilibrium where the two firms choose process integrated abatement;*

- *when the two equilibria coexist, firms earn higher profits in the end-of-pipe equilibrium.*

Proof. See Appendix A.5. □

When choosing between end-of-pipe and process integrated abatement, firms must solve the following trade-off. On the one hand, as previously analyzed, firms that use process integrated abatement do not enjoy an increase of their profits due to the market for emission permits, as opposed to firms that use end-of-pipe abatement. On the other hand, if firm i chooses process integrated abatement while its rival chooses end-of-pipe abatement, then firm i can benefit from its lower production cost on the product market. Indeed, denoting by y_i i's level of abatement given that it chose process integrated abatement, the marginal production costs of the firms are given by: $c_i = (\bar{\alpha} - y_i)\sigma < \bar{\alpha}\sigma = c_j$. As a consequence, equilibrium prices and demands are such that: $p_i^* < p_j^*$ and $q_i^* > q_j^*$. However, the positive effect of choosing process integrated abatement on the product market profit never offsets the losses due to pollution abatement.

We now consider that free allowances are a means for the regulator to induce firms to choose process integrated abatement over end-of-pipe abatement. The regulator commits to offer firms free allowances in the competition stage, provided that they chose process integrated abatement in the first stage of the game.

We denote by $\pi_i^*(K, L)$ the profit of firm i in the equilibrium of the subgame starting in stage 2, when i chooses technology K ($K \in \{EP, I\}$) and $j \neq i$ chooses technology L ($L \in \{EP, I\}$). For each firm to choose process integrated abatement in equilibrium, the two following conditions must be satisfied:

$$\pi_i^*(I, I) > \pi_i^*(EP, I), \tag{9}$$

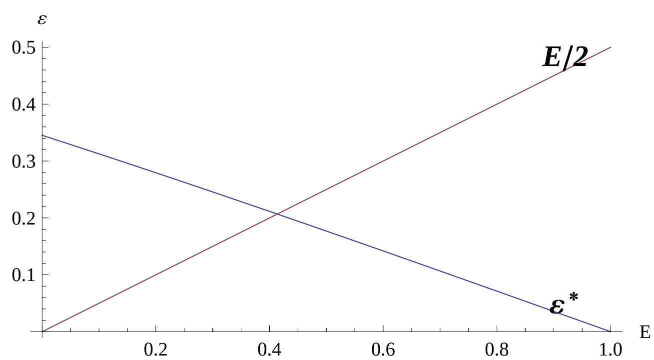
$$\max\{\pi_i^*(I, I), \pi_i^*(I, EP)\} > \pi_i^*(EP, EP). \tag{10}$$

The first condition ensures that there is an equilibrium where the two firms choose process integrated abatement. The second condition ensures that the equilibrium where the two firms choose end-of-pipe abatement is preferred by the former, if it even exists.

We compare this to the case where firms cannot choose their technology and the technology of the industry is process integrated abatement. Then, if the regualtor seeks profit-neutrality, it must ensure that $\pi_i^*(I, I) \geq \pi_i^{\varnothing}$, where $\pi_i^{\varnothing}$ is the profit of firm i when there is no environmental regulation. Then, we find two contradictory effects of endogeneizing the choice of technology, which appear in equation (10). On the one hand, we have shown previously that $\pi_i^*(EP, EP) > \pi^{\varnothing}$: the environmental regulation benefits industries that use end-of-pipe technologies. Therefore, it is more difficult to satisfy constraint (10) than the profit-neutrality constraint, in the sense that the profit firm i needs to earn to choose process integrated abatement is higher than its profit prior to any regulation. On the other hand, for most values of the parameters, we have $\pi_i^*(I, EP) > \pi_i^*(I, I)$: firm i earns a higher profit by choosing process integrated abatement when its rival chooses end-of-pipe abatement than process integrated abatement, as only in the former case has firm i a lower marginal cost than its rival. This tends to make constraint (10) easier to satisfy than the profit-neutrality constraint. Finally, the former effect tends to offset the latter and the regulator must grant more free allowances to firms to induce them to choose process integrated abatement than simply to ensure profit neutrality when the abatement process is given and is process integrated abatement.

Importantly, when the emission cap is low enough or when process integrated abatement is expensive enough relative to end-of-pipe abatement, the regulator may not be able to induce firms to choose process integrated abatement. Indeed, there are cases in which the optimal amount of free allowances ε^* is such that $2\varepsilon^* > E$: the regulator would have to give more permits than the amount available. The following figure gives the optimal level of free allowances when the choice of the technology is endogenous and $\alpha = \beta = \gamma = t = 1$. In that case, the ratio of free allowances is 100% when the regulator's objective is to reduce emissions by 59%. By comparison, when the objective is profit-neutrality, a ratio of free allowances of 100% enables the regulator to reduce emissions by 67%.

Focusing as in Section 3 on the objectives set by the EU for 2020, if the regulator wants to reduce emissions by 20% (respectively 30%), then the ratio of free allowances it should grant is 10% (resp. 15%) on the ground of profit-neutrality and 12.5% (resp. 18.75%) to create incentives for firms to choose process integrated abatement rather than end-of-pipe abatement.



5.3 Cooperative end-of-pipe abatement

We now consider the case where firms share the same end-of-pipe abatement technology. Firms store emissions at the same place. Such a cooperative system already exists for some industries, although they are often still experimental. For instance, in Alberta, a project called ICO2N proposes a carbon capture and storage system that involves thirteen firms from various industries.[18]

One concern raised by the development of such cooperative systems is their effect on competition on final markets. Indeed, allowing for cooperation in pollution abatement may facilitate cooperation on the product market. We thus compare two situations: First, firms share the total cost of abatement and determine their abatement level cooperatively (by maximizing the joint profit of the industry). Second, they still share the total cost of abatement, but each firm determines its own abatement level individually. We suppose that the total abatement cost is equal to $\frac{\gamma}{2}(\sum_i x_i)^2$ and each firm supports a share $1/n$ of that total cost.[19] We focus on abatement decisions.

Consider first that firms set their abatement level cooperatively. Then firm i sets x_i to maximize the total profit of the industry on the market for permits, that is solves the program $\max_{x_i} \sigma \sum_i x_i - \frac{\gamma}{2} \left(\sum x_i\right)^2$. It is immediate that the total abatement level is equal to that of a monopoly facing the abatement cost function $\frac{\gamma}{2}x^2$: the former analysis thus tells us that the total abatement level is $\frac{\sigma}{\gamma}$ and given that firms equally share the cost, abatement is similarly shared equally among firms.

Assume now that because of competition concerns, firms cannot cooperate on abate-

[18]These firms are Agrium Inc., Air Products Canada Inc., Canadian Natural Resources Ltd., ConocoPhillips Company, EPCOR, Husky Energy Inc., Imperial Oil Ltd., Keyera, Nexen Inc., Shell Canada Ltd., Sherritt International Corporation, Suncor Energy Inc., Syncrude Canada Ltd., Total E&P Canada Ltd., TransAlta Corporation. Note that a complementary project has been announced recently. It concerns a group of 19 companies which plan to identify deep saline aquifers suitable for the permanent storage of CO2 in Alberta.

[19]We consider the case where firms cannot store pollution individually, because there is only one site available, and it must be shared amongst all firms in the same geographic area. Therefore, we assume that the collective abatement cost function in that case is the same as the former individual abatement cost function.

ment decisions, although the cost is still shared among firms. Then the total level of abatement is equal to $\frac{n\sigma}{\gamma}$, that is equal to the total abatement level in the case of individual abatement technologies. At equilibrium, each firm abates $\frac{\sigma}{\gamma}$, as in the case with individual end-of-pipe abatement. The resulting indiviual profit is $\pi^*_{CEP} = \frac{tm}{n^2} - (n-2)\frac{\sigma^2}{2\gamma}$. Firms now lose profits on the market for permits as long as $n > 2$. Indeed, contrary to the cooperative case, a firm does not take into account the negative externality its decision has on its rivals. As a consequence, the level of abatement is higher than with total cooperation, which increases the total cost of abatement more than the total gain of abatement. The opportunity profit earned on the market for permits thus becomes negative.

Finally, this anaylsis underlines another characteristics that may help distinguish between industries and determine those that need free allowances: the degree of cooperation and cost-sharing in abatement should also be taken into account.

6 Conclusion

In this paper, we offer some good economic reasons to adapt the European environmental policy in favour of firms. More precisely, we show that both free allowances to incumbents and the reserve for entrants may be justified to facilitate the coordination between the environmental regulation and both competition and industrial policies. However, the use of both these instruments should be contingent on the type of abatement technology used by the firms. We compare two extreme types of technology: end-of-pipe abatement and process integrated.

When the regulator seeks to ensure profit-neutrality, we find that only firms that use process integrated technologies should be granted free allowances. Indeed, although in both cases, firms pass-through all their marginal cost to consumers, and firms' profits on the product market is thus always the same, with process integrated technologies, each firm incurs the cost of abatement but does not benefit from it as all the decrease in marginal cost is passed-through to consumers. Besides, new entrants that use process integrated technologies should benefit from the reserve for entrants. On the contrary, in the case of end-of-pipe abatement, the regulator should use a preemption right to buy permits so as to reduce the pollution cap when new firms enter the market.

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A Appendix

A.1 U.S. CO_2 emissions and cost of capture and storage in 2000

Emission Source	Capture and storage cost ($ /tC avoided)
Electricity generation	200-250
Petroleum refining (combustion)	200-250
Petroleum refining (non-combustion)	50-90
Chemicals (combustion)	245
Chemicals (non-combustion)	50-75
Iron and steel	195
Cement	180-915
Lime	180-915
Hydrogen production	50-75

The source for this table is Anderson and Newell (2003).

A.2 Optimal number of firms and free allowances

We consider the free entry equilibrium. Firms enter the market as long as they earn a non-negative profit, and the equilibrium number of firms is thus such that $\pi_k^* - F = 0$ (for $k = EP, I$). The resulting number of firms is denoted $n_k^*(E, \varepsilon)$. For $k \in \{EP, I\}$ and since $\frac{\partial \pi_k^*}{\partial \varepsilon} > 0$, we have that for all E $n_k^*(E, \varepsilon > 0) > n_k^*(E, \varepsilon = 0)$.

We now show that for any E, $n_k^*(E, \varepsilon = 0) > n_k^{opt}$, the optimal size of the industry. The regulator plays before firms. Assuming that the regulator can set the cap of emissions allowed E, the amount of free allowances ε and the number of firms n, then it reaches social optimum by maximizing total welfare, anticipating the equilibrium of the game (i.e. the firms' abatement and output decisions).

For each type of abatement, total welfare is equal to $W = SC + \sum_i (\pi_i - F) - \lambda \sum_i e_i + RR$. Therefore, in the case of end-of-pipe abatement, we find that:

$$\begin{aligned} W_{EP} &= m\left(v - p_{EP}^* - \frac{t}{4n}\right) + n\left(p_{EP}^* q_{EP}^* - \sigma_{EP}^* e_{EP}^* - \gamma \frac{(x_{EP}^*)^2}{2} + \sigma_{EP}^* \varepsilon - F\right) \quad (11) \\ &\quad -\lambda E + n\sigma_{EP}^*(e_{EP}^* - \varepsilon), \\ &= mv - \frac{tm}{4n} - nF - \lambda E - \frac{n}{2\gamma}\left(\frac{\gamma(\bar{\alpha} m - E)}{n}\right)^2 . \quad (12) \end{aligned}$$

We develop the expression of the profit so as to emphasize that some effects offset each other. The amount paid by firms for each permit bought is totally recovered by the regulator. Moreover, free allowances are permits that the regulator does not sell. Finally, the product price increase is completely passed-through to consumers.

In the case of process integrated technology, we obtain:

$$\begin{aligned} W_I &= m\left(v - p_I^* - \frac{t}{4n}\right) + n\left(p_I^* q_I^* - \sigma_I^* e_I^* - \beta\frac{(y_I^*)^2}{2} + \sigma_I^*\varepsilon - F\right) - \lambda E + n\sigma_I^*(e_I^* - \varepsilon), \\ &= mv - \frac{tm}{4n} - nF - \lambda E - \left(\frac{n\beta}{2}\left(\bar{\alpha} - \frac{E}{m}\right)^2\right). \end{aligned} \tag{13}$$

This case mirrors that with end-of-pipe abatement. Note that we can easily compare these expressions to welfare when the regulator is not concerned with environmental regulation, which is merely the sum of consumers surplus (when the product price is $p^{\varnothing}$) and of the firms' profits: $W_{\varnothing} = mv - \frac{tm}{4n} - nF$. The optimal market structure in this benchmark case is $n_{\varnothing}^{opt}\frac{1}{2}\sqrt{\frac{tm}{F}}$.

In order to ensure that the solution of the regulator's programme is well defined, we assume that $F > \frac{\lambda^2}{2\gamma}$ and that $t\beta > 2\lambda^2$.

Free allowances have no effect on total welfare. Therefore, the regulator sets n and E to solve $\max_{E,n} W_k(E, n)$ for $k \in \{EP, I\}$.[20] The standard result obtained in the Salop model holds: too many firms enter the market. Indeed, we know that when the regulator has no concern for environment, the number of firms at the free entry equilibrium is always excessive from the point of view of the regulator: $n_{\varnothing}^* = 2n_{\varnothing}^{opt}$. When the regulator has environmental concerns and maximizes the welfare functions given by equations (12) and (13), the optimal caps of permits and market structures in the case of end-of-pipe abatement and process integrated technology are respectively:

$$\begin{aligned} n_{EP}^{opt}(E) &= \sqrt{\frac{tm}{4F} + \frac{\gamma(\bar{\alpha}m - E)^2}{2F}} \quad \text{and} \quad E_{EP}^{opt}(n) = \bar{\alpha}m - \frac{\lambda}{\gamma}n, \\ n_I^{opt}(E) &= \sqrt{\frac{tm}{2\beta(\bar{\alpha} - \frac{E}{m})^2 + 4F}} \quad \text{and} \quad E_I^{opt}(n) = \bar{\alpha}m - \frac{\lambda m^2}{\beta n}. \end{aligned}$$

We compare the optimal values of n to the equilibrium values of n when $\varepsilon = 0$:

$$\begin{aligned} n_{EP}^{opt}(E) < n_{EP}^*(E, \varepsilon = 0) &= \sqrt{\frac{tm}{F} + \frac{\gamma(\bar{\alpha}m - E)^2}{2F}}, \\ n_I^{opt}(E) < n_I^*(E, \varepsilon = 0) &= 2m\sqrt{\frac{tm}{2\beta(m\bar{\alpha} - E)^2 + 4Fm^2}}. \end{aligned}$$

[20] It is possible that this programme has no interior solution, in which case the optimum is achieved by choosing $E^{opt} = 0$, which immediately gives $n^{opt} = \frac{1}{2}\sqrt{\frac{m}{F}\left(2\bar{\alpha}^2\gamma + t\right)}$.

This implies that $n_k^{opt} < n_k^*$ for any non-negative value of ε ($k \in \{EP, I\}$). In the case of end-of-pipe abatement, the difference between the free entry and the optimal number of firms $(n_{EP}^*(E, \varepsilon = 0) - n_{EP}^{opt}(E, \varepsilon = 0))$ decreases with γ: as the cost parameter increases, the number of firms at equilibrium gets closer to the optimal number of firms. In the case of process integrated technology, we find that $n_I^*(E, \varepsilon = 0) = 2n_I^{opt}$. Therefore, whatever the abatement technology used by firms, the regulator should not grant firms free allowances, and more generally, should not use free allowances as a means to regulate entry.

A.3 Results with price competition and a general demand function

We consider that 2 firms named 1 and 2 sell differentiated goods and compete in price. The demand function $q_i(p_1, p_2)$ is such that $\frac{\partial q_i}{\partial p_i} < 0$ and $\frac{\partial q_i}{\partial p_j} > 0$. As in the model given in Section 2, if firm i produces a quantity q_i, it emits pollution $\bar{\alpha} q_i$. We consider first the case where the firm can use only end-of-pipe abatement to reduce this pollution by x_i, which then costs $\gamma x_i^2/2$. Second, we consider the case where the firm can use only a process integrated technology to reduce pollution, in which case it reduces the pollution factor by y_i at cost $\beta y_i^2/2$. We denote by η_{ii} the direct price elasticity of q_i and by η_{ij} its cross-price elasticity.

End-of-pipe abatement. The problem of firm i is:

$$\max_{p_i, x_i} \pi_i = (p_i - \bar{\alpha}\sigma) q_i(p_1, p_2) - \gamma \frac{x_i^2}{2} + \sigma x_i.$$

The first order conditions are:

$$\frac{\partial \pi_i}{\partial p_i} = (p_i - \sigma\bar{\alpha}) \frac{\partial q_i}{\partial p_i} + q_i = 0, \tag{14}$$

$$\frac{\partial \pi_i}{\partial x_i} = \gamma x_i - \sigma = 0. \tag{15}$$

As before, price and abatement decisions are separable. Therefore, equation (15) still gives $x_{EP}^*(\sigma) = \frac{\sigma}{\gamma}$, and as firms are identical, the equilibrium price is symmetric for all i and denoted by $p_{EP}^*(\sigma)$. We denote the equilibrium output of firm i by $q_i^*(\sigma) = q_i(p_{EP}^*(\sigma), p_{EP}^*(\sigma))$ and $\pi_{EP}^*(\sigma) = \pi_i(p_{EP}^*(\sigma), x_{EP}^*(\sigma))$ the corresponding equilibrium profit.

We want to determine how the equilibrium profit is affected by an increase of the permits price σ. This variation is given by:

$$\frac{\partial \pi_{EP}^*}{\partial \sigma} = \left(\frac{\partial p_{EP}^*}{\partial \sigma} - \bar{\alpha}\right) q_i(p_1, p_2) + (p_{EP}^* - \bar{\alpha}\sigma)\left(\frac{\partial q_i}{\partial p_i} + \frac{\partial q_i}{\partial p_j}\right)\frac{\partial p_{EP}^*}{\partial \sigma} + \frac{\sigma}{\gamma}. \tag{16}$$

Using (14), we have that $q_i(p_{EP}^*, p_{EP}^*) = -(p_{EP}^* - \sigma\bar{\alpha})\frac{\partial q_i}{\partial p_i}$. Replacing $q_i(p_{EP}^*, p_{EP}^*)$ in (16), we find that:

$$\frac{\partial \pi_{EP}^*}{\partial \sigma} = (p_{EP}^* - \sigma\bar{\alpha})\left(\bar{\alpha}\frac{\partial q_i}{\partial p_i} + \frac{\partial p_{EP}^*}{\partial \sigma}\frac{\partial q_i}{\partial p_j}\right) + \frac{\sigma}{\gamma}.$$

Then, the equilibrium profit of i increases with σ if the following condition is satisfied:

$$q_i(p_{EP}^*, p_{EP}^*)\left(1 - \frac{\sigma\bar{\alpha}}{p_{EP}^*}\right)\bar{\alpha}\left(pt\eta_{ij} + \eta_{ii}\right) + \frac{\sigma}{\gamma} > 0.$$

Then, since $\bar{\alpha}$ and $\frac{\partial p_{EP}^*}{\partial \sigma} > 0$, we see that two characteristics determine the effect of σ on the market product profit:

- First, the higher the cross-price elasticity with regards to the direct-price elasticity, the more likely it is that the market product profit will increase with σ;

- Second, the higher the pass-through of the cost increase to the consumers (the higher $\frac{\partial p_{EP}^*}{\partial \sigma}$ relative to α), the more likely again that the market product profit will increase with σ.

Process integrated technology. The problem of firm i is:

$$\max_{p_i, y_i} \pi_i = (p_i - \sigma\bar{\alpha})\, q_i(p_1, p_2) - \beta\frac{y_i^2}{2} + \sigma y_i q_i(p_1, p_2).$$

The first order conditions are:

$$\frac{\partial \pi_i}{\partial p_i} = (p_i - (\bar{\alpha} - y_i)\sigma)\frac{\partial q_i(p_1, p_2)}{\partial p_i} + q_i(p_1, p_2) = 0, \tag{17}$$

$$\frac{\partial \pi_i}{\partial y_i} = \sigma q_i(p_1, p_2) - \beta y_i = 0. \tag{18}$$

As before, here output and abatement decisions are not separable. Equation (18) gives $y_i^*(\sigma) = \frac{\sigma}{\beta} q_i(p_I^*(\sigma), p_I^*(\sigma))$. We can replace y_i by this expression in the expression of firm

i's equilibrium profit, which gives:

$$\begin{aligned}\pi_I^*(\sigma) &= \left(p_I^* - \sigma\left(\bar{\alpha} - \frac{\sigma}{\beta} q_i(p_I^*, p_I^*)\right)\right) q_i(p_I^*, p_I^*) + \frac{\sigma^2}{2\beta} q_i(p_I^*, p_I^*)^2, \\ &= q_i(p_I^*, p_I^*)\left(p_I^* - \left(\bar{\alpha} - \frac{y^*}{2}\right)\sigma\right).\end{aligned}$$

As in the former case, we want to determine how the equilibrium profit is affected by an increase of the permits price σ. This variation is given by:

$$\frac{\partial \pi_I^*}{\partial \sigma} = \left(\frac{\partial p_I^*}{\partial \sigma} - (\bar{\alpha} - y^*) + \sigma \frac{\partial y^*}{\partial \sigma}\right) q_i(p_I^*, p_I^*) + (p_I^* - (\bar{\alpha} - y^*)\sigma)\left(\frac{\partial q_i}{\partial p_i} + \frac{\partial q_i}{\partial p_j}\right)\frac{\partial p_I^*}{\partial \sigma}. \quad (19)$$

Besides, from (18) we have the following expression:

$$\frac{\partial y^*}{\partial \sigma} = \frac{1}{\beta}\left(q_i(p_I^*, p_I^*) + \sigma\left(\frac{\partial q_i}{\partial p_i} + \frac{\partial q_i}{\partial p_j}\right)\frac{\partial p_I^*}{\partial \sigma}\right). \quad (20)$$

Using (20), (19) and (17), we have a new expression of $\frac{\partial \pi_I^*}{\partial \sigma}$:

$$\begin{aligned}\frac{\partial \pi_I^*}{\partial \sigma} &= (p_I^* - (\bar{\alpha} - y^*)\sigma)\frac{\partial p_I^*}{\partial \sigma}\frac{\partial q_i}{\partial p_j} - (\bar{\alpha} - y^*) q_i(p_I^*, p_I^*), \\ &= q_i(p_I^*, p_I^*)\left(1 - \frac{(\bar{\alpha} - y^*)\sigma}{p_I^*}\right)(\bar{\alpha} - y_I^*)(pt\eta_{ij} + \eta_{ii}).\end{aligned}$$

Note that at equilibrium $p_I^* > (\bar{\alpha} - y^*)\sigma$ and $y^* \in [0, \alpha]$. As a consequence, the profit of firm i increases with σ if and only if:

$$pt\eta_{ij} + \eta_{ii} > 0.$$

Note that we can separate to some extent the effect of σ on a firm's profit into two into two effects: on the one hand its effect on the product market profit and on the other hand its effect on the profits associated with abatement. The effect of σ on the permits market profit is then given by $\frac{\beta}{2}(y^*)^2$, which is always positive. The effect of σ on the product market profit denoted by $\hat{\pi}_I^*(\sigma) = (p_I^* - \sigma\bar{\alpha})\, q_i(p_I^*, p_I^*)$ is given by the following expression:

$$\begin{aligned}\frac{\partial \hat{\pi}_I^*}{\partial \sigma} &= (p_I^* - \bar{\alpha}\sigma)\left(\frac{\partial q_i}{\partial p_i} + \frac{\partial q_i}{\partial p_j}\right)\frac{\partial p_I^*}{\partial \sigma} + \left(\frac{\partial p_I^*}{\partial \sigma} - \bar{\alpha}\right) q_i(p_I^*, p_I^*) \\ &= q_i(p_I^*, p_I^*)\left((p_I^* - \bar{\alpha}\sigma)\eta_{ij} - \bar{\alpha} - \frac{\partial p_I^*}{\partial \sigma}\frac{\sigma^2}{\beta}\frac{\partial q_i}{\partial p_i}\right).\end{aligned}$$

In the case of end-of-pipe abatement, the variation of the product market profit is given by $\frac{\partial \hat{\pi}^*_{EP}}{\partial \sigma} = q_i(p^*_{EP}, p^*_{EP})\left((p^*_{EP} - \bar{\alpha}\sigma)\eta_{ij} - \bar{\alpha}\right)$. Therefore, assuming first that the equilibrium price is the same with end-of-pipe and with process integrated abatement, the product market profit decreases more with σ for end-of-pipe abatement, for the real cost increase is higher in that case ($\bar{\alpha}$ versus $\bar{\alpha} - y^*$). However, now taking into account the different effects of σ on final prices depending on the technology used, it is clear that final prices increase less with σ in the case of process integrated abatement, as the real cost increase is lower in that case than with end-of-pipe abatement.

A.4 Results with price competition and a linear demand with differentiated goods

With end-of-pipe abatement. Firms compete in price and firm i faces the following demand function: $q_i(p_1, p_2) = 1 - p_i + ap_j$, with $a \in [0, 1]$. Firm i solves the following programme:

$$\max_{p_i, x_i} \pi_i = (p_i - \bar{\alpha}\sigma)(1 - p_i + ap_j) - \gamma\frac{x_i^2}{2} + \sigma x_i.$$

The first-order conditions are then:

$$\begin{aligned} 2p_i - ap_j &= 1 + \bar{\alpha}\sigma, \\ x_i &= \frac{\sigma}{\gamma}. \end{aligned}$$

The equilibrium profit is $\pi^*_{EP} = \frac{(1-\bar{\alpha}(1-t)\sigma)^2}{(2-t)^2} + \frac{\sigma^2}{\gamma}$. When the permit price is exogenous, firms' profits are convex in σ. There exists a threshold $\underline{\sigma} = \frac{2\alpha(1-t)\gamma}{(2-t)^2 + 2\alpha^2(1-t)^2\gamma}$ such that π^*_{EP} is decreasing in σ if $\sigma < \sigma^*$ and increasing in σ otherwise.

With process integrated abatement. The demand function is given in the previous paragraph. Firm i then solves the following programme:

$$\max_{p_i, y_i} \pi_i = (p_i - \sigma(\bar{\alpha} - y_i))\,(1 - p_i + tp_j) - \beta\frac{y_i^2}{2}.$$

The first-order conditions are then:

$$\begin{aligned} 2p_i - tp_j + \sigma y_i &= 1 + \bar{\alpha}\sigma, \\ y_i &= \frac{\sigma}{\beta}(1 - p_i + \gamma p_j). \end{aligned}$$

which gives $p_I^* = \frac{\sigma^2-\beta(1+as)}{\sigma^2(1-t)-\beta(2-t)}$ and $y_I^* = \frac{\sigma}{\beta}q_I^*$. The equilibrium profit is then $\pi_I^* = \frac{\beta\left(2\beta-\sigma^2\right)(1-\alpha\sigma(1-t))^2}{2(\beta(2-t)-\sigma^2(1-t))^2}$. The derivative of this profit with respect to σ is negative for all relevant values of the parameters.

A.5 Endogenous choice of abatement technology

We show here that when firms can choose their abatement technology before they compete on the final market and choose their abatement levels, both firms choose to use end-of-pipe abatement rather than process integrated technology at equilibrium. We consider a Hotelling framework in which only two firms compete. Firms are located at the extremities of a segment of length $m = 1$. Then, the demand faced by firm i is $q_i(p_1, p_2) = \frac{p_j - p_i + t}{2t}$ $(j \neq i)$, where t is the unit transport cost. The timing is as follows: first each firm chooses either end-of-pipe or process integrated abatement; second, firms compete on the final market and choose their abatement levels simultaneously; third, the market for permits clears.

Price and abatement decisions. We consider three cases depending on the firms' choices in the first stage. Both firms may have chosen end-of-pipe abatement or process integrated abatement, or one firm may have chosen end-of-pipe abatement while the other chose process integrated abatement.

If both firms chose end-of-pipe abatement, then firm i $(i = 1, 2)$ solves the following problem

$$\max_{p_i, x_i}(p_i - \bar{\alpha}\sigma)q_i(p_1, p_2) - \gamma\frac{x_i^2}{2} + \sigma x_i.$$

First order conditions are:

$$\begin{aligned}
\frac{\partial \pi_i}{\partial p_i} &= -\frac{p_i - \bar{\alpha}\sigma}{2t} + \frac{p_j - p_i + t}{2t} = 0, \quad \Rightarrow \quad 2p_i - p_j = t + \bar{\alpha}\sigma, \\
\frac{\partial \pi_i}{\partial x_i} &= -\gamma x_i + \sigma = 0 \quad \Rightarrow \quad x_i = \tfrac{\sigma}{\gamma}.
\end{aligned}$$

The equilibrium prices and abatement levels are thus equal and given by $p^*(\sigma) = t + \bar{\alpha}\sigma$ and $x^*(\sigma) = \frac{\sigma}{\gamma}$. At equilibrium, each firm's output is $q^* = \frac{1}{2}$.

The market clearing condition on the market for emission permits is given by $E = 2(\bar{\alpha}q^* - x^*) = \bar{\alpha} - 2\frac{\sigma}{\gamma}$, and the equilibrium permits price is thus $\sigma^* = \frac{\bar{\alpha}-E}{2\gamma}$. Firm i earns a profit $\pi^*(EP, EP) = \frac{(\bar{\alpha}-E)^2\gamma + 4t}{8}$.

If both firms chose process integrated technology, then firm i $(i = 1, 2)$ solves the problem:

$$\max_{p_i, y_i} (p_i - (\bar{\alpha} - y_i)\sigma) q_i(p_1, p_2) - \beta \frac{y_i^2}{2}.$$

First order conditions are:[21]

$$\begin{aligned}
\frac{\partial \pi_i}{\partial p_i} &= \frac{p_j - p_i + t}{2t} - \frac{p_i - s(a - y_i)}{2t} = 0, \quad \Rightarrow \quad 2p_i - p_j = t + (\bar{\alpha} - y_i)\sigma, \\
\frac{\partial \pi_i}{\partial x_i} &= \sigma(p_j - p_i + t) - \beta y_i 2t = 0.
\end{aligned}$$

The equilibrium prices and abatement levels are thus equal and given by $p^*(\sigma) = t + \bar{\alpha}\sigma - \frac{\sigma^2}{2\beta}$ and $y^*(\sigma) = \frac{\sigma}{2\beta}$. At equilibrium, each firm's output is $q^* = \frac{1}{2}$.

The market clearing condition on the market for emission permits is given by $E = 2(\bar{\alpha} - y^*)q^*$, and the equilibrium permits price is thus $\sigma^* = 2\beta(\bar{\alpha} - E)$. Firm i earns a profit $\pi^*(I, I) = \frac{t - \beta(\bar{\alpha} - E)^2}{2}$.

Consider now the case where firm 1 chose end-of-pipe abatement and firm 2 chose process integrated abatement. Then firms' problems are given by:

$$\begin{aligned}
&\max_{p_1, x_1} (p_1 - \bar{\alpha}\sigma) D_1(p_1, p_2) - \gamma \frac{x_1^2}{2} + \sigma x_1, \\
&\max_{p_2, y_2} (p_2 - (\bar{\alpha} - y_2)\sigma) D_2(p_1, p_2) - \beta \frac{y_2^2}{2}.
\end{aligned}$$

First order conditions give the following equilibrium values:

$$\begin{aligned}
p_1^* &= t + \bar{\alpha}\sigma - \frac{\sigma^2 t}{6\beta t - \sigma^2}, \quad \text{and} \quad x_1^* = \frac{\sigma}{\gamma}, \\
p_2^* &= t + \bar{\alpha}\sigma - \frac{2\sigma^2 t}{6\beta t - \sigma^2}, \quad \text{and} \quad y_2^* = \frac{3\sigma t}{6\beta t - \sigma^2}.
\end{aligned}$$

Corresponding outputs are $q_1^* = \frac{3\beta t - \sigma^2}{6\beta t - \sigma^2}$ and $q_2^* = \frac{3\beta t}{6\beta t - \sigma^2}$.

The market clearing condition on the market for emission permits is $E = (\bar{\alpha} q_1^* - x_1^*) + (\bar{\alpha} - y_2^*) q_2^*$. We denote by $\sigma^*(EP, I)$ the equilibrium permits price, which is the first root of the following polynom:

$$P(\sigma) = (\gamma(E - \bar{\alpha}) + \sigma) \left(6\beta t - \sigma^2\right)^2 + 9\beta\gamma t^2 \sigma.$$

[21] The second order conditions are satisfied if and only if $\beta > \frac{\sigma^2}{4t}$.

Equilibrium profits are thus:

$$\begin{aligned}\pi_1^*(EP,I) &= 2t\left(\frac{3\beta t-(\sigma^*(EP,I))^2}{6\beta t-(\sigma^*(EP,I))^2}\right)^2+\frac{(\sigma^*(EP,I))^2}{2\gamma},\\ \pi_2^*(EP,I) &= \frac{3\beta t^2}{6\beta t-(\sigma^*(EP,I))^2}\left(1-\frac{(\sigma^*(EP,I))^2}{2\left(6\beta t-(\sigma^*(EP,I))^2\right)}\right).\end{aligned}$$

Choice of the abatement technology. Comparing profits in the various cases, we find that $\pi_i^*(EP,EP)>\pi_i^*(I,EP)$ for all values of t, $\bar{\alpha}$, γ, β and $E<\bar{\alpha}$ (the level of pollution without an environmental regulation). As a consequence, if one firm chooses end-of-pipe abatement, then its rival's best reply is to choose end-of-pipe abatement too. For all values of the parameters, it is thus an equilibrium for both firms to choose end-of-pipe abatement.

Second, we find that $\pi_i^*(I,I)>\pi_i^*(EP,I)$ if and only if $\beta<\gamma\left(\sqrt{\frac{5}{6}}-\frac{3}{4}\right)\approx 0.163\gamma$, and t is higher than a threshold $\tilde{t}$ that is increasing in α and β and decreasing in E and γ (the detailed analysis is available from the authors upon request). When $t>\tilde{t}$, it is thus an equilibrium for both firms to choose process integrated abatement. However, we always have $\pi^*(I,I)<\pi^*(EP,EP)$: when the two symmetric equilibria are possible, end-of-pipe abatement brings both firms a higher profit than process integrated abatement. When $t<\tilde{t}$, the choice of end-of-pipe by both firms is the unique equilibrium.

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