# Pollution Permits in Oligopolies: The role of abatement technologies*

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Abstract. This paper examines, under imperfect competition, the effect of a cap-and-trade system on industry profits and the interaction between cap-and-trade system and the evolution of the market structure, both depending on the type of abatement technologies used by firms. Two extreme types are considered: end-of-pipe abatement technology – meaning, filtration and other mechanisms that are largely independent of production decisions – and process-integrated technology, which entails integrating cleaner or more energy-efficient methods into production. This paper prescribes that the distribution of free allocation should depend on the kind of abatement technologies. Finally, a reserve of pollution permits for new entrants is justified when the industry uses a process-integrated abatement technology, while a system with a preemption right may be justified in the case of end-of-pipe abatement technology.

Keywords. Cap-and-trade system, imperfect competition, end-of-pipe abatement, process-integrated abatement, reserve for entrants.

JEL codes. L13, Q53, Q58.

## 1. Introduction

In order to reduce carbon emissions and limit global warming, the European Union, Australia, New Zealand, Kazakhstan, China, Canada, Switzerland, some cities in Japan and some states in the United States have set up pollution permit markets, while Japan,

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Indonesia, Taiwan, Turkey, Vietnam and Chile are considering doing the same.[1] Firms subject to such a mechanism must hold permits to emit pollutants, and have two options to reduce emissions, reducing their production and using abatement technologies that are extremely broad in scope. The sectors covered by the pollution permits markets are in the large majority of cases oligoposlistic ones.[2] Firms subject to this type of regulation are strategic and exercise market power. The regulator faces various constraints such as the acceptability of environmental policies by firms, losses of competitiveness and the risk of relocation. These issues are related to how firms' decisions and profits are altered by the introduction of the pollution permits markets. This article examines to what extent the kind of abatement technologies used by firms affects the effect of the introduction of pollution permit markets and their implementation under imperfect competition.

In this paper, we focus on oligopolistic markets facing a cap-and-trade system. We show that the type of pollution abatement technology that is used in an industry has a strong impact on the way the cap-and-trade system affects the product market equilibrium, and hence the profits of firms in these markets. In some cases, these profits may increase with the price of permits. Second, entry to the market affects the price of permits differently depending on the type of abatement. This implies that the policy regarding entry (and in particular the implementation of a reserve of permits) should be contingent on the type of abatement technology.

Two extreme types are considered: end-of-pipe abatement technology and process-integrated technology. End-of-pipe abatement corresponds to capture and storage systems, pollution filters, and clean development mechanisms, all of which are largely independent of production decisions.[3] Process-integrated abatement involves a process investment that firms incur to reduce their marginal cost of producing the final good. Examples of this type of abatement include shifting to a cleaner technology or reducing the energy intensity of production. This distinction between these two kinds of technologies is in line with both the technical guidelines of the Society of German Engineers (VDI 2001) and the OECD Guidelines (1997), and has also been widely analyzed in the literature.[4] Nevertheless, many technologies differ from these two aforementioned abatement technologies and Montero (2005) considers that any emission reduction technology can be modeled as a combination of the two extreme emission reduction technologies presented above. Therefore, we analyze first the two extreme technologies and finally the combination of those latter.

We study the effect of a cap-and-trade system in which all permits are auctioned off on the product market equilibrium, depending on the abatement technology at hand in the industry. Specifically, we focus on Cournot competition. We assume that firms are price-takers in the market for permits even if they are price-makers in the markets

[1]See World Bank [2019] for more information.

[2]For instance, the European market covers cement, steel and iron.

[3]Pollution filters are used after both production and pollution have occurred. Clean development mechanisms are projects through which firms obtain pollution permits in exchange for the abatement done in foreign and developing countries and are thus, by definition, independent of the home firm's production decisions. Carbon capture and storage consists of capturing carbon once pollution has occurred and storing it, and are thus mainly independent of production decisions, although there are several kinds of carbon capture and storage, some of which may depend on production decisions.

[4]For instance, Frondel *et al.* (2007) study a variety of factors that might enhance firms' propensity to implement process integrated technologies instead of end-of-pipe technologies.

for products. For instance, the EU-ETS covers oligopolistic sectors but concerns more than three thousand firms.[5] Although some firms may appear important in the market for permits, the three biggest emitting firms - RWE, E.ON and Vattenfall - represent respectively only 7.1%, 4.7 % and 4.2% of the total amount of emissions. Even power companies are not big enough to manipulate the price of permits alone.[6]

With end-of-pipe abatement, the cap-and-trade system has two independent effects on profits, because the profit on the product market and the profit on the permit market can be separated. On the product market, the effect of the cap-and-trade system is simply to assign a monetary value to pollution and hence to increase the opportunity cost of production, which in turn increases final prices. Under monopoly or perfect competition, this would automatically reduce firms' profits. However, with imperfect competition in the product market, the production cost increase that follows an increase in the price of permits may have a counterintuitive effect, as initially emphasized by Seade (1985): when the slope of the demand function is sufficiently inelastic, it may indeed increase firms' profits (not taking abatement into account).

On the permit market, firms abate their pollution up to the point where the marginal cost of abatement equals the price of permits. Indeed, reducing pollution (that is, "producing" emission reduction) is an activity independent of production, the higher the price of permits, the more profitable this new activity. In parallel, the effect of a cap-and-trade system on the product market profit is exactly the same as if there were no abatement. Therefore, in the standard case, in which firms' product market profits decrease following an increase in the price of permits, a cap-and-trade system has two contradictory effects, and total profits may increase as a result of the system.

By contrast, in the case of process-integrated technology, abatement amounts to reducing the marginal cost of production, and is therefore not independent of production. The production cost always increases to a lesser degree following an increase in the price of permits than it does without abatement or with end-of-pipe abatement. There is, however, no additional positive effect of abatement on profits. As a consequence, in the standard case in which profits decrease following a cost increase, profits of firms using process-integrated abatement decrease with respect to the price of permits.

The effect of the implementation of pollution permits on profits may be positive with end-of-pipe while it cannot under reasonable assumptions with process-integrated abatement. Moreover, if the implementation of pollution permits is detrimental in the case of end-of-pipe abatement it is also detrimental in the process-integrated abatement case.

Turning back to the combination of technologies, the impact of a cap-and-trade system on profits depends on the trade-off between the contradictory effects stemming from the two technologies. The strength of the "end-of-pipe effect" described above essentially depends on the cost of end-of-pipe abatement. The "process-integrated effect" depends not only on the cost of process-integrated abatement, but also on demand elasticity and market structures.

[5] To be more specific, the EU-ETS applies to more than eleven thousand plants.

[6] It was however shown that when firms are not price-takers, they may have incentives to over-purchase permits. See Hintermann (2011) and Hintermann (2014).

Our model thus predicts that the impact of a cap-and-trade system on industry profitability is quantitatively and qualitatively different according to the type of abatement technology that characterizes the industry. These results are robust to price competition and international competition. As an implication for policy, the distribution of grandfathered free allowances (a common tool used for political and industrial purposes in the context of cap-and-trade) must depend on abatement technologies.[7] Moreover, the development of CCS in the forthcoming years may develop end-of-pipe abatement to some extent to alleviate the cost borne by firms and make the environmental regulation more acceptable from their standpoint.

A second contribution concerns the adjustment of the global pollution cap to entry. During the third phase of EU-ETS (2013-2020), 5% of all the European emission permits have been set aside for new entrants. The European directive mentions that both new installations and significant capacity extensions are considered as new entrants. The reserve for entrants is ordinarily justified to encourage competition in the market for products or to promote new technologies. The reserve for new entrants will be maintained for Phase 4 (2021-2030). The allowances set aside will come from allowances that were not allocated from the total amount available for free allocation by the end of phase 3 (2020), and 200 million allowances from the Market Stability Reserve. In January 2019, the latter was activated and consists of a permit reserve used to control the price of permits.[8] Here, we first consider the case in which the regulator implements a Pigovian price of permits, and we analyze how the pollution cap should be adjusted to the increase of the number of firms.

The two aforementioned abatement technologies have different effects on the equilibrium price of permits: the pollution cap, which allows the price to be set at the marginal damage, should be increased or decreased with the number of firms under end-of-pipe abatement, whereas it should always increase with the number of firms under process-integrated abatement. We thus provide a new justification for the existence of a reserve of permits for potential entrants,[9] especially with the process-integrated abatement. In contrast, in cases in which the regulator should reduce the pollution cap when firms enter the market, we propose a different system: if necessary, the regulator may buy permits from incumbents with a preemption right and sell or give a share of these to entrants. However, such a mechanism can also be incorporated into the Market Stability Reserve.

Our results are still valid for new installations. Indeed, we consider the case of a monopolistic firm holding several plants and show that the adjustment of the pollution cap to the increase of the number of plants is similar to its adjustment to the entry of new firms. In addition, our results still hold with optimal regulation.

The structure of the article is as follows: we start by relating the paper to the literature in Section 2. In Section 3, we describe our model. In Section 4, we determine the effect of the implementation of pollution permits on firms' profits, depending on their abatement technology. We also compare the two technologies to one another and analyze a mix of

[7] Free grandfathered allowances are a means of reducing profit losses, which is necessary for the success of a new cap-and-trade system.

[8] For more information, see Perino (2018).

[9] Note that the problem that we consider is orthogonal to the issue of giving free allowances to entrants: we merely focus on how to adjust the emission cap to entry.

both technologies. In Section 5, we determine the adjustment of the global pollution cap to entry. Section 6 concludes.

## 2. Literature

Our analysis borrows from Seade (1985), who first established that an increase in firms' marginal cost can increase their profits if the slope of the demand function is sufficiently elastic. Kimmel (1992) extends this analysis to an oligopoly, where firms face different costs of production but are subject to an identical negative shock. Février and Linnemer (2004) synthesize this literature by studying a general framework with heterogeneous costs and idiosyncratic shocks. Kotchen and Salant (2011) analyze the impact of a tax on industry profits in the context of a common-pool resource and highlight some analogies with Seade's (1985) analysis. Meunier and Nicolaï (2014) assess the effect of a cost increase on firms' profit, under both perfect and imperfect competitions, considering the production process as endogenous. Indeed, in reaction to shocks on cost, firms can decide to modify their strategies or to adapt their use of technologies.

We contribute to this literature by introducing two different abatement technologies and analyzing the effect of an environmental regulation on profits, which can be understood as a common shock on firms' production costs. In particular, we show that the use of process-integrated technology diminishes the effect (positive or negative) emphasized by Seade (1985). In the case of end-of-pipe abatement, the introduction of the market for permits has an additional positive effect.

The closest paper to our analysis is Hepburn et al. (2013). They study the effect of introducing a market for pollution permits on a product market with imperfect competition. They focus on the free allocation of permits and show that in oligopolistic industries, profit-neutral allowances are partial, as the level of permits allocated for free is lower than total emissions. In some cases, the total industry profits may even increase following the introduction of the market for permits. Hepburn et al. (2013) focus on the effect on profits considering cost asymmetries among firms whereas we assume identical firms but focus on the role of abatement technologies.[10] Moreover, Hepburn et al. (2013) do not disentangle abatement costs from production costs whereas our result stems from the assumption that different abatement technologies induce different relations between a firm's production and its abatement decisions.

Finally, the paper contributes to the literature that studies the introduction of a reserve for entrants. The few papers that analyze this issue focus essentially on how the distribution of the permits put aside in the reserve to the entrants affect the emissions (Ahman et al. (2005), Matthes et al., 2005; Engenhofer et al., 2006; Neuhoff et al., 2006, Ellerman (2008) and Dardati (2016)). Ellerman (2008) shows that granting to new entrants free allowances leads to excess capacity and to more output, although the effect on emissions is ambiguous. Dardati (2016) compares two commonly used pollution permits systems. In the first, closing plants keep their permits and new entrants do not get them, while in the second, closing plants lose their permits and new entrants get

[10]If firms have asymmetric costs, either of production or of abatement, our results are qualitatively the same, provided these asymmetries are reasonable (i.e., they do not lead to corner solutions). More efficient firms simply lose less profits as a result of the cap-and-trade system.

free allowances.[11] By calibrating the model with data from power plants participating in the US program, Dardati (2016) shows that, compared to the first system, in the second system, plants stay in the market longer and there are a greater number of highly polluting and less efficient plants. We depart from this literature in that we define the reserve for entrants as an increase of the pollution cap following entry, and do not analyze at all how these new permits should be distributed to entrants (auctioned or granted for free) but how the pollution cap should vary according to entry. We consider a regulator that implements either a Pigovian or an optimal price of permits, and show that in some cases, when firms use end-of-pipe abatement technologies, the global pollution cap should be reduced when firms enter the market. Thus, a reserve for either entrants or new installations should be forbidden in such a case. This issue is orthogonal to that of free allowances to entrants, and our analysis does not preclude the use of such free allowances to diffuse new technologies.

## 3. Model

Product Market Competition. We consider an oligopoly formed by $n$ symmetric firms producing a perfectly homogeneous product and competing in quantity à la Cournot. $P(Q)$ denotes the market price when a total quantity $Q \geq 0$ is produced, with $P'(\cdot) < 0$. Assume that $(n+1)P'(Q) + QP''(Q) < 0$ (a usual stability requirement) and $P''(Q) + QP'''(Q) \leq 0$ (so that a firm's marginal revenue is weakly concave in its production). Last, but not least, the elasticity of the demand slope, or demand curvature, is denoted by $\eta(Q) = \frac{P''(Q)Q}{P'(Q)}$.

Pollution and Abatement Technologies. When firm $i$ produces a quantity $q_i$, it emits an amount $\bar{\alpha} q_i$ of pollution. Parameter $\bar{\alpha} > 0$ is the polluting factor, which characterizes the polluting intensity of the production technology. We consider two different technologies to abate pollution: end-of-pipe and process-integrated technologies.

Suppose 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 $x_i = \bar{\alpha} q_i - e_i$, that firm has to bear a cost $\gamma x_i^2/2$, where $\gamma \geq 0$. This type of technology does not modify the production process and, therefore, does not modify the polluting factor $\bar{\alpha}$.

The process-integrated abatement technology alters the production process in a more environmentally-friendly way through a reduction of the polluting factor. If firm $i$ invests $y_i$ at a cost $\beta y_i^2/2$, where $\beta \geq 0$, then its polluting factor becomes $\alpha(y_i) = \bar{\alpha} - y_i$.[12]

To keep symmetry, we assume that all firms use the same abatement technology, which is either end-of-pipe abatement or process-integrated abatement.

[11] The first corresponds to the model used in the United States for SO2 regulation, while the second is the model used by the U-ETS

[12] 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 the marginal abatement curve associated with the abatement function to be defined. 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 rather, only depends on the difference between the initial and final polluting factors $y_i$. One can show that our results hold qualitatively with that specification.

MARKETS FOR POLLUTION PERMITS. A regulator implements a market for permits. A firm must own a permit for each unit of pollution emitted. Firms can buy, or sell, permits in that market, depending on their needs. We assume that competition in this market is perfect and denote the price of permits by $\sigma$. The pollution cap, that is, the total amount of pollution allowed, is denoted by $E$.

## 4. FIRMS' PROFITABILITY AND POLLUTION PERMITS

For each type of abatement technology we analyze how the market equilibrium is altered by the introduction of the market for permits. This analysis provides insights into the effect of the cap-and-trade system on the profits of firms.

END-OF-PIPE ABATEMENT. When firm $i$ uses the end-of-pipe abatement, its problem writes as follows:

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

We can decompose the profit into two parts, each of which depends only on one of the two decision variables: the product market profit given the baseline pollution, $(P(Q)-\bar{\alpha}\sigma)q_i$, and an additional gain due to abatement $\sigma x_i - \gamma x_i^2/2$. Hence, in this framework, firm $i$ operates as if it produces two independent goods: the final good in quantity $q_i$, sold on the product market at price $P(Q)$; emission permits in quantity $x_i$, sold on the market of permits at price $\sigma$. With an end-of-pipe technology, everything happens as if the decision to produce is decoupled from the decision to abate pollution. The first-order conditions associated to firm $i$'s problem highlight the independence of $q_i$ and $x_i$:[13]

$$\frac{\partial \pi_i}{\partial q_i} = P(Q) + q_i P'(Q) - \bar{\alpha}\sigma = 0, \tag{4.1}$$

$$\frac{\partial \pi_i}{\partial x_i} = \sigma - \gamma x_i = 0. \tag{4.2}$$

Condition (4.2) simply states that the optimal abatement level is such that the marginal cost of abatement $\gamma x_i$ is equal to the revenue from selling one additional permit $\sigma$. Condition (4.1) expresses the equality between the marginal revenue of production and its marginal cost, where the marginal cost relates to the cost of buying permits to cover emissions if the firm were not abating at all.

The symmetric equilibrium individual output $q^*_{EP}$ and abatement $x^* = \frac{\sigma}{\gamma}$ are then easily obtained. Total output is equal to $Q^*_{EP} = nq^*_{EP}$. The symmetric equilibrium profit of firm $i$ for a given $\sigma$ is then:

$$\pi^*_{EP}(\sigma) = \left(P(Q^*_{EP}) - \sigma\bar{\alpha}\right) q^*_{EP} + \frac{\sigma^2}{2\gamma}.$$

The expression $(P(Q^*_{EP}) - \sigma\bar{\alpha})q^*_{EP}$ represents the firm's profit if the firm cannot abate. The difference between the firm's profits with end-of-pipe abatement and without abatement is given by $\sigma^2/(2\gamma)$.

[13]Sufficient conditions are always satisfied and hence omitted in the following analysis.

In Appendix C.1, we show that the variation of $\pi^*_{EP}$ with respect to $\sigma$ may be written as follows:

$$\frac{d\pi^*_{EP}}{d\sigma} = q^*_{EP}\left[\frac{\partial Q^*_{EP}}{\partial\sigma}\frac{n-1}{n}P'(Q^*_{EP}) - \bar{\alpha}\right] = -\frac{\eta+2}{(n+1)+\eta}\bar{\alpha}q^*_{EP} + \frac{\sigma}{\gamma}. \tag{4.3}$$

The first part of the right-hand side expression represents the impact on profits of the variation of the price of permits when firms cannot abate; its sign is ambiguous and depends, as first shown by Seade (1985), on the elasticity of the curvature of demand $\eta$. The second part is the effect on the value of abatement of a variation of the price of permits; it is obviously positive. From equation (4.3), we deduce the following proposition.

Proposition 1. *Assume firms use end-of-pipe abatement. Then:*

- *if $\eta > -2$, the profit of a firm may decrease or increase with $\sigma$;*
- *if $\eta < -2$, the profit of a firm increases with $\sigma$.*

*Proof.* See Appendix C.1. □

Increasing $\sigma$ has two independent effects on a firm's equilibrium profit. The first corresponds to the effect of $\sigma$ on the product market profit. An increase in $\sigma$ increases the final price and reduces individual and total output. When $\eta < -2$, at the level of an individual firm, the price increases more than compensates for the contraction of output, leading to a higher profit.[14] Not surprisingly, this is precisely the condition found by Seade (1985) for an increase of the marginal cost of all firms to increase individual profits. In our setting, the implementation of a permit market helps firms to coordinate in order to increase their prices and, possibly, their profits. Remark that this profit-increasing effect is not related to the availability of abatement.

The second effect is the impact of the price of permits $\sigma$ on the gain due to abatement. The higher the price of permits, the more firms abate, and thus, the higher the gain due to abatement.[15] The intuition is simple. Abatement is independent of production. Firms then abate if and only if it is profitable to do so. In other words, abatement may be considered as a second profitable activity of the firm.

The effect of the price of permits on the total profit depends on the trade-off between these two effects. In the case in which $\eta > -2$, the product market profit is decreasing with $\sigma$, whereas the abatement profit is increasing with $\sigma$. Depending on the form of the demand function, the total effect of $\sigma$ on profits may still be positive. In the case of a linear demand, for example, there exists a threshold value of $\sigma$ such that the equilibrium profit is decreasing with $\sigma$ below this threshold and increasing with $\sigma$ otherwise.

Process-Integrated Technology. Assuming that all firms use a process-integrated technology, the problem of firm $i$ writes now as follows:

$$\max_{q_i, y_i} \pi_i = \left(P(Q) - \sigma(\bar{\alpha} - y_i)\right) q_i - \beta\frac{y_i^2}{2}.$$

[14] The condition $\eta < -2$ is not satisfied with a linear demand. In contrast, with an isoelastic demand, it is satisfied when the elasticity of demand is low enough. Vives (2000) provides a full analysis of this effect.

[15] It should be noted that this result holds with a more general end-of-pipe abatement function such that the cost $A(\cdot)$ of abating satisfies the following properties: $A' > 0$, $A'' > 0$, $A(0) = 0$ and $\lim_{x\to+\infty} A(x) = +\infty$.

In this case, we cannot simply disentangle the product market profit from the gain due to abatement, as the abatement and output decisions are interdependent. Indeed, increasing abatement reduces the marginal cost of production perceived by firm $i$, $\sigma(\bar{\alpha} - y_i)$, and, therefore, affects the output of that firm.

The necessary first-order conditions yield:

$$\frac{\partial \pi_i}{\partial q_i} = P + q_i P' - (\bar{\alpha} - y_i)\sigma = 0, \tag{4.4}$$

$$\frac{\partial \pi_i}{\partial y_i} = \sigma q_i - \beta y_i = 0. \tag{4.5}$$

We denote the symmetric equilibrium individual output and abatement level by $q_I^*$ and $y^*$, respectively, and denote the total output by $Q_I^* = nq_I^*$. Let us first focus on the effect of $\sigma$ on $y^*$. From equation (4.5), we get:

$$\frac{dy^*}{d\sigma} = \frac{1}{\beta}\left(q_I^* + \sigma\frac{\partial q_I^*}{\partial \sigma}\right). \tag{4.6}$$

We can deduce that the equilibrium level of abatement increases with $\sigma$ as long as the equilibrium individual output does not decrease too much with $\sigma$. By replacing $y^*$ with $\frac{\sigma}{\beta}q_I^*$, the symmetric equilibrium profit of a firm for a given $\sigma$ is given by :

$$\pi_I^*(\sigma) = \left(P(Q_I^*) - \sigma\left(\bar{\alpha} - \frac{\sigma q_I^*}{\beta}\right)\right) q_I^* - \frac{\sigma^2 (q_I^*)^2}{2\beta}.$$

In Appendix C.2, we show that the variation of $\pi_I^*$ with respect to $\sigma$ may be rewritten as follows:

$$\frac{d\pi_I^*}{d\sigma}(\sigma) = -\frac{\eta+2}{n+1+\eta}\left((\bar{\alpha} - y^*) - \sigma\frac{\partial y^*}{\partial \sigma}\right) q_I^* - \beta y^* \frac{\partial y^*}{\partial \sigma}, \tag{4.7}$$

$$= -\frac{\eta+2}{n+1+\eta}(\bar{\alpha} - y^*)\, q_I^* + \left(\frac{\eta+2}{n+1+\eta} q_I^* \sigma \frac{\partial y^*}{\partial \sigma} - \beta y^* \frac{\partial y^*}{\partial \sigma}\right), \tag{4.8}$$

$$= -(\bar{\alpha} - y^*)\frac{\eta+2}{n+1+\eta} q_I^* + \frac{1-n}{n+1+\eta}\frac{\partial y^*}{\partial \sigma}\sigma q_I^*. \tag{4.9}$$

From equation (4.9), the following proposition is deduced.

PROPOSITION 2. *Assume firms use process-integrated abatement. Then:*

- *if $\eta > -2$, the profit of a firm decreases with $\sigma$;*
- *if $\eta < -2$, the profit of a firm may decrease or increase with $\sigma$. In particular, it decreases with $\sigma$ if the equilibrium output decreases with $\sigma$.*

*Proof.* See Appendix C.2. □

The first term of equation (4.9) represents the effect of an increase in the price of permits on the profits made on the product market while the second term represents the effect of an increase in the price of permits on the net gain of abatement.

When firms use process-integrated abatement, the resulting polluting factor $\bar{\alpha} - y^*$ is lower than the polluting factor without abatement $\bar{\alpha}$. For this reason, the first term of equation (4.9) results in a less negative (resp. positive) effect of $\sigma$ in the case in which, without abatement, the effect of $\sigma$ on the product market profit is negative (resp. positive).

If the abatement increases with the price of permits, the increase in the abatement will lead to a decrease in the price of products and potentially a decrease in revenues from the sales of the good. It is questionable why firms would invest more in an activity that would reduce their profit. This is mainly a problem of coordination, the higher the price of permits, the more firms have an incentive to cut in order to gain market share. However, the firms are identical and in equilibrium the firms always have the same market share.

Comparison of Technologies. Before considering a mix of the two abatement technologies, let us first compare them to one another. From the analysis above, it is clear that the environmental regulation has three different and possibly contradictory effects on profits.

First, the environmental regulation induces a change in output. Output decreases regardless of the type of technology, but more so with end-of-pipe than with process integrated abatement. Indeed, the marginal cost increase that follows the introduction of a permit market is the larger with end-of-pipe abatement. Second, because of this output change, the value of the elasticity of the slope of demand is also affected. Finally, increasing the permit price affects also the net gain of abatement. In the end-of-pipe case, the net gain is always positive, and increases with respect to $\sigma$. In the process integrated case, the net gain of abatement may be negative.

Let $\eta_I$ and $\eta_{EP}$ be respectively the elasticity of the slope of demand associated with the case with process-integrated technology and the case with end-of-pipe abatement. Assuming isoelastic demand allows to get $\eta_I = \eta_{EP}$ and to ease the comparison between the two technologies. Under an isoelastic demand function, profits may still increase with constant marginal cost. It corresponds to a weak elasticity of demand and then a pass-through higher than 100%.

The following corollary compares the two technologies.

Corollary 1. *Assume that the demand is iso-elastic. The effect of pollution permits on firms' profitability is quantitatively and qualitatively different according to the type of abatement technology.*

*(i) If the equilibrium output decreases with the price of permits, profits in the process-integrated abatement case always decrease, whereas they may increase under end-of-pipe abatement.*

*(ii) Under isoelastic demand, if profits decrease in the end-of-pipe abatement case, profits also decrease in the process-integrated abatement case.*

*Proof.* $\frac{\partial \pi_I^*}{\partial \sigma} = -(\bar{\alpha} - y^*)\frac{\eta+2}{n+1+\eta} q_I^* + \frac{1-n}{n+1+\eta}\frac{\partial y^*}{\partial \sigma}\sigma q_I^*$ and $\frac{\partial \pi_{EP}^*}{\partial \sigma} = -\frac{\eta+2}{(n+1)+\eta}\bar{\alpha} q_{EP}^* + \frac{\sigma}{\gamma}$. If $\frac{\partial \pi_{EP}^*}{\partial \sigma} < 0$, then $-(\bar{\alpha} - y^*)\frac{\eta+2}{n+1+\eta} q_I^* < 0$. We deduce $\frac{\partial \pi_I^*}{\partial \sigma} < 0$. □

When production decreases, profits may be positive with end-of-pipe while they cannot with process-integrated abatement. Moreover, if the implementation of pollution permits is detrimental in the case of end-of-pipe abatement it is also detrimental in the process-integrated abatement case.

MIX OF TECHNOLOGIES. Most industries use abatement technologies that neither completely belong to the end-of-pipe abatement nor the process-integrated type. Indeed, they use some technologies that are a mix of both technologies.

We now consider that both abatement technologies are available. We can write firm $i$'s final profit as follows:

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

This modeling is close to the framework of Montero (2005), which combines end-of-pipe technology and process-integrated abatement.[16] Let denote by EPI the equilibrium in the case of a mix of the two technologies. We find that at equilibrium, $x^*_{EPI} = x^*_{EP}$ and $y^*_{EPI} = y^*_I$. The equilibrium product price is equal to $p^*_{PI}$. As a consequence, firm $i$'s equilibrium profit may be written as follows:

$$\pi^*_{EPI}(\sigma) = \left(P(Q^*_{EPI}) - \sigma\left(\bar{\alpha} - \frac{\sigma q^*_{EPI}}{\beta}\right)\right)q^*_{EPI} - \frac{\sigma^2(q^*_{EPI})^2}{2\beta} + \frac{\sigma^2}{2\gamma}.$$

The variation of $\pi^*_{EPI}$ with respect to $\sigma$ is then equal to:

$$\frac{d\pi^*_{EPI}}{d\sigma} = -(\bar{\alpha} - y^*)\frac{\eta+2}{n+1+\eta}q^*_{EPI} + \frac{1-n}{n+1+\eta}\frac{\partial y^*}{\partial\sigma}\sigma q^*_{EPI} + \frac{\sigma}{\gamma}. \tag{4.10}$$

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 product market effect, the profit-increasing effect of end-of-pipe abatement, measured by $\frac{\sigma}{\gamma}$, and the profit-decreasing effect of process-integrated abatement, measured by $\frac{1-n}{n+1+\eta}\frac{\partial y^*}{\partial\sigma}\sigma q^*_I$. The effect of the regulation on profits depends on which effect is the strongest. The following corollary is deduced from equation (4.10) and determines the cases under which profits may increase with the price of permits.

COROLLARY 2. *Firms' profit may increase with the implementation of pollution permits if:*

*(i) the cost parameter of end-of-pipe is sufficiently low,*

*(ii) the cost parameter of process-integrated abatement is sufficiently high,*

*(iii) the number of firms is sufficiently low,*

*(iv) the elasticity of the slope of the demand function is sufficiently high.*

The profit-increasing effect of end-of-pipe abatement and the profit-decreasing effect of process-integrated abatement are both at stake in this result. Their relative magnitude

[16] The single difference is that the cost associated to end-of-pipe by Montero (2005) is linear while it is quadratic in our model.

is explained by the two cost parameters as well as the market structure and the elasticity of the slope of the demand function. An interesting result is that as the number of firms increases, each invests more for strategic reasons and all firms lose more at equilibrium.

Extensions and Discussion. Our first result is that profits may increase with the price of permits even without free allowances of permits. This result is not new in the literature and well known from Seade (1985) but we show how abatement technology affects it. Moreover, in Appendixes A and B, we extend our result to, respectively, price competition and a framework with international trade. Following Anderson et al. (2001), it is possible to build a counterpart of $\eta$ in the case of price competition, which is a normalized elasticity of the slope of the demand of a given firm in the symmetric equilibrium. The same effects are at play, regardless of the competition format. In particular, in the most standard case, when the normalized elasticity of the slope of the demand is sufficiently low, the profit always decreases with respect to the price of permits under process-integrated abatement, whereas it may increase with respect to the price of permits under end-of-pipe abatement.

In Appendix B, we analyze the case in which $n$ domestic firms, subject to the cap-and-trade system, are also competing with a competitive fringe of foreign firms. The latter firms are not subject to the cap-and-trade system, i.e. they do not have to purchase permits in order to emit pollution. We assume that these competitive foreign firms do not have access to abatement and have a production cost function, which is strictly increasing and strictly convex. First, international competition unsurprisingly diminishes the potential positive effect of the cap-and-trade system on domestic firms' profits when firms use end-of-pipe abatement. Second, with process-integrated abatement, the product market profit is less likely to increase with the price of permits in the presence of unregulated foreign competition. The effect of this new competition on the net gain of abatement (the second term of the equation) is ambiguous. In particular, if the inverse demand function is convex, then the net effect of abatement on profits is greater (whether positive or negative) in the presence of international competition than without it.

We can now examine the distribution of free allowances and whether the allowances should be distributed according to the type of technology used. It should be noted that the objectives retained by the European Commission for the allocation of permits have evolved over time: to make the regulation acceptable initially, to reduce losses of competitiveness after and finally to limit the relocation risk.

According to Bovenberg et al. (2005) and Goulder et al. (2010), the success of an environmental regulation depends on the attitude of the industry toward this regulation, which justifies the use of free allowances. Said differently, firms may lobby to block the adoption of environmental regulations, which then might push regulators to set compensations in their favor. Grand-fathered free allocations are a lump-sum transfer from the regulator to firms. This partly explains why during the first two phases (2005-2012) of the European Emission Trading Scheme (EU ETS), all pollution permits were granted for free to firms. In order to avoid to give too many compensations, it is crucial to determine the right level of free allowances to grant. The appropriate criterion retained in the literature is the profit-neutral permit allocations. Profit-neutral permit allocations are defined as the number of permits that the regulator should give for free so that profits after regulation (i.e., profits that the firm realizes in the market for products plus the value of the allowances granted for free) are equal to profits before regulation. Using the previous results, we deduce that the profit-neutral permit allocations clearly depend on the kind of abatement technologies. All other things being equal, the regulator should give more free allocations to sectors using process-integrated technologies than to those using end-of-pipe abatement according to this criterion.

For the third phase (2013-2020), the main objective was to reduce competitiveness losses and carbon leakage, and give allocations to sectors exposed to international competition. The introduction of a cap-and-trade system generates losses of competitiveness and a substitution of emissions produced in the regulated area by emissions in regions without an environmental policy. The rules agreed upon for the 2013-2020 period show a clear change of direction regarding the allocation of permits. In particular, producers of electric power, which, in previous phases, received 100% of their permits for free, now have to buy 100% of their permits through auctions.[17] Moreover, the method used to determine free allocations is similar to allocations proportional to production.[18] They therefore depend on the firm's current decisions. The more the firm produces, the more allowances it receives, which reduces the marginal cost of production. Allocations proportional to production thus reduce the losses in competitiveness generated by environmental regulation. In such a case, all other things being equal, sectors using end-of-pipe abatement should receive more allocations than sectors using process-integrated technologies because with the latter the marginal cost of production is lower.

For the fourth phase, "the sectors at the highest risk of relocating their production outside of the EU will receive 100% of their allocation for free, while for less exposed sectors, free allocation is foreseen to be phased out after 2026 from a maximum of 30% to 0 at the end of phase 4 (2030)".[19] Relocation decisions depend on many factors, including exposure to international competition, the quality of infrastructure, wage and input supply conditions, as well as the regulations in place in the host country and regulations in the domestic country. Put differently, relocation decisions depend on how profit is affected by the cap-and-trade system but also on o a large number of other factors. As we have seen in Appendix B, in the presence of international competition the effects on profit of the implementation of a cap-and-trade system depend both on the type of abatement technology and on demand. The European Commission must take into account the interplay between abatement technology and demand in order to determine the sectors at risk.

## 5. Adjustment of the global pollution cap to entry

We have shown that the effect of environmental regulation on firms, which are already in the market for products, depends on the type of abatement technology they use. In this section, we focus on the policy of the regulator towards entry, and show that the environmental policy must adapt to entry. As for incumbents, policy regarding entry should be adjusted depending on the type of abatement technology used in the industry. The purpose of this section is to analyze how the emission cap should adjust to an exogenous change in the number of firms.

[17]Full auctioning applies to electricity firms only in the EU-15, but not in the "new" EU countries.

[18]For a description of the current rules, see Branger et al. (2015).

[19]For more information, see the official website of the EU: "Revision for phase 4 (2021-2030)" https://ec.europa.eu/clima/policies/ets/revision$_e n$.

Let us consider that the regulator implements a Pigovian price of permits (equal to the marginal damage of pollution). The use of a Pigovian price of permits simplifies the analysis tremendously but we will, however, discuss the case of an optimal price of permits, which maximizes the welfare, at the end of this Section. If the number of firms increases, the demand for permits will be affected and the regulator will have to adjust the pollution cap so that the price of the permit equals the marginal damage. If the demand for permits increases, the regulator must then increase the emission cap.

As in the previous section, for clarity, we consider the two technologies separately.

Consider first that firms use end-of-pipe abatement. The equilibrium in the market for permits is given by:

$$E^*_{EP}(n) = \bar{\alpha} Q^*_{EP}(n, \sigma = \lambda) - n x^*(\sigma = \lambda), \tag{5.1}$$

where $E^*_{EP}(n)$ is the level fixed by the regulator such that $\sigma = \lambda$.

Given that $\sigma$ is equal to the marginal damage, the effect of the increase of the number of firms on the emission cap that will be set by the regulator is simply given by:

$$\frac{\partial E^*_{EP}}{\partial n} = \underbrace{\bar{\alpha}\frac{\partial Q^*_{EP}}{\partial n}}_{(+)} - \underbrace{x^*}_{(+)}. \tag{5.2}$$

We show in Appendix D that the total output $Q^*_{EP}$ increases with the number of firms (the larger the number of firms, the greater the total output). The increase of the number of firms has two contradictory effects on the demand for permits. The first results from an increase in the level of output (we show in Appendix D that the total output $Q^*_{EP}$ increases with the number of firms) and hence of pollution, everything else being equal. The second, in contrast, is due to the increase in total abatement. Indeed, when firms use end-of-pipe abatement, they always individually abate the same amount of pollution regardless of the number of firms in the market when the price of permits is exogenous; then, the total abatement increases with $n$. The effect of the increase of the number of firms on the aggregate demand for permits is ambiguous.

Consider now that firms use process-integrated abatement. The equilibrium in the market for permits is given by:

$$E^*_I(n) = (\bar{\alpha} - y^*(n, \sigma = \lambda)) Q^*_I(n, \sigma = \lambda), \tag{5.3}$$

where $E^*_I(n)$ is the level fixed by the regulator such that $\sigma = \lambda$.

The effect of the number of firms on the cap set by the regulator is thus:

$$\frac{\partial E^*_I}{\partial n} = (\bar{\alpha} - y^*)\frac{\partial Q^*_I}{\partial n} - \frac{\partial y^*}{\partial n} Q^*_I. \tag{5.4}$$

We show in Appendix D that under reasonable conditions, $\frac{\partial Q^*_I}{\partial n} > 0$ and $\frac{\partial y^*}{\partial n} < 0$. From this, it is immediately clear that the cap set by the regulator is increasing with $n$ under process-integrated abatement. An increase in the number of firms increases total output and thus pollution, everything else being equal. Moreover, as the number of firms increases, a firm's marginal gain to abate pollution decreases: reducing its marginal cost of production by a given amount $dy$ increases a firm's market share all the more that the market is more concentrated. Firms thus have an incentive to set a lower abatement level $y^*$ as $n$ increases. To conclude, the aggregate demand for permits increases with the number of firms.

The following proposition summarizes our results considering that the price of permits is equal to the marginal damage.

Proposition 3. *A regulator's optimal policy toward entry should be contingent on the abatement technology that is available in the industry. As the number of firms in the market increases, the regulator that implements a Pigovian price of permits should:*

- *reduce or increase the pollution cap available in the industry with end-of-pipe abatement;*
- *increase the pollution cap available in the industry with process-integrated technology.*

Thus, when the regulator implements a price of permits equal to the Pigovian tax, the pollution cap may increase or decrease with the number of firms with end-of-pipe abatement and should always increase with process-integrated abatement. In the case in which the regulator should increase the number of permits that are available when the number of firms increases, it may foresee a reserve of permits that are available to potential entrants, hence increasing the official cap of emissions in the event of firms' entry. We thus provide a new justification for the existence of a reserve of permits. In contrast, in the case in which the regulator should reduce the pollution cap when firms enter the market, we propose a different system: if necessary, the regulator may buy permits from incumbents with a preemption right and sell or give a share of these to entrants. Therefore, although the total number of permits that are available to firms then decreases, the entrants have access to the market.

Discussion and Extensions. To assess the robustness of our results, we first analyze adjustment of the pollution cap to new capacities, and, second, focus on the optimal degree of regulation.

The European directive, which sets aside emission permits for new entrants, mentions that are considered as new entrants either new installations or significant capacity extensions. Our results are still valid for new installations. In Appendix (E) we focus on the case of a monopolistic firm holding several installations and analyze the adjustment of the pollution cap to the increase of the number of installations under end-of-pipe abatement technology. We show that the results hold with the increase of the number of installations if each installation can abate.

Until now, we have assumed for simplicity that the price of permits is equal to the Pigovian tax. However, since we consider a market for products with imperfect competition, we extend our results to the case of optimal regulation. Indeed, we know from Barnett (1980) that in presence of market power, a regulator does not implement a Pigovian tax. We therefore assume here that the regulator maximizes a welfare function, taking into account the environmental damage of pollution. As before, we assume that the marginal damage of pollution is constant. We show in Appendix F that with both end-of-pipe abatement and process-integrated abatement, the optimal price of permits is lower than the marginal damage of pollution. This result is frequently found in the literature. It comes from the fact that the regulator has a single instrument at its disposal to correct two distortions: the environmental externality and the distortion on the demand side. We show that this result does not depend on the abatement technology.[20] Moreover, we know that under perfect competition, the optimal price of permits is equal to the marginal damage. Therefore, the optimal price of permits increases with the number of firms.[21] Therefore, to come back to the adjustment of the pollution cap according to the number of firms, we note that in the presence of optimal regulation, there is an additional effect to take into account that always goes in the direction of a reduction in the pollution cap. Put differently, the pollution cap is less likely to increase with the number of firms when the regulator implements optimal regulation instead of a Pigovian price.

It is important to note that the rules on reserves will evolve for the fourth phase of the EU-ETS.[22] First, a market stability reserve started being operational in January 2019. The reserve deals with the current surplus of allocations and makes the system more responsive to major shocks by adjusting the supply of allowances to be auctioned so that the price of permits is neither too low nor too high. The market stability reserve (MSR) functions entirely in accordance with pre-defined rules that do not allow the Commission or the Member States any latitude in its application. Second, a significant number of free allowances will be put in reserve for new and growing installations. This consists of allowances that have not been distributed out of the total amount that will be available for free allocation at the end of phase 3 (2020) and 200 million permits from the MSR. Our results allow us to discuss these policy decisions. For sectors with end-of-pipe abatement technologies, where the pollution cap is expected to decrease with the number of companies, reserves for new entrants should be banned. In such cases, only the Market stability reserve should be allowed. The rules governing the MSR must then take into account the number of entrants. For other cases, the coexistence of both reserves is permitted.

## 6. Conclusion

This paper has two main findings. First, we show that the effect of an environmental regulation on profits depends on the type of abatement technology available to firms. More precisely we consider two types of abatement: end-of-pipe abatement, mechanisms that are largely independent of production decisions, and process integrated technologies, which include more energy-efficient methods into production. In the standard case, in which profits decrease with the price of permits when firms are unable to abate pollution, we find that profits may increase when firms use end-of-pipe abatement, whereas they

[20] However, if firms are asymmetric, the regulator may implement an optimal tax that is higher than the marginal damage in order to reallocate production, as shown by Simpson (1995) for a Cournot duopoly with two asymmetric firms.

[21] Under reasonable conditions, the price of permits is monotonic with respect to the number of firms.

[22] For more information, see the official website of the EU: "Revision for phase 4 (2021-2030)" https://ec.europa.eu/clima/policies/ets/revision$_e n$.

always decrease with the price of permits when firms use process-integrated technologies. If, in addition, profits increase with the price of permits while firms do not have access to abatement technologies, then profits also increase when firms use end-of-pipe abatement, and may even increase when firms use process-integrated technologies. Hence, under reasonable conditions on abatement technologies and on the demand function, implementing an environmental regulation may increase profit.

Second, we emphasize that the type of abatement technology of the new entrants should be taken into account by the regulator when adapting the pollution cap to entry. Importantly, we show that the adjustment may go both ways, in that the regulator should not only have access to a reserve of permits but also be able to reduce the pollution cap following the entry of a firm. This conclusion contradicts the attitude of the European regulator toward entry in polluting industries until the end of 2018. Indeed, until then a preemption right to reduce the amount of available permits, if necessary, did not exist. However, the introduction of the MSR is a step in the right direction. Nevertheless, under certain conditions it should not be coupled with a reserve for new entrants.

Our analysis has been performed under the assumption that abatement technologies are available. A natural extension would be to consider the development of technologies and determine how the conditions in the market where these technologies are sold would affect the type of technologies that are developed by innovators. Such an extension is left for future research.

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# Appendix

## A. Price competition

Assume in this subsection that firms now compete in price. To this end, we follow the analysis of Anderson *et al.* (2001), who study the effect a (unit or ad valorem) tax on a differentiated product oligopoly and derive a result similar to that of Seade (1985) in a model of price competition. We assume again that there are $n$ firms in the market. Demand functions are symmetrically differentiated. $D(p_i, p_{-i})$ denotes the demand for product $i$ given the price of product $i$ $p_i$ and the prices of all other goods $p_{-i}$. $D$ is such that $\frac{\partial D}{\partial p_i} < 0$ and $\frac{\partial D}{\partial p_{-i}} > 0$. Abatement costs are as presented in Section 3.

Following Anderson *et al.* (2001), we use the following notations:

$$\varepsilon_{dd} = \frac{\partial D}{\partial p_i}\frac{p^*}{D}, \quad \varepsilon_{DD} = \frac{\partial D}{\partial p}\frac{p^*}{D}, \quad \varepsilon_m = \frac{\partial}{\partial p}\left(\frac{\partial D}{\partial p_i}\right)\frac{p^*}{\frac{\partial D}{\partial p_i}}, \quad \tilde{E} = \frac{\varepsilon_m}{\varepsilon_{DD}}.$$

$\varepsilon_{dd}$ denotes the elasticity of the demand of firm $i$ in equilibrium, when only the price of firm $i$ changes. $\varepsilon_{DD}$ denotes the elasticity of the demand of firm $i$ in equilibrium, when all prices change: in particular, we have $\frac{\partial D}{\partial p} = \frac{\partial D}{\partial p_i} + \frac{\partial D}{\partial p_{-i}}$. $\varepsilon_m$ represents the elasticity of the slope of the demand of firm $i$ in the symmetric equilibrium. Finally, $\tilde{E}$ represents a normalized elasticity of the slope of the demand of firm $i$ in the symmetric equilibrium and can be interpreted as the counterpart of $\eta$ under price competition.

In our context, $\bar{\alpha}\sigma$ plays the role of a unit tax. The main difference between our analysis and that of Anderson *et al.* (2001) is, again, the capacity of firms to abate pollution. We find, as with quantity competition, that adding the technology only adds a positive effect with end-of-pipe abatement, whereas the effect of the technology is ambiguous with process-integrated abatement.

Assume first that firms use end-of-pipe abatement. The problem of firm $i$ is then:

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

As with quantity competition, the product market profit given the baseline pollution and the gain due to abatement are separable. The first-order conditions are:

$$\frac{\partial \pi_i}{\partial p_i} = (p_i - \sigma\bar{\alpha})\frac{\partial D}{\partial p_i} + D = 0, \quad \frac{\partial \pi_i}{\partial x_i} = -\gamma x_i + \sigma = 0.$$

We thus still have $x^*(\sigma) = \frac{\sigma}{\gamma}$. As firms are symmetrically differentiated, the equilibrium price is identical for all firms and denoted by $p^*_{EP}(\sigma)$. We denote the corresponding individual profit by:

$$\pi^*_{EP}(\sigma) = (p^*_{EP} - \bar{\alpha}\sigma)D(p^*_{EP}, p^*_{EP}) + \frac{\sigma^2}{2\gamma}.$$

Therefore, as with quantity competition, the gain due to abatement increases with the price of permits and does not depend on the firm's production. The effect of $\sigma$ on the product market profit depends on the value of $\tilde{E}$.

The variation of the equilibrium price $p^*_{EP}$ with respect to $\sigma$ is given by:

$$\frac{\partial p^*_{EP}}{\partial \sigma} = \frac{\bar{\alpha}\varepsilon_{dd}}{\varepsilon_{dd} + \varepsilon_{DD} - \varepsilon_m},$$

which corresponds to the conditions in Anderson *et al.* (2001) and implies that the price increases with $\sigma$ for all values of the parameters. From this, we can deduce, as they do, that the variation of $(p^* - \bar{\alpha}\sigma)$ carries the same sign as that of $\tilde{E} - 1$ and that the variation of the product market profit carries the same sign as that of $\tilde{E} - 2$. More precisely, the effect of $\sigma$ on the total profit is given by:

$$\frac{\partial \pi^*_{EP}}{\partial \sigma} = \frac{\bar{\alpha}\varepsilon_{DD}}{\varepsilon_{dd} + \varepsilon_{DD} - \varepsilon_m} D(p^*_{EP}, p^*_{EP}) \left(\tilde{E} - 2\right) + \frac{\sigma}{\gamma}.$$

If $\tilde{E} > 2$, then both the product market profit and the gain due to abatement increase with $\sigma$. If $\tilde{E} < 2$, then the product market profit decreases with $\sigma$, whereas the gain due to abatement still increases with $\sigma$. As with quantity competition, there exists a threshold value of $\sigma$ such that the total profit of a firm increases with $\sigma$ (and thus with the strictness of the cap-and-trade system) above this threshold.

Consider now that firms use process-integrated abatement. As with quantity competition, this case is more complicated, because a change in the abatement decision $y_i$ resulting from a change in $\sigma$ will also affect the final price $p_i$ set by firm $i$. The problem of firm $i$ is:

$$\max_{p_i, y_i} \pi_i = (p_i - (\bar{\alpha} - y_i)\sigma) D(p_i, p_{-i}) - \beta \frac{y_i^2}{2}.$$

The first-order conditions are:

$$\frac{\partial \pi_i}{\partial p_i} = (p_i - \sigma(\bar{\alpha} - y_i)) \frac{\partial D}{\partial p_i} + D = 0, \quad \frac{\partial \pi_i}{\partial y_i} = \sigma D(p_i, p_{-i}) - \beta y_i = 0.$$

We denote the individual equilibrium profit by:

$$\pi^*_I(\sigma) = (p^*_I - (\bar{\alpha} - y^*)\sigma) D(p^*_I, p^*_I) - \beta \frac{(y^*)^2}{2}.$$

The variation of the equilibrium price $p^*_I$ with respect to $\sigma$ is given by:

$$\frac{\partial p^*_I}{\partial \sigma} = \frac{\bar{\alpha}\varepsilon_{dd}}{\varepsilon_{dd} + \varepsilon_{DD} - \varepsilon_m} \left( (\bar{\alpha} - y^*) - \sigma \frac{\partial y^*}{\partial \sigma} \right),$$

from which we can deduce that if the abatement level $y^*$ is decreasing with $\sigma$, then the final price $p^*_I$ is increasing with $\sigma$, and in contrast, if $p^*_I$ is decreasing with $\sigma$, then $y^*$ is increasing with $\sigma$.

Finally, we can make some comments based on the following expressions of $\frac{\partial \pi^*_I}{\partial \sigma}$:

$$\text{(A.1)} \qquad \frac{\partial \pi^*_I}{\partial \sigma} = (p^*_I - (\bar{\alpha} - y^*)\sigma) \frac{\partial p^*_I}{\partial \sigma} \frac{\partial D}{\partial p_{-i}} - (\bar{\alpha} - y^*) D,$$

$$\text{(A.2)} \qquad = \left( \frac{\varepsilon_{DD}}{\varepsilon_{dd} + \varepsilon_{DD} - \varepsilon_m} \left(\tilde{E} - 2\right) (\bar{\alpha} - y^*) + \sigma \frac{\partial y^*}{\partial \sigma} \right) D.$$

From equation (A.1), we find that if the price decreases with $\sigma$, then the equilibrium profit of a firm also decreases with $\sigma$ (regardless of the value of $\tilde{E}$). From equation (A.2), we obtain the comparative statics on profits if the final price is increasing with $\sigma$, knowing then that $\frac{\partial y^*}{\partial \sigma} < 0$:

- If $\tilde{E} < 2$, then the profit is decreasing with $\sigma$.
- If $\tilde{E} > 2$, there are two contradictory effects: given the level of pollution, the profit tends to increase through the Seade effect (or, in this case, the "Anderson *et al.*" effect). In contrast with end-of-pipe abatement, the reduction of abatement following an increase in the price of permits diminishes the Seade effect by reducing the price increase.

Therefore, we can see that the same effects are at play, regardless of the competition format. In particular, in the most standard case, when $\tilde{E} < 2$, the profit always decreases with $\sigma$ under process-integrated abatement, whereas it may increase with $\sigma$ under end-of-pipe abatement.

## B. International competition

Assume now that firms compete in quantity and that the $n$ domestic firms subject to the cap-and-trade system are also competing with a competitive fringe of foreign firms. The latter firms are not subject to the cap-and-trade system, however (i.e., they do not have to buy permits in order to emit pollution). We assume that this competitive fringe of foreign firms does not have access to abatement and has a production cost function $C : q_f \mapsto C(q_f)$. $C$ is twice differentiable, strictly increasing, and strictly convex.

Consider first that firms use end-of-pipe abatement. The problem of firm $i$ is:

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

with $Q = q_f + \sum_{i=1}^{n} q_i$ the total quantity supplied. The problem of the fringe of foreign firms is:

$$\max_{q_f} \pi_f = Pq_f - C(q_f),$$

with $P$ given, as the fringe of firms are assumed price takers.

The first-order conditions are:

$$\frac{\partial \pi_i}{\partial q_i} = P'(Q)q_i + (P(Q) - \bar{\alpha}\sigma) = 0, \quad \frac{\partial \pi_i}{\partial x_i} = \gamma x_i - \sigma = 0, \quad \frac{\partial \pi_f}{\partial q_f} = P - C'(q_f) = 0.$$

We still obtain $x^*(\sigma) = \frac{\sigma}{\gamma}$, and as the home (strategic) firms are identical, the equilibrium output is symmetric for all $i$ and is still denoted by $q^*_{EP}(\sigma)$. $Q^*_{EP}(\sigma)$ still denotes the total equilibrium output; that is, $Q^*_{EP}(\sigma) = nq^*_{EP}(\sigma) + q^*_f(\sigma)$.$Q^*_{-f}(\sigma) = nq^*_{EP}(\sigma)$ denotes the total output of home firms. Finally, the equilibrium profit of firm $i$ is $\pi^*_{EP}(\sigma) = \pi_i(q^*_{EP}(\sigma), q^*_f(\sigma), x^*(\sigma))$.

As before, we want to determine how the equilibrium profit of a home firm is affected by an increase in the price of permits $\sigma$. This variation is given by:

$$\frac{\partial \pi^*_{EP}}{\partial \sigma} = \left(P'\frac{\partial Q^*_{EP}}{\partial \sigma} - \bar{\alpha}\right) q^*_{EP} + (P(Q^*_{EP}) - \bar{\alpha}\sigma)\frac{\partial q^*_{EP}}{\partial \sigma} + \frac{\sigma}{\gamma}.$$

The only difference from the case without a fringe of foreign firms is that now we have $\frac{\partial Q^*_{EP}}{\partial \sigma} = n\frac{\partial q^*_{EP}}{\partial \sigma} + \frac{\partial q^*_f}{\partial \sigma}$. We compute this by acknowledging that for any $\sigma$, it is always true that at equilibrium $\frac{\partial \pi_i}{\partial q_i} = 0$ and that $P(Q^*_{EP}) - C'(q^*_f) = 0$. Deriving the latter expression with respect to $\sigma$, we obtain the following equation:

$$\frac{\partial Q^*_{EP}}{\partial \sigma} = \frac{C''(q^*_f)}{C''(q^*_f) - P'(Q^*_{EP})} \frac{\partial Q^*_{-f}}{\partial \sigma}, \tag{B.1}$$

from which we obtain an expression of the effect of $\sigma$ on the domestic firms' profit:

$$\frac{\partial \pi^*_{EP}}{\partial \sigma} = -\frac{\theta\eta + 2\frac{C''-P'}{C''}}{(\theta\eta + n) + \frac{C''-P'}{C''}} \bar{\alpha} q^*_{EP} + x^*,$$

where $\theta = \frac{Q^*_{-f}}{Q^*_{EP}}$ denotes the market share of domestic firms and thus is always within the interval $[0, 1]$. In this framework, the product market profit of the home firms increases with the cap-and-trade system if and only if:

$$\eta < -\frac{2}{\theta} \frac{C'' - P'}{C''}.$$

These conditions are more constraining than those found in the case without the fringe of foreign firms because $\theta < \frac{C''-P'}{C''}$. As the effect of $\sigma$ on the permit market profit is unchanged, international competition unsurprisingly diminishes the potential positive effect of the cap-and-trade system on domestic firms' profits when firms use end-of-pipe abatement.

With process-integrated abatement, the analysis is more ambiguous. The first-order conditions for the domestic firms are given by equations (4.5), and the first-order conditions for the fringe of firms are the same as those with end-of-pipe abatement. The effect of $\sigma$ on domestic firms' profits is then given by:

$$\frac{\partial \pi^*_I}{\partial \sigma} = -(\bar{\alpha} - y^*) \frac{\theta\eta + 2\frac{C''-P'}{C''}}{(\theta\eta + n) + \frac{C''-P'}{C''}} q^*_I + \frac{\frac{C''-P'}{C''} - n}{(\theta\eta + n) + \frac{C''-P'}{C''}} \frac{\partial y^*}{\partial \sigma} \sigma q^*_I.$$

As with end-of-pipe abatement, the product market profit is less likely to increase with $\sigma$ in the presence of unregulated foreign firms. The effect of this new competition on the net gain of abatement (the second term of the equation) is ambiguous, however:

$$\frac{\frac{C''-P'}{C''} - n}{(\theta\eta + n) + \frac{C''-P'}{C''}} < \frac{1-n}{n+1+\eta} \quad \Leftrightarrow \quad \eta > \frac{2n}{1 - \frac{C''}{P'}(1-n)(\theta - 1)}.$$

In particular, if the inverse demand function is convex (if $\eta < 0$), then the net effect of abatement on profits is greater (whether positive or negative) in the presence of international competition than without it.

## C. COMPARATIVE STATICS WITH RESPECT TO $\sigma$

We determine the effect of the price of permits $\sigma$ on $x^*$, $y^*$, $q^*_i$, $Q^*_i$ and $\pi_i$ ($i \in \{EP, I\}$). We consider first the case of end-of-pipe abatement and then the case of process integrated abatement.

### C.1. End-of-pipe abatement

The problem of firm $i$ is:

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

First-order conditions are given by equations (4.1 and 4.2), and we obtain $x^*(\sigma) = \frac{\sigma}{\gamma}$. As firms are identical, the equilibrium output is symmetric for all $i$ and denoted by $q^*_{EP}(\sigma)$. We denote the total equilibrium output by $Q^*_{EP}(\sigma) = nq^*_{EP}(\sigma)$ and $\pi^*_{EP}(\sigma) = \pi_i(q^*_{EP}(\sigma), x^*(\sigma))$ the corresponding equilibrium profit.

The effect of $\sigma$ on the equilibrium profit is given by:

$$\frac{\partial\pi^*_{EP}}{\partial\sigma} = \left(P'\frac{\partial Q^*_{EP}}{\partial\sigma} - \bar{\alpha}\right)q^*_{EP} + (P - \bar{\alpha}\sigma)\frac{\partial q^*_{EP}}{\partial\sigma} + \frac{\sigma}{\gamma}. \tag{C.1}$$

As $\sigma$ changes, firm $i$ changes its output $q_i$ so that we still have $\frac{\partial\pi_i}{\partial q_i} = 0$. Therefore, at equilibrium, we can write:

$$\partial\left(\frac{\partial\pi_i}{\partial q_i}\right)/\partial\sigma = P''\frac{\partial Q^*_{EP}}{\partial\sigma}q^*_{EP} + P'\frac{\partial q^*_{EP}}{\partial\sigma} + P'\frac{\partial Q^*_{EP}}{\partial\sigma} - \bar{\alpha} = 0. \tag{C.2}$$

Noting that $\sum_i \frac{\partial q^*_{EP}}{\partial\sigma} = n\frac{\partial q^*_{EP}}{\partial\sigma} = \frac{\partial Q^*_{EP}}{\partial\sigma}$, we sum equation (C.2) over $i$ and find:

$$\frac{\partial Q^*_{EP}}{\partial\sigma}(P''Q^*_{EP} + (n+1)P') = \frac{\partial Q^*_{EP}}{\partial\sigma}(\eta + n + 1)P' = n\bar{\alpha}. \tag{C.3}$$

As $x^* = \frac{\sigma}{\gamma}$, this allows us to write equation (C.1) as follows:

$$\frac{\partial\pi^*_{EP}}{\partial\sigma} = \left(\frac{n\bar{\alpha}}{\eta + n + 1} - \bar{\alpha}\right)q^*_{EP} + \frac{P - \bar{\alpha}\sigma}{P'}\frac{\bar{\alpha}}{\eta + (n+1)} + x^*.$$

Finally, as $q^*_{EP}(\sigma) = -\frac{P-\bar{\alpha}\sigma}{P'}$, we can write the variation of the profit as a function of $q^*_{EP}$, $x^*$, $\bar{\alpha}$, $n$ and $\eta$:

$$\frac{\partial\pi^*_{EP}}{\partial\sigma} = -\frac{2+\eta}{(n+1)+\eta}\bar{\alpha}q^*_{EP} + x^*.$$

### C.2. Process integrated technology

The problem of firm $i$ is:

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

First-order conditions are given by equation (4.5). We obtain $y^*(\sigma) = \frac{\sigma}{\beta}q^*_I(\sigma)$, and as firms are identical, the equilibrium output is symmetric for all $i$ and denoted by $q^*_I(\sigma)$. We denote the total equilibrium output by $Q^*_I(\sigma) = nq^*_I(\sigma)$ and $\pi^*_I(\sigma) = \pi_i(q^*_I(\sigma), y^*(\sigma))$ the corresponding equilibrium profit.

We then use the same method as in the end-of-pipe case to find an expression of $\frac{\partial \pi_I^*}{\partial \sigma}$:

$$
\begin{aligned}
\frac{\partial \pi_I^*}{\partial \sigma} &= \left[P'\frac{\partial Q_I^*}{\partial \sigma} - (\bar{\alpha} - y^*) + \sigma\frac{\partial y^*}{\partial \sigma}\right] q_I^* + \left[P - (\bar{\alpha} - y^*)\sigma\right]\frac{\partial q_I^*}{\partial \sigma} - \beta y^* \frac{\partial y^*}{\partial \sigma}, \\
&= \left[P'\frac{\partial Q_I^*}{\partial \sigma} - (\bar{\alpha} - y^*)\right] q_I^* + \left[P - (\bar{\alpha} - y^*)\sigma\right]\frac{\partial q_I^*}{\partial \sigma}. \qquad \text{(C.4)}
\end{aligned}
$$

Deriving $\frac{\partial \pi_i}{\partial q_i}$ with respect to $\sigma$ at the equilibrium values yields:

$$\partial\left(\frac{\partial \pi_i}{\partial q_i}\right)/\partial\sigma = \left(\frac{\partial Q_I^*}{\partial \sigma} + \frac{\partial q_I^*}{\partial \sigma}\right)P' + q_I^*\frac{\partial Q_I^*}{\partial \sigma}P'' - (\bar{\alpha} - y^*) + \sigma\frac{\partial y^*}{\partial \sigma} = 0.$$

As in the end-of-pipe case, we have $\frac{\partial Q_I^*}{\partial \sigma} = n\frac{\partial q_I^*}{\partial \sigma}$, which implies:

$$\frac{\partial Q_I^*}{\partial \sigma}(P''Q_I^* + (n+1)P') = \frac{\partial Q_I^*}{\partial \sigma}[\eta + (n+1)]P' = n\left[(\bar{\alpha} - y^*) - \sigma\frac{\partial y^*}{\partial \sigma}\right].$$

We thus have:

$$\frac{\partial Q_I^*}{\partial \sigma} = \frac{n}{(\eta + n + 1)P'}\left[(\bar{\alpha} - y^*) - \sigma\frac{\partial y^*}{\partial \sigma}\right]. \qquad \text{(C.5)}$$

The denominator of this expression is negative. Besides, if $\frac{\partial y^*}{\partial \sigma} < 0$, then the numerator is positive. Therefore, if $\frac{\partial y^*}{\partial \sigma} < 0$ then $\frac{\partial Q_I^*}{\partial \sigma} < 0$. In contrast, if $\frac{\partial Q_I^*}{\partial \sigma} > 0$ then $\frac{\partial y^*}{\partial \sigma} > 0$.

Replacing $\frac{\partial Q_I^*}{\partial \sigma}$ in (C.4) by the expression given in (C.5), we obtain the following expression:

$$
\begin{aligned}
\frac{\partial \pi_I^*}{\partial \sigma} &= -\frac{\eta + 2}{n + 1 + \eta}\left((\bar{\alpha} - y^*) - \sigma\frac{\partial y^*}{\partial \sigma}\right) q_I^* - \beta y^* \frac{\partial y^*}{\partial \sigma}, \\
&= -(\bar{\alpha} - y^*)\frac{\eta + 2}{n + 1 + \eta} q_I^* + \frac{1 - n}{n + 1 + \eta}\frac{\partial y^*}{\partial \sigma}\sigma q_I^*. \qquad \text{(C.6)}
\end{aligned}
$$

From the two expressions of $\frac{\partial \pi_I^*}{\partial \sigma}$ given by equations (C.4) and (C.6), we can make some comparative statics:

- If total output is a decreasing function of $\sigma$, then equation (C.4) implies that the equilibrium profit is also a decreasing function of $\sigma$.
- If total output is an increasing function of $\sigma$, then from equation (C.6) we see that the effect of $\sigma$ on $\pi_I^*$ depends on $\eta$:
  - If $\eta > -2$, then $\pi_I^*$ is decreasing in $\sigma$.
  - If $\eta < -2$, then the product market profit increases with $\sigma$ whereas the net gain of additional abatement is negative. The total effect is ambiguous.

## D. COMPARATIVE STATICS WITH RESPECT TO $n$

We now determine the effect of $n$ on $q_i^*$, $Q_i^*$ ($i \in \{EP, I\}$) and $E_I^*$.

*D.1. End-of-pipe abatement*

Deriving the first order conditions with respect to $n$, we obtain:

$$\partial\left(\frac{\partial\pi_i}{\partial q_i}\right)/\partial n = P''\frac{\partial Q^*_{EP}}{\partial n}\frac{Q^*_{EP}}{n} + P'\frac{\partial Q^*_{EP}}{\partial n} + \frac{P'}{n}\left(\frac{\partial Q^*_{EP}}{\partial n} - \frac{Q^*_{EP}}{n}\right) = 0,$$

from which we deduce:

$$\frac{\partial Q^*_{EP}}{\partial n} = \frac{P'Q^*_{EP}}{n(P''Q^*_{EP} + (n+1)P')} > 0. \tag{D.1}$$

*D.2. Process integrated technology.*

We show here that in the case of process integrated technology, $E^*_I$ always increases with $n$. Henceforth, we assume that $\eta > -n$ and that $P(Q^*_I) > \bar{\alpha}\sigma$. This is not always the case: the actual condition should be $P(Q^*_I) > (\bar{\alpha} - y^*)\sigma$, which implies that we can have $P - \bar{\alpha}\sigma < 0$, in which case we have also $P' + \sigma^2/\beta > 0$. This may imply $\frac{\partial q^*_I}{\partial n} > 0$ and it always implies $\frac{\partial Q^*_I}{\partial n} < 0$. It is thus better and more reasonable to assume $P' + \frac{\sigma^2}{\beta} < 0$.

We first deduce from the first-order conditions that:

$$P + q^*_I P' - \left(\bar{\alpha} - \frac{\sigma}{\beta}q^*_I\right)\sigma = 0 \quad\Leftrightarrow\quad q^*_I = -\frac{P - \bar{\alpha}\sigma}{P' + \frac{\sigma^2}{\beta}} > 0 \quad\Rightarrow\quad P' + \frac{\sigma^2}{\beta} < 0.$$

We can now determine an expression of the derivative of $q^*_I$ with respect to $n$ and deduce comparative statics results. Deriving $\frac{\partial \pi_i}{\partial q_i}$ with respect to $n$ at the equilibrium values yields:

$$\partial\left(\frac{\partial\pi_i}{\partial q_i}\right)/\partial n = P'\frac{\partial Q^*_I}{\partial n} + \frac{\partial q^*_I}{\partial n}P' + q^*_I P''\frac{\partial Q^*_I}{\partial n} + \frac{\partial y^*}{\partial n}\sigma = 0.$$

Besides, since $Q^*_I = nq^*_I$, we have $\frac{\partial Q^*_I}{\partial n} = q^*_I + n\frac{\partial q^*_I}{\partial n}$, we can rewrite the former expression as follows:

$$(q^*_I P'' + P')\left(q^*_I + n\frac{\partial q^*_I}{\partial n}\right) + \frac{\partial q^*_I}{\partial n}P' + \frac{\sigma^2}{\beta}\frac{\partial q^*_I}{\partial n} = 0,$$

from which we deduce:

$$\frac{q^*_I}{n} = -\frac{\partial q^*_I}{\partial n}\frac{(\eta + n + 1)P' + \frac{\sigma^2}{\beta}}{(\eta + n)P'}. \tag{D.2}$$

Since $\eta > -n$ and $P' + \frac{\sigma^2}{\beta} < 0$, it is immediate that $\frac{(\eta+n+1)P' + \frac{\sigma^2}{\beta}}{(\eta+n)P'} > 0$. Thus, as $\frac{q^*_I}{n} > 0$ we have $\frac{\partial q^*_I}{\partial n} < 0$. From this and (4.5) we conclude that $\frac{\partial y^*}{\partial n} < 0$.

We now determine the sign of $\frac{\partial Q^*_I}{\partial n}$, noticing that $\frac{\partial Q^*_I}{\partial n} > 0$ is equivalent to $\frac{q^*_I}{n} > -\frac{\partial q^*_I}{\partial n}$. Then, from equation (D.2) we have:

$$\frac{\partial Q^*_I}{\partial n} > 0 \quad\Leftrightarrow\quad \frac{(\eta + n + 1)P' + \frac{\sigma^2}{\beta}}{(\eta + n)P'} > 1 \quad\Leftrightarrow\quad \frac{P' + \frac{\sigma^2}{\beta}}{(\eta + n)P'} > 0,$$

which under our assumptions is always true since $\eta > -n$, $P' < 0$ and $P' + \frac{\sigma^2}{\beta} < 0$. Therefore, we have $\frac{\partial Q^*_I}{\partial n} > 0$. Finally, we can deduce the effect of $n$ on $E^*_I$ when the regulator uses a pigovian tax $\sigma = \lambda$:

$$\frac{\partial E_I^*}{\partial n} = -\frac{\partial y^*}{\partial n} Q_I^* + (\bar{\alpha} - y^*)\frac{\partial Q}{\partial n} > 0. \tag{D.3}$$

## E. Adjustment of the global pollution cap to new capacities' installations

In order to account for new capacities, we consider an industry in which a monopolistic firm may build several plants. The inverse demand function is $P(Q)$. The capacity of each plant is exogenous and given by $\overline{K}$, so that the marginal production cost is 0 for any quantity lower than $\overline{K}$, and $+\infty$ otherwise. The fixed cost of building a new plant is $F$.

Assume that the firm has $n$ plants. All plants use end-of-pipe abatement, and have a symmetric cost of abatement. In order to reduce emissions from the baseline level $\bar{\alpha} q_k$ to a given target $e_k$, that is, abate pollution by an amount of $x_k = \bar{\alpha} q_k - e_k$, plant $k \in \{1, \cdots, n\}$ bears a cost $\gamma x_i^2/2$, with $\gamma \geq 0$.

In order to anaylze the effect of an increase of the capacity of the firm (an increase of the number of plants $n$), we consider that at a given point in time, the number of plants of the firm is given. This assumption is reasonable in the sense that building a capacity is not something that can be done overnight: the building of new plants is progressive, and there may be a period of time during which the capacity $n\overline{K}$ of the firm is binding. This can for instance be explained by operational or financial constraints.

If the firm owns $n$ plants, then its problem reads:

$$\max_{q_1,\cdots,q_n,x_1,\ldots,x_n} \pi = \left(P\left(\sum_{k=1}^n q_k\right) - \bar{\alpha}\sigma\right)\sum_{k=1}^n q_k - \gamma\frac{\sum_{k=1}^n x_k^2}{2} + \sigma\sum_{k=1}^n x_k - nF,$$

$$s.t. \sum_{k=1}^n q_k \leq n\overline{K},$$

with $q_k$ the output and $x_k$ the abatement level of plant $k$.

Then there are two possible outcomes: either the constraint is binding or it is not. We denote $q_k^*$ the optimal unconstrained quantity of each plant, and $\overline{Q}^* = \sum_{k=1}^n q_k^*$ the total output of the firm if its capacity is not binding.

If the constraint is not binding, this means that the firm has already built the profit-maximizing number of firms $n^*$, which is given by $(n^* - 1)\overline{K} < Q^* \leq n^*\overline{K}$. In this case, because the marginal production cost (taking into account the permits market) is constant, the firm sets its total output so as to maximize its profit, and the sharing of this output between its $n^*$ plants is irrelevant. The sharing of abatement, however, is not relevant: the firm has an incentive to smoothe abatement over all its plants so as to minimize the cost of abatement. As a consequence, it is possible to simplify the program as follows, denoting $x$ the abatement level in each plant:[23]

$$\max_{Q,x} \pi = (P(Q) - \bar{\alpha}\sigma)Q - n\left(\gamma\frac{x^2}{2} - \sigma x\right) - nF.$$

[23] We assume that fixed costs associated to the building of a new plant are such that firms always have an incentive to build enough plants so that the constraint $Q \leq n\overline{K}$ is not binding, but never have an incentive to build plants so as to reduce their abatement costs by flattening the cost function.

The necessary first-order conditions highlight the independence of $Q$ and $x$:[24]

$$\frac{\partial \pi}{\partial Q} = P + P'(Q) - \bar{\alpha}\sigma = 0, \tag{E.1}$$

$$\frac{\partial \pi}{\partial x} = \sigma - \gamma x = 0. \tag{E.2}$$

All the plants abate the same $x^* = \frac{\sigma}{\gamma}$, and the firm sets $n^*$ so as to ensure that $(n^* - 1)\overline{K} < Q \leq n^*\overline{K}$. In what follows, we assume that the price of permits ensures that $0 \leq \overline{\alpha}Q^* - x^* \leq \overline{\alpha}Q^*$, that is, with a Pigovian price of permits, the environmental damage is low enough that firms abate weakly less than they pollute. This corresponds to the following assumption on $\sigma$ (or on the environmental damage):

$$0 \leq \sigma \leq \frac{\alpha\gamma}{2 + \alpha^2\gamma}.$$

If the constraint is binding, that is if the firm has not yet built the profit-maximizing number of firms $n^*$, then each plant produces $\overline{K}$ and abates $x^{**} = \min\left\{\frac{\sigma}{\gamma}, \alpha\overline{K}\right\}$.

The equilibrium in the market for permits is given by:

$$E^*_{EP}(n, \sigma) = n\left(\bar{\alpha}\overline{K} - x^{**}\right).$$

We focus on the adjustment of the total pollution cap to the increase of the number of plants of the firm. Given that $\sigma$ is the Pigovian price and is, therefore, unaffected by $n$, the effect of the increase of the number of plants on the emission cap that will be set by the regulator is simply given by:

$$\frac{\partial E^*_{EP}}{\partial n} = \bar{\alpha}\overline{K} - x^{**}. \tag{E.3}$$

This equation is similar to the one analyzed above in the case of a new entrant, only simpler because of the capacity constraint. From this, it is immediate that when the number of plants increases, the Pigovian reply for the regulator is to set a larger cap.

## F. Optimal regulation

We assume that the regulator maximizes a welfare function and corrects two distortions: environmental externality and market power. Total welfare is thus given by:

$$W = CS + \sum_{i=1}^{n} \pi_i - \lambda \sum_{i=1}^{n} e_i + RR,$$

where $CS$ is the consumers' surplus, $\pi_i$ the profit of firm $i$ and $RR$ the regulator's revenue. We analyze then the optimal price of permits for each abatement technology.

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

### *F.1. End-of-pipe abatement*

In the case of end-of-pipe abatement, the welfare at the product market equilibrium for a given price of permits $\sigma$ is given by:

$$W_{EP} = \int_0^{Q^*_{EP}} P(Q)dQ - n\frac{\gamma}{2}(x^*)^2 - \lambda(\alpha Q^*_{EP} - nx^*).$$

The optimal value of $\sigma$ is then given by the first-order condition:

$$\frac{\partial W_{EP}}{\partial \sigma} = (P(Q^*_{EP}) - \alpha\lambda)\frac{\partial Q^*_{EP}}{\partial \sigma} - \frac{n}{\gamma}(\sigma - \lambda) = 0. \tag{F.1}$$

The first term of the expression corresponds to the marginal welfare if there were no abatement. As total output does not depend on abatement, marginal welfare without abatement is simply the sum of the effect of $\sigma$ on the consumer surplus and its effect on environmental damage due only to the variation of output. The second term is the marginal social cost of abatement. It is the difference between the reduction of environmental damage due to abatement, equal to $\lambda n\frac{\partial x^*}{\partial \sigma}$ and the additional cost of abatement $n\frac{\gamma}{2}\frac{\partial x^*}{\partial \sigma}x^*$. The marginal gain of abatement is actually unaffected by $\sigma$, as the variation of abatement with $\sigma$ is $\frac{1}{\gamma}$ regardless of the value of $\sigma$; by contrast, the marginal cost of abatement increases with $\sigma$ because of the convexity of abatement costs. Replacing $P(Q^*_{EP})$ in equation (F.1) using the first expression in (4.1), we obtain:

$$\frac{\partial W_{EP}}{\partial \sigma} = ((\sigma - \lambda)\alpha - P'q^*_{EP})\,\frac{\partial Q^*_{EP}}{\partial \sigma} - \frac{n}{\gamma}(\sigma - \lambda) = 0,$$

from which we can deduce that the optimal tax $\sigma^{opt}_{EP}$ is lower than $\lambda$, i.e. lower than the Pigovian tax. Indeed, if it were not, then we would have $((\sigma - \lambda)\alpha - P'q^*_{EP})\,\frac{\partial Q^*_{EP}}{\partial \sigma} < 0$, hence $\frac{n}{\gamma}(\sigma - \lambda) < 0$ which would imply $\sigma < \lambda$, hence a contradiction.

### *F.2. Process-integrated technology*

In the case of process-integrated technology, the welfare at the product market equilibrium for a given price of permits $\sigma$ is given by:

$$W_I = \int_0^{Q^*_I} P(Q)dQ - \beta n\frac{(y^*)^2}{2} - \lambda(\alpha - y^*)Q^*_I. \tag{F.2}$$

The optimal value of $\sigma$ is then given by the first-order condition:

$$\frac{\partial W^*}{\partial \sigma} = \frac{\partial Q^*_I}{\partial \sigma}\left(P(Q^*_I) - \alpha\lambda\right) - \frac{\partial Q^*_I}{\partial \sigma}y^*\left(\sigma - 2\lambda\right) - y^*Q^*_I\frac{\sigma - \lambda}{\sigma} = 0.$$

By contrast with the end-of-pipe case, total output depends on abatement. Nevertheless, as in the end-of-pipe case, the first term of the latter equation can be understood as the marginal welfare if there were no abatement, which corresponds to the sum of the effect of $\sigma$ on the consumer surplus and its effect on environmental damage due only to the variation of output following the regulation. The two other terms represent the net gain due to abatement. More precisely, the second term represents the marginal gain of abatement while the third term represents the marginal cost of abatement.

Replacing $P(Q_I^*)$ in equation (F.2) using the first expression in (4.5), we obtain:

$$\frac{\partial W_I^*}{\partial \sigma} = \frac{\partial Q_I^*}{\partial \sigma}\left((\alpha - y^*)(\sigma - \lambda) - q_I^* P'\right) - y^* \frac{\sigma - \lambda}{\sigma}\left(Q_I^* + \sigma \frac{\partial Q_I^*}{\partial \sigma}\right) = 0,$$

from which we can deduce that the optimal tax $\sigma_I^{opt}$ is lower than $\lambda$, i.e. lower than the Pigovian tax. Indeed, if it were not, then we would have $\frac{\partial Q_I^*}{\partial \sigma}\left((\alpha - y^*)(\sigma - \lambda) - q_I^* P'\right) < 0$, hence $y^* \frac{\sigma-\lambda}{\sigma}\left(Q_I^* + \sigma \frac{\partial Q_I^*}{\partial \sigma}\right) < 0$ which would imply $\sigma < \lambda$, hence a contradiction.