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Working Paper**Author(s):**

Christin, Clémence; Nicolai, Jean-Philippe; Pouyet, Jerome

Publication date:

2013-11

Permanent link:

<https://doi.org/10.3929/ethz-a-010018836>

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Originally published in:

Economics Working Paper Series 13/186



CER-ETH – Center of Economic Research at ETH Zurich

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Working Paper 13/186
November 2013

Economics Working Paper Series



Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich

Pollution Permits, Imperfect Competition and Abatement Technologies*

Clémence Christin[†] Jean-Philippe Nicolai[‡] Jerome Pouyet[§]

October 2013

Abstract

Under imperfect competition, the effect of a cap-and-trade system on industry profits depends on the type of abatement technology that is used by firms: industries that use process-integrated technologies are more affected than those using end-of-pipe abatement technologies. The interaction between environmental policy and the evolution of the market structure is then studied. In particular, 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.

JEL Classification: L13, Q53, Q58.

Keywords: Cap-and-trade system, imperfect competition, abatement technologies.

*We thank Rabah Amir, Jean-Marc Bourgeon, Anna Creti, Bouwe Dijkstra, Roger Guesnerie, Bruno Jullien, Guy Meunier, Juan-Pablo Montero, Karsten Neuhoff, Jean-Pierre Ponssard, Philippe Quirion, Bernard Sinclair-Desgagne, Catherine Thomas, participants at EARIE 2008, EAERE 2008, AFSE 2008, JMA 2008, Journ?es Louis-Andre Gerard-Varet 2010 conferences for their comments and useful references. Financial support from the Business Economics and Sustainable Development Chaires of Ecole Polytechnique, Cepremap and Swiss Re is gratefully acknowledged.

[†]Université de Caen Basse-Normandie and CREM, Address: 19 rue Claude Bloch, 14000 Caen, France, E-mail: clemence.christin@unicaen.fr.

[‡]ETH Zürich, Address: Chair of Integrative Risk Management and Economics,, Zürichbergstrasse 18 8032 Zürich, Switzerland. E-mail: jnicolai@ethz.ch.

[§]Paris School of Economics, 48 boulevard Jourdan, 75014 Paris, France. E-mail: pouyet@pse.ens.fr.

1 Introduction

An issue common to the implementation of environmental regulations (e.g., regarding a market for pollution permits or an environmental tax) concerns the acceptability of such regulation by the agents affected by it. A cap-and-trade system, in particular, is likely to fail if the industries concerned by the said system lobby against it. This may happen if industry profits fall as a result of the cap-and-trade system. Judging by the results of the European Union Emissions Trading System (EU ETS), however, it is not clear what the effect of a cap-and-trade system on firms' profits will be. The cap-and-trade system may in fact benefit some industries, in which case the issue of whether the system is acceptable to firms should not even be raised.

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. From this, we derive two sets of conclusions. First, profits are affected differently by the cap-and-trade system depending on the type of abatement technology at hand in the industry. In some cases, firm 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.

During the first two phases of the EU ETS, less than 10% of all pollution permits were auctioned, while the rest were grandfathered (i.e., granted for free regardless of the firms' output). This approach was widely criticized, as it led, in some cases, to an increase in profits (Grubb and Neuhoff, 2006, Ellerman and Joskow, 2008). Focusing on the steel industry, Demailly and Quirion (2008) argue that not more than 50% of the permits should have been granted for free in order to compensate for profit losses.

More important, there is some evidence that profits in the power industry would have increased even if all the permits had been auctioned (Sijm et al., 2006). Although all industries seemed to benefit from having too many free allowances, the impact of the EU ETS prior to such allowances varied considerably among industries.

We argue that one of the reasons for this variation is the variety of abatement technologies and their availability, or lack thereof, in the different industries. Any industry has access to various types of abatement technologies. However, some abatement technologies are relatively more available in some industries, as illustrated by Anderson and Newell (2003), for example, who argue that the cost of using capture and storage depends to a great extent on the type of industry.

Following Requate (2005), we consider two types of technologies: end-of-pipe abatement and process-integrated abatement. End-of-pipe abatement corresponds to capture and storage systems, pollution filters and clean development mechanisms, all of which are mainly independent of production decisions.¹ 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 are shifting to a cleaner technology or reducing the energy intensity of production.

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. To do so, we make two types of comparison. We first compare each technology to a benchmark case in which firms do not have access to abatement. Then, we compare the two technologies to one another, focusing on a case in which the same level of abatement in equilibrium yields the same total cost of abatement for both technologies. We focus on Cournot competition.

In the benchmark case without abatement, 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 a monopoly market structure or perfect competition, this would automatically reduce firms' profits. With imperfect competition in the product market, however, the production cost increase that follows an increase in the price of permits may have a counter-intuitive 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).

Comparing each technology to the benchmark, we obtain different effects. With end-of-pipe abatement, access to abatement does not affect the decisions of firms on the product market. Indeed, reducing pollution (that is, "producing" emission reduction) is a new activity, the profitability of which is independent from the production of the final good. Firms abate their pollution up to the point where the marginal cost of abatement equals the price of permits. The higher the price of permits is, the more profitable this new activity is. 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 permit price, a cap-and-trade system has two contradictory effects, and total profits may increase as a result of the system. In contrast, in the case of process-integrated technology, abatement amounts to reducing the marginal cost of production and is therefore not independent of production. In that case, the production cost always increases to a lesser degree following an increase in the permit price than without abatement: the total effect on profits, whether positive or negative, is thus smaller with process-integrated abatement than without abatement.

Comparing the two technologies, we then find that in standard cases (when product market profits decrease with the price of permits), firms are always better off using end-of-pipe abatement than using process-integrated abatement. In the less common

case, in which an increase in the permit price increases the product market profit, then it is unclear which technology is better from the point of view of firms. We know, however, that with end-of-pipe abatement firms' profits always increase with the price of permits, whereas with process-integrated abatement firms' profits may increase or decrease following an increase in the price of permits.

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 at hand in the industry. As an implication for policy, the criteria for allocating grandfathered free allowances (a common tool to compensate firms' profit losses due to the cap-and-trade system) must depend on abatement technologies.² We extend this result to price competition and to a framework with international competition, assuming the presence of a competitive fringe of foreign firms that are not subject to the cap-and-trade system.

A second contribution concerns the adjustment of the global pollution cap to 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. The reserve for entrants is ordinarily justified to encourage competition in the market for products. Here, we consider the case in which the regulator implements a Pigovian permit price, and we analyze how the cap of permits should be adjusted to entry.

The two aforementioned abatement technologies have different effects on the equilibrium permit price: the cap of permits may increase or decrease with the number of firms with end-of-pipe abatement, whereas it should always increase with competition with process-integrated abatement. We thus provide a new justification for the existence of a reserve of permits for potential entrants,³ especially with the process-integrated abatement. In contrast, in cases in which the regulator should reduce the cap of permits 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.

The structure of the article is as follows: We start by relating the paper to the literature in Section 2. Section 3 describes our model. In Section 4, we determine the effect of the implementation of pollution permits on firms' profits, depending on their abatement technology, and extend our analysis to price competition and international competition. In Section 5, we determine the adjustment of the global pollution cap to entry. Section 6 concludes.

2 Relation to the Literature

The paper contributes to three strands of the literature.

First, the paper contributes to the literature on the effect of a marginal cost increase on profits under quantity competition. Seade (1985) 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 analogues with Seade's analysis. 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. We show in particular 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.

Second, our investigation is part of a body of literature on the acceptability of the implementation of pollution permits from firms' viewpoint. 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. The profit-neutral permit allocations are mainly analyzed with a general equilibrium approach in the literature. However, two papers focus on this issue in a partial equilibrium framework. Guesnerie et al. (2012) analyze the percentage of permits that a regulator should give for free in order to offset profit losses. They show that in most cases, few permits are required and that free allowances should not even be given with low demand elasticity. We extend this analysis by allowing firms to use abatement technologies. Interestingly, the share of free allowances obtained without abatement may not be an upper bound, as firms may be worse off when they have access to process-integrated abatement than when abatement is not available.

The paper closest to our analysis is Hepburn et al. (2012), who independently study the effect of introducing a market for emission 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. Although we obtain similar results, there are important differences between the two papers, and the effects at stake are, therefore, orthogonal. Indeed, Hepburn et al. (2012) focus on the effect on profits of cost asymmetries among firms in the market, whereas we consider a market with identical firms but focus on the role of abatement technologies. Thus, Hepburn et al. (2012) do not disentangle abatement costs from production costs but merely assume that the lower a firm's total cost is, the lower its emission intensity, i.e., the level of pollution per unit of output, is. In this framework, introducing

a market for permits allows for a more efficient allocation of production, from the industry point of view, as the market share of more efficient firms increases, which increases the joint profits in the final market. In contrast, our result stems from the assumption that different abatement technologies induce different correlations between the production and abatement decisions of a firm. As a consequence, even in a market with symmetric firms, depending on the abatement technology, it is possible to observe a profit-increasing effect of the permit market.⁴

Finally, the paper contributes to the literature that criticizes the introduction of a reserve for entrants. The few papers that study this issue focus essentially on the effect of the reserve on emissions, rather than on competition, and analyze perfectly competitive markets. Besides, the issue raised in this literature is whether entrants should be granted free allowances or not. Ellerman (2008) shows that granting new entrants free allowances leads to excess capacity and to more output, although the effect on emissions is ambiguous. One important question about entrants regards the diffusion of environmentally-friendly technologies. Focusing on the French National Allocation Plan, 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. More generally, an important body of literature focuses on the gradual process of diffusion of the technology. Jaffe and Stavins (1994) detail the different barriers which prevent the full diffusion of technology and determine the conditions (market failures) under which the government should ease this diffusion. Jaffe, Newell and Stavins (2001) show the positive link between technology diffusion and the rate of capital stock turnover. Moreover, a debate exists to know whether auctioning or tradable permits ease the diffusion of technology (Milliman and Prince, 1989; Jung et al., 1996; Kehohane, 1999).

We depart from this literature in that we do not consider entrants that are more

efficient than incumbents. We define the reserve for entrants as an increase of the cap of permits following entry, and do not analyze at all how these new permits should be distributed to entrants (auctioned or granted for free). We consider the effect of entry on total welfare in an industry with imperfect competition, 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 entrants 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

Assume that n identical firms compete in quantity. The inverse demand function is $P(Q)$, such that $P' < 0$ and the stability condition given by Seade (1985) is satisfied: $(n + 1)P'(Q) + QP''(Q) < 0$. Moreover, we denote the elasticity of the demand slope, or demand curvature, by $\eta = \frac{P''Q}{P'}$.

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 that is 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 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 process-integrated abatement technology alters the production process in a more environmentally friendly way and therefore reduces 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 $\alpha(y_i) = \bar{\alpha} - y_i$.⁵

We assume in the following analysis that all firms in the market use the same abatement technology, which is either end-of-pipe abatement or process-integrated abatement. The type of abatement technology that is used is determined by the sector-based characteristics.

The regulator implements a market for permits. A firm must own a permit for each unit of pollution that it emits, and it can buy or sell permits in the market for permits, depending on its needs. We assume that competition in this market is perfect and denote the price of permits by σ . Finally, we consider the social damage caused by pollution to be a linear function of total emissions and denote λ as the marginal damage.

4 Firms' profitability and environmental regulation

4.1 Symmetric firms in a closed economy

Let us analyze for each type of abatement technology 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 and therefore into the acceptability of the cap-and-trade system from the point of view of a given industry. We first compare each technology to a case without abatement and then compare the two technologies to one another.

End-of-pipe abatement. We first assume that each firm uses end-of-pipe abatement. The problem of firm i reads:

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

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, $(P(Q) - \bar{\alpha}\sigma)q_i$, that determine the optimal output, and an additional gain due to abatement $\sigma x_i - \gamma x_i^2/2$, that determines the optimal abatement level.⁶ Interestingly, in this framework, firm i operates as if it produced two independent goods: the final good in quantity q_i , sold on the final market at price $P(Q)$, and emission permits in quantity x_i , sold on the permit market at price σ . The necessary first-order conditions highlight the independence of q_i and x_i .⁷

$$\frac{\partial \pi_i}{\partial q_i} = P + q_i P' - \bar{\alpha}\sigma = 0, \quad \frac{\partial \pi_i}{\partial x_i} = \sigma - \gamma x_i = 0. \quad (1)$$

In particular, it is immediately clear that the optimal abatement level is such that the marginal cost of abatement γx_i is equal to the revenue from selling one more permit σ . From equation (1), we deduce the symmetric equilibrium individual output q_{EP}^* and abatement $x^* = \frac{\sigma}{\gamma}$, and the total output is equal to $Q_{EP}^* = nq_{EP}^*$. The symmetric equilibrium profit of firm i for a given σ is:⁸

$$\pi_{EP}^*(\sigma) = (P(Q_{EP}^*) - \sigma \bar{\alpha}) q_{EP}^* + \frac{\sigma^2}{2\gamma}.$$

The variation of π_{EP}^* with respect to σ is then:

$$\frac{\partial \pi_{EP}^*}{\partial \sigma} = q_{EP}^* \left[\frac{\partial Q_{EP}^*}{\partial \sigma} \frac{n-1}{n} P' - \bar{\alpha} \right] = -\frac{\eta+2}{(n+1)+\eta} \bar{\alpha} q_{EP}^* + \frac{\sigma}{\gamma}. \quad (2)$$

Proposition 1. *When firms use end-of-pipe abatement, then:*

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

Proof. See Appendix A.1. □

Increasing σ has two independent effects on a firm's equilibrium profit. The first effect is frequently found in the industrial organization literature and corresponds to the effect of σ on the product market profit. An increase in σ increases the final price and reduces individual and total output, which in most cases reduces firms' revenue. However, Seade (1985) shows that under some conditions, even this part of the firm's profit may increase following an increase in σ . In other words, the implementation of a permit market helps firms coordinate in order to increase their prices and consequently their profits. This effect depends on the demand curvature. The product market profit increases if and only if $\eta < -2$.⁹ This profit increasing effect does not exist with linear demand. In contrast, with an isoelastic demand function, profits may increase when the elasticity of demand is low enough. Then, the price increase prevails over the reduction in output.

The second effect is the effect of σ on the gain due to abatement. The higher the permit price is, the more firms abate, and thus, the higher the gain due to abatement is.¹⁰ 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 a second profitable activity of the firm.

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

Consider now the stage in which the market for pollution permits is opened. The

total supply of permits corresponds to the cap E , while the total demand is $n(\bar{\alpha}q_{EP}^* - x^*)$. The perfectly competitive permit market clears when supply equals demand, and we deduce from this an expression of the effect of the cap E on the equilibrium price of permits σ_{EP}^* :

$$\frac{\partial \sigma_{EP}^*}{\partial E} \left(\bar{\alpha} \frac{\partial q_{EP}^*}{\partial \sigma} - \frac{1}{\gamma} \right) = \frac{1}{n}.$$

The effect of E on the equilibrium price of permits is thus, as expected, unambiguously negative, as q_{EP}^* always decreases with σ : as regulation becomes more strict, the price of permits increases.

Process-integrated technology. Assuming now that all firms use process-integrated technology, the problem of firm i is:

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

In this case, we cannot simply separate 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 i . Nevertheless, we can disentangle two effects: first, the standard effect of an industry-wide cost increase highlighted by Seade (1985), that is, the effect of σ on $(P(Q) - \sigma(\bar{\alpha} - y_i)) q_i$ for a given level of abatement, and, second, the indirect effect of σ on profits through the variation of abatement $\frac{\partial y^*}{\partial \sigma}$.

The necessary first-order conditions yield:

$$\frac{\partial \pi_i}{\partial q_i} = P + q_i P' - (\bar{\alpha} - y_i) \sigma = 0, \quad \frac{\partial \pi_i}{\partial y_i} = \sigma q_i - \beta y_i = 0. \quad (3)$$

We denote the symmetric equilibrium individual output and abatement by q_I^* and y^* , respectively, and denote the total output by $Q_I^* = nq_I^*$. The symmetric equilibrium

profit of a firm for a given σ is:

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

The variation of π_I^* with respect to σ is then equal to:

$$\frac{\partial \pi_I^*}{\partial \sigma} = -(\bar{\alpha} - y^*) \frac{\eta + 2}{n + 1 + \eta} q_I^* + \frac{1 - n}{n + 1 + \eta} \frac{\partial y^*}{\partial \sigma} \sigma q_I^*. \quad (4)$$

The first term of this expression represents the product market effect, or “Seade effect”, which is more complicated than that with end-of-pipe abatement. The second term represents the net gain of abatement, that is, the difference between the gain of polluting less for a given cost of pollution and a given output, $\frac{\eta+2}{n+1+\eta} \frac{\partial y^*}{\partial \sigma} \sigma q_I^*$, net of the cost of additional abatement, $\beta y^* \frac{\partial y^*}{\partial \sigma}$.

Proposition 2. *When firms use process-integrated abatement, then:*

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

Proof. See Appendix A.2. □

Again, two effects are at stake. Consider first the product market effect, or the “Seade effect”. This effect corresponds to the effect of σ on the marginal cost of production, which depends both on the permit price and on the value of the polluting factor. When firms use process-integrated abatement, the polluting factor $\bar{\alpha} - y^*$ is lower than the polluting factor without abatement $\bar{\alpha}$. For this reason, the first term of equation (4) represents a “diminished” Seade effect, which results in a less negative (resp. positive) effect of σ in the case in which, absent abatement, the effect of σ on the product market profit is negative (resp. positive).

The second term of (4) is the net gain of a variation of abatement by $\frac{\partial y^*}{\partial \sigma}$ following an increase in the price of permits. This net gain is negative if and only if the equilibrium abatement level increases with σ . Although the effect of σ on y^* is not clear, we have $\frac{\partial y^*}{\partial \sigma} = \frac{1}{\beta} \left(q_I^* + \sigma \frac{\partial q_I^*}{\partial \sigma} \right)$, from which we can deduce that the equilibrium level of abatement increases with σ as long as the equilibrium individual output does not decrease too much with σ .

This second term implies that if all firms increase their abatement following an increase in the price of permits, they incur an additional net cost. Indeed, while the cost of abatement is completely borne by the firm, the gain of polluting less is partly passed through to consumers because of competition. The share of the cost reduction that firms actually benefit from is roughly represented by $\frac{\eta+2}{n+1+\eta}$, which is positive but decreases with n as long as $\eta > -2$. In other words, as competition in the market increases, more of the cost reduction is passed through to consumers. This pass-through results from the prisoners' dilemma: For given prices set by its rivals, firm i 's abatement allows it to reduce its price and gain market shares. At the symmetric equilibrium, however, all firms abate the same amount so that competition becomes fiercer. One particular case is the monopoly case, where the two effects cancel out, and the net gain of abatement is zero. Indeed, this is the only market structure in which the firm can fully benefit from its gain in efficiency.

Eventually, we find that in the most standard case, when total profits decrease with σ without abatement, they do so too even when firms use process-integrated abatement.¹¹

Consider now the stage in which the market for pollution permits is opened. The total supply of permits corresponds to the cap E , while the total demand is $n(\bar{\alpha} - y^*(\sigma))q_I^*(\sigma)$. The market clears when supply equals demand, and we deduce from this

an expression of the effect of the cap E on the equilibrium price of permits σ_I^* :

$$\frac{\partial \sigma_I^*}{\partial E} \left((\bar{\alpha} - y^*) \frac{\partial q_I^*}{\partial \sigma} - \frac{q_I^*}{\beta} \left(q_I^* + \sigma \frac{\partial q_I^*}{\partial \sigma} \right) \right) = \frac{1}{n}. \quad (5)$$

Obviously, $\frac{\partial \sigma_I^*}{\partial E}$ carries the same sign as that of the effect of σ on total pollution costs $(\bar{\alpha} - y^*)\sigma q_I^*$, since total supply is inelastic with respect to σ . As for all costs, the effect of σ on pollution costs is twofold: it affects the marginal cost of pollution $(\bar{\alpha} - y^*)\sigma$, which corresponds to the second term on the left-hand side of equation (5), and it also affects output q_I^* and hence total costs, which corresponds to the first term on the left-hand side of equation (5). Eventually, it is difficult to derive general conclusions, but we find that if abatement increases and output decreases with σ , the price of permits decreases with E . In particular, with linear demand, σ always decreases with E .

Comparison of the two technologies In the previous analysis, we only compared the profits for each technology to the profit that firms would earn if no technology was available. In order to make the two technologies properly comparable, we focus on cases in which the same cost of abatement induces the same level of abatement. We leave aside the equilibrium on the permit market. As we consider industries that are in the same permit market, we assume that the price of permits is identical for all industries, regardless of their abatement technology.

Lemma 1. *In equilibrium, with both technologies, for the same price of permits, the same individual level of abatement induces the same total cost of abatement.*

We obviously cannot consider a case in which the same cost is incurred with both technologies for any level of abatement, as this would simply amount to having two identical technologies. We therefore limit our analysis to the equilibrium path and assume in what follows that we have the same equilibrium level of total abatement in

both cases; that is, $x^* = y^* q_I^*$. As we know already that $x^* = \frac{\sigma}{\gamma}$ and $y^* = \frac{\sigma}{\beta} q_I^*$, we have unique expressions of output and investment (y) in the case of process-integrated abatement and can deduce the total costs of abatement for both technologies:

$$y^* = \frac{\sigma}{\sqrt{\beta\gamma}}, \quad q_I^* = \sqrt{\frac{\beta}{\gamma}}, \quad \gamma \frac{(x^*)^2}{2} = \frac{\sigma^2}{2\gamma} = \beta \frac{(y^*)^2}{2}.$$

On the equilibrium path, for any value of σ , the same level of abatement induces the same cost for both technologies. It is thus relevant to compare the two technologies in this particular case.

In addition, as we now have expressions of y^* and q_I^* as functions of σ , γ and β , we can simplify equation (4):

$$\begin{aligned} \frac{\partial \pi_I^*}{\partial \sigma} &= -(\bar{\alpha} - y^*) \frac{\eta + 2}{n + 1 + \eta} q_I^* + \frac{1 - n}{n + 1 + \eta} \frac{\partial y^*}{\partial \sigma} \sigma q_I^*, \\ &= -\frac{\eta + 2}{n + 1 + \eta} \bar{\alpha} q_I^* + \frac{\sigma}{\gamma} \frac{\eta + 3 - n}{n + 1 + \eta}. \end{aligned} \tag{6}$$

The latter expression can easily be compared to the corresponding expression for the end-of-pipe technology, given by equation (2):

$$\frac{\partial \pi_{EP}^*}{\partial \sigma} = -\frac{\eta + 2}{(n + 1) + \eta} \bar{\alpha} q_{EP}^* + \frac{\sigma}{\gamma}.$$

It is immediately clear that the first term on the right-hand side of both equations is identical, except for the equilibrium output. The first-order conditions on output ensure that for all values of the parameters, for the same number of firms in the industry, the individual output is larger with process-integrated abatement than with end-of-pipe abatement. The second term is always lower with process-integrated abatement and is negative as long as $\eta < n - 3$. We can now compare the two technologies, distinguishing between two cases: $\eta < -2$ and $\eta > -2$.

Proposition 3. *Assume that in equilibrium, firms set the same level of abatement regardless of the technology at hand. Then, when $\eta > -2$, the profit of firms decreases more with σ when firms use process-integrated abatement than when they use end-of-pipe abatement.*

The most standard case is $\eta > -2$, as it is typically the case in which the product market profit is decreasing with σ . In this case, we have already shown that the total profit of a firm may still increase with σ with end-of-pipe abatement because of the profit from the permit market. From equation (6), we see that with process-integrated abatement, the negative effect is reinforced because of the higher output, and at the same time, the positive effect is diminished because firms pass through part of their cost gain to the consumers. As a result, in this standard case, when both technologies imply an equal abatement level and equal abatement costs, industries using process-integrated abatement are affected to a greater extent by the cap-and-trade system than those using end-of-pipe abatement. If $\eta < n - 3$, then the effect of the cap-and-trade system on industries with process-integrated abatement is negative for all σ .

Proposition 4. *Assume that in equilibrium, firms set the same level of abatement regardless of the technology at hand. Then, when $\eta < -2$, the profit of firms increases with σ when firms use end-of-pipe abatement, whereas it may increase or decrease with σ when they use process-integrated abatement.*

In the less common case, in which $\eta < -2$, the effect of the cap-and-trade system on firms using end-of-pipe abatement is unambiguously positive because both the product market profit and the permit market profit increase with σ . With process-integrated abatement, the product market profit increases even more than with end-of-pipe abatement. Indeed, as the equilibrium output of a firm is larger with process-integrated abatement than with end-of-pipe abatement, the effect of σ on the product market

profit, represented by $\frac{\eta+2}{(n+1)+\eta}\bar{\alpha}q_k^*$ ($k = EP, I$) is always greater, independently of the sign of this effect. In addition, when $\eta < -2$, the sign of this term is positive. In contrast, in this case, the effect of σ on the profits resulting solely from abatement, summarized by the term $\frac{\sigma}{\gamma}\frac{\eta+3-n}{n+1+\eta}$, is negative, as $\eta + 3 - n \leq 0$ and $n + 1 + \eta > 0$. The total effect of the cap-and-trade system on industries using process-integrated abatement is thus ambiguous when $\eta < -2$.

Finally, it is important to note that it cannot be that the cap-and-trade system is more lenient on firms using process-integrated abatement, unless both industries benefit from the cap-and-trade system. Whenever the cap-and-trade system has a negative effect on profits with at least one abatement technology, the system is more lenient with end-of-pipe abatement. In other words, in cases in which a regulator should worry about the acceptability of the cap-and-trade system, it should always worry more about industries using process-integrated technology.

4.2 Extensions

We now test the robustness of our results to two alternative assumptions. First, we consider price competition instead as quantity competition. Second, we determine the effect of foreign competition, in the form of a competitive fringe of firms that are not subject to the cap-and-trade system. Note that in both extensions, we only focus on the effect of the price of permits on final prices, abatement and profits; that is, we will not analyze the opening of the permit market.

Price competition Assume in this part 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 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:

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

ε_{dd} denotes the elasticity of the demand of firm i in equilibrium, when only the price of firm i changes. ε_{DD} denotes the elasticity of the demand of firm i in equilibrium, when all prices change: in particular, we have $\frac{\partial D}{\partial p} = \frac{\partial D}{\partial p_i} + \frac{\partial D}{\partial p_{-i}}$. ε_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 η with price competition.

In our context, if the permit market is not open, $\bar{\alpha}\sigma$ 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 abatement opportunity profit 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 abatement opportunity profit increases with the price of permits and does not depend on the firm's production. The effect of σ on the product market profit depends on the value of \tilde{E} .

The variation of the equilibrium price p_{EP}^* with respect to σ 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 σ 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 σ on the total profit is given by:

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

If $\tilde{E} > 2$, then both the product market profit and the abatement opportunity profit increase with σ . If $\tilde{E} < 2$, then the product market profit decreases with σ , whereas the abatement opportunity profit still increases with σ . As with quantity competition, there exists a threshold value of σ such that the total profit of a firm increases with σ (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 com-

petition, this case is more complicated because a change in the abatement decision y_i resulting from a change in σ 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 σ 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 σ , then the final price p_I^* is increasing with σ , and in contrast, if p_I^* is decreasing with σ , then y^* is increasing with σ .

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

$$\frac{\partial \pi_I^*}{\partial \sigma} = (p_I^* - (\bar{\alpha} - y^*)\sigma) \frac{\partial p_I^*}{\partial \sigma} \frac{\partial D}{\partial p_{-i}} - (\bar{\alpha} - y^*)D, \quad (7)$$

$$= \left(\frac{\varepsilon_{DD}}{\varepsilon_{dd} + \varepsilon_{DD} - \varepsilon_m} (\tilde{E} - 2) (\bar{\alpha} - y^*) + \sigma \frac{\partial y^*}{\partial \sigma} \right) D. \quad (8)$$

From equation (7), we find that if the price decreases with σ , then the equilibrium profit of a firm also decreases with σ (regardless of the value of \tilde{E}). From equation (8), we obtain the comparative statics on profits if the final price is increasing with σ , knowing

then that $\frac{\partial y^*}{\partial \sigma} < 0$:

- If $\tilde{E} < 2$, then the profit is decreasing with σ .
- 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 permit price 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 σ with process-integrated abatement, whereas it may increase with σ with end-of-pipe abatement.

International competition. Assume now that firms compete in quantity again 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 do not have access to abatement and have 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 permit price σ . 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 foreign fringe of 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 σ 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 σ , we obtain the following equation:

$$\frac{\partial Q_{EP}^*}{\partial \sigma} = \frac{C''(q_f^*)}{C''(q_f^*) - P'(Q_{EP}^*)} \frac{\partial Q_{-f}^*}{\partial \sigma} \quad (9)$$

from which we obtain an expression of the effect of σ 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 σ 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 (3), and the first-order conditions for the fringe of firms are the same as those with end-of-pipe abatement. The effect of σ 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 σ 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, however:

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

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.

5 Adjustment of the global pollution cap to entry

In the former section, we have shown that the effect on environmental regulation on the incumbents is contingent 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 that is used in the industry. Nevertheless, the regulator should adapt policy by changing the cap of pollution rather than the level of free allowances for entrants. We analyze this point by doing comparative static of the pollution cap over the number of firms.

In order to emphasize the effect of entry on a regulator's decisions, we focus on the adjustment of the global pollution cap when the regulator implements a Pigovian price of permits, that is, sets σ to be equal to the marginal damage of pollution, not the optimal price of permits. The use of a Pigovian price simplifies the analysis tremendously. We will, however, discuss the use of an optimal permit price at the end of this Section.

Proposition 5. *A regulator's optimal policy toward entry is 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:*

- *reduces or increases the cap of permits available in the industry with end-of-pipe abatement,*
- *increases the cap of permits available in the industry with process-integrated technology.*

Proposition 5 results from the fact that an increase in 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. 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:

$$E_{EP}^*(n, \sigma) = \bar{\alpha} Q_{EP}^*(n, \sigma) - nx^*(\sigma) \quad (10)$$

Given that σ is the Pigovian price and is, therefore, unaffected by n , the effect of the market structure on the emission cap that will be set by the regulator is simply given by:

$$\frac{\partial E_{EP}^*}{\partial n} = \underbrace{\bar{\alpha} \frac{\partial Q_{EP}^*}{\partial n}}_{(+)} - \underbrace{x^*}_{(+)} \quad (11)$$

Even if the regulator only corrects the environmental externality, it should still adapt the cap to entry. We show in Appendix B that the total output Q_{EP}^* increases with the number of firms. The market structure thus has two contradictory effects on the emission cap. The first results from an increase in the level of output and hence of pollution, everything else being equal. The second, in contrast, is due to the increase in total abatement.

On the one hand, when the number of firms increases, the total output Q_{EP}^* increases, which leads to an increase in pollution of $\bar{\alpha} \frac{\partial Q_{EP}^*}{\partial n}$. As a result, for a given cap of permits E , the marginal abatement cost for society increases as more firms enter the market. Since the marginal gain of polluting less is fixed to the marginal damage of pollution, the optimal cap of permits is increasing with n : when a firm enters the market, the regulator wants to apply more lenient environmental regulation.

On the other hand, as we have seen in the previous section, the individual abatement level with end-of-pipe abatement is unaffected by the structure of the market for permits

and only depends on the relationship between the marginal gain of selling permits on the permit market and the marginal cost of abatement, i.e., on σ and γ . When firms use end-of-pipe abatement technology, they always individually abate the same amount of pollution regardless of the number of firms in the market when the permit price is exogenous; then, the aggregate demand for permits decreases with n . Therefore, the equilibrium price of permits decreases with n as well. As a result, for a given cap of permits E , the marginal abatement cost for society decreases as more firms enter the market. The cap of permits if the regulator implements a Pigovian price of permits is thus decreasing with n : when a firm enters the market, the regulator wants to apply more severe environmental regulation.

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

$$E_I^*(n, \sigma) = (\bar{\alpha} - y^*(n, \sigma))Q_I^*(n, \sigma). \quad (12)$$

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

$$\frac{\partial E_I^*}{\partial n} = (\bar{\alpha} - y^*) \frac{\partial Q_I^*}{\partial n} - \frac{\partial y^*}{\partial n} Q_I^*. \quad (13)$$

We show again in Appendix B 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 with process-integrated abatement.

Indeed, as with end-of-pipe abatement, an increase in the number of firms increases total output and thus pollution, everything else being equal. The effect of n on abatement, however, is different with process-integrated abatement than with end-of-pipe abatement. Indeed, 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 in-

creases a firm's market share even more since the market is more concentrated. Firms thus have an incentive to set a lower abatement level y^* as n increases, which increases the aggregate demand for permits. Therefore, the equilibrium price of permits increases with n , and for a given cap of permits E , the marginal abatement cost for society increases with n as well. As a consequence, the optimal cap of permits increases with n : with more firms in the market, the regulator wants to impose a lighter burden on firms.

Thus, when the regulator implements a price of permits equal to the Pigovian tax, the cap of permits 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 caps 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 cap of permits 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 now access to the market.

Discussion We assess the robustness of our results. We first focus on the optimal degree of regulation and then analyze how free allowances for entrants may be used to diffuse technology.

Until now, we have assumed that the permit price is equal to the Pigovian tax. However, since we consider a market 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. Let us assume 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 C that with both end-of-pipe abatement and process-integrated abatement, the optimal permit price is lower than the marginal damage of pollution. This result is frequently found in the literature. Indeed, there are two distortions: (i) the environmental externality and (ii) the distortion on the demand side. However, the regulator has a single instrument at its disposal. Barnett (1980) focuses on the case of a monopoly; Requate (2005) surveys this literature. We show that this result does not depend on the abatement technology. 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.

Now focusing on the comparative statics of the permit price with respect to n , we know that under perfect competition, the optimal permit price is equal to the marginal damage. Therefore, the optimal permit price increases with the number of firms.¹² When the regulator applies optimal regulation, there is an additional effect relative to the implementation of the Pigovian price, which induces the regulator with both end-of-pipe abatement and process-integrated abatement to reduce the pollution cap as the number of firms increases. In other words, the conditions under which the regulator can implement a reserve for entrants are less likely to be fulfilled.

However, the free allowances given to entrants are ordinarily considered a tool for regulators to diffuse technology. This is the case in the European Union, where energy intensive sectors are already well settled and innovation can only be gradual. The reserve for entrants is ordinarily designed to facilitate entry. Thus, the entrants will be able to choose the appropriate level of technology. However, this approach is orthogonal to ours. A reserve for entrants is at the same time an adjustment of the cap to entry

and the free allowances dedicated to entrants. The standard approach in the literature is to have free allowances for entrants and not to adjust the pollution cap to entry. We thus recommend that the pollution cap be adapted to entry if a regulator implements a Pigovian price of permits. However, it is possible to design mechanisms such that the pollution cap is adjusted and entrants receive free allowances. Indeed, the preemption system that we propose may be designed such that allowances are bought by the regulator and given to entrants for free.

6 Conclusion

This paper has two main findings. First, we show that the effect of an environmental regulation depends on the type of abatement technology that is available to firms. In some cases, implementing an environmental regulation may increase profits in the industries subject to the regulation, particularly those of firms using end-of-pipe abatement. This conclusion is consistent with the changes that we currently observe in decision making concerning environmental regulation. In the case of the EU ETS, for instance, 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, will now have to buy 100% of their permits through auctions.

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 current attitude of the European regulator toward entry in polluting industries. Indeed, phase

III of the EU ETS does not include the introduction of a preemption right to reduce the amount of available permits, if necessary. Moreover, entrants will benefit from this reserve depending only on the cleanness of their technologies; however, the type of abatement technology that entrants use should be considered.

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.

Notes

¹Pollution filters are used once 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, developing countries and are thus, by definition, independent of the home firm's production decisions. Carbon capture and storage consist 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.

²Free grandfathered allowances are a means to reduce profit losses, which is necessary for the success of a new cap-and-trade system.

³Note 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.

⁴If firms have asymmetric costs, either of production or of abatement, our result are qualitatively the same, provided these asymmetries are reasonable (i.e. do not lead to corner solutions). More efficient firms simply lose less profits as a result of the cap-and-trade system.

⁵In 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 pollution factors y_i . It is possible to show that our results hold qualitatively with that specification.

⁶Note that the profit can be decomposed into two parts because the abatement cost only depends on the abatement level x_i and not directly on the firm's output q_i .

⁷Sufficient second-order conditions are always satisfied and hence omitted in the following analysis.

⁸The intermediate calculations to obtain to this result are given in Appendix A.1.

⁹Vives (2000) provides a full analysis of this effect.

¹⁰It 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 $\lim_{x \rightarrow +\infty} A(x) = +\infty$.

¹¹When investments are gradual and partial, our results are altered. In the case of end-of-pipe abatement, firms cannot choose the optimal level of abatement, and the activity of abatement is then less profitable. However, in the case of process-integrated abatement, this constraint modifies the coordination between firms, and they then invest less. However, firms will lose less than if they invest at an optimal level. Indeed, they invest in order not to lose market shares. If investment is partial, in the case of process-integrated abatement, firms may lose less.

¹²Under reasonable conditions, the permit price is monotonic with respect to the number of firms.

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Appendix

A Comparative statics with respect to σ

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

A.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 equation (1), 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 σ on the equilibrium profit is given by:

$$\frac{\partial \pi_{EP}^*}{\partial \sigma} = \left(P' \frac{\partial Q_{EP}^*}{\partial \sigma} - \bar{\alpha} \right) q_{EP}^* + (P - \bar{\alpha}\sigma) \frac{\partial q_{EP}^*}{\partial \sigma} + \frac{\sigma}{\gamma}. \quad (14)$$

As σ 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:

$$\partial \left(\frac{\partial \pi_i}{\partial q_i} \right) / \partial \sigma = P'' \frac{\partial Q_{EP}^*}{\partial \sigma} q_{EP}^* + P' \frac{\partial q_{EP}^*}{\partial \sigma} + P' \frac{\partial Q_{EP}^*}{\partial \sigma} - \bar{\alpha} = 0. \quad (15)$$

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 (15) over i and find:

$$\frac{\partial Q_{EP}^*}{\partial \sigma} (P'' Q_{EP}^* + (n+1)P') = \frac{\partial Q_{EP}^*}{\partial \sigma} (\eta + n+1)P' = n\bar{\alpha}. \quad (16)$$

As $x^* = \frac{\sigma}{\gamma}$, this allows us to write equation (14) 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 η :

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

A.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 (3). 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 $Q_I^*(\sigma) = n q_I^*(\sigma)$ 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 $\frac{\partial \pi_I^*}{\partial \sigma}$:

$$\begin{aligned} \frac{\partial \pi_I^*}{\partial \sigma} &= \left[P' \frac{\partial Q_I^*}{\partial \sigma} - (\bar{\alpha} - y^*) + \sigma \frac{\partial y^*}{\partial \sigma} \right] q_I^* + [P - (\bar{\alpha} - y^*)\sigma] \frac{\partial q_I^*}{\partial \sigma} - \beta y^* \frac{\partial y^*}{\partial \sigma}, \\ &= \left[P' \frac{\partial Q_I^*}{\partial \sigma} - (\bar{\alpha} - y^*) \right] q_I^* + [P - (\bar{\alpha} - y^*)\sigma] \frac{\partial q_I^*}{\partial \sigma}. \end{aligned} \quad (17)$$

Deriving $\frac{\partial \pi_i}{\partial q_i}$ with respect to σ 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:

$$\frac{\partial Q_I^*}{\partial \sigma} = \frac{n}{(\eta + n + 1)P'} \left[(\bar{\alpha} - y^*) - \sigma \frac{\partial y^*}{\partial \sigma} \right]. \quad (18)$$

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 (17) by the expression given in (18), we obtain the following expression:

$$\begin{aligned} \frac{\partial \pi_I^*}{\partial \sigma} &= -\frac{\eta + 2}{n + 1 + \eta} \left((\bar{\alpha} - y^*) - \sigma \frac{\partial y^*}{\partial \sigma} \right) q_I^* - \beta y^* \frac{\partial y^*}{\partial \sigma} \\ &= -(\bar{\alpha} - y^*) \frac{\eta + 2}{n + 1 + \eta} q_I^* + \frac{1 - n}{n + 1 + \eta} \frac{\partial y^*}{\partial \sigma} \sigma q_I^*. \end{aligned} \quad (19)$$

From the two expressions of $\frac{\partial \pi_I^*}{\partial \sigma}$ given by equations (17) and (19), we can make some comparative statics:

- If total output is a decreasing function of σ , then equation (17) implies that the equilibrium profit is also a decreasing function of σ .
- If total output is an increasing function of σ , then from equation (19) we see that the effect of σ on π_I^* depends on η :
 - If $\eta > -2$, then π_I^* is decreasing in σ .

- If $\eta < -2$, then the product market profit increases with σ whereas the net gain of additional abatement is negative. The total effect is ambiguous.

B Comparative statics with respect to n

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

B.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:

$$\frac{\partial Q_{EP}^*}{\partial n} = \frac{P' Q_{EP}^*}{n(P'' Q_{EP}^* + (n+1)P')} > 0. \quad (20)$$

B.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 always implies $\frac{\partial Q_I^*}{\partial n} < 0$. It is thus better and more reasonable to keep $P' + \frac{\sigma^2}{\beta} < 0$.

We first deduce from the first order conditions that:

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

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 $Q_I^* = n q_I^*$, 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:

$$\frac{q_I^*}{n} = - \frac{\frac{\partial q_I^*}{\partial n} (\eta + n + 1) P' + \frac{\sigma^2}{\beta}}{(\eta + n) P'}. \quad (21)$$

Since $\eta > -n$ and $P' + \frac{\sigma^2}{\beta} < 0$, it is immediate the $\frac{(\eta+n+1)P' + \frac{\sigma^2}{\beta}}{(\eta+n)P'} > 0$. Thus, as $\frac{q_I^*}{n} > 0$ we have $\frac{\partial q_I^*}{\partial n} < 0$. From this and (3) 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 (21) we have:

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

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 $\sigma = \lambda$:

$$\frac{\partial E_I^*}{\partial n} = -\frac{\partial y^*}{\partial n} Q_I^* + (\bar{\alpha} - y^*) \frac{\partial Q}{\partial n} > 0. \quad (22)$$

C Optimal regulation

We assume then that the regulator maximizes a welfare function and corrects two distortions: the 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, π_i the profit of firm i and RR the regulator's revenue. We analyze then the optimal permits price for each abatement technology.

C.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 σ 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 σ is then given by the first order condition:

$$\frac{\partial W_{EP}}{\partial \sigma} = (P(Q_{EP}^*) - \alpha\lambda)\frac{\partial Q_{EP}^*}{\partial \sigma} - \frac{n}{\gamma}(\sigma - \lambda) = 0. \quad (23)$$

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 absent abatement is simply the sum of the effect of σ 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 σ , as the variation of abatement with σ is $\frac{1}{\gamma}$ regardless of the value of σ ; by contrast, the

marginal cost of abatement increases with σ because of the convexity of abatement costs. Replacing $P(Q_{EP}^*)$ in equation (23) using the first expression in (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 σ_{EP}^{opt} is lower than λ , 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.

C.2 Process-integrated abatement

In the case of process-integrated abatement, the welfare at the product market equilibrium for a given price of permits σ is given by:

$$W_I = \int_0^{Q_I^*} P(Q)dQ - \beta n \frac{(y^*)^2}{2} - \lambda(\alpha - y^*)Q_I^* \quad (24)$$

The optimal value of σ is then given by the first order condition:

$$\frac{\partial W^*}{\partial \sigma} = \frac{\partial Q_I^*}{\partial \sigma} (P(Q_I^*) - \alpha\lambda) - \frac{\partial Q_I^*}{\partial \sigma} y^* (\sigma - 2\lambda) - y^* Q_I^* \frac{\sigma - \lambda}{\sigma} = 0$$

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 σ 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 (24) using the first expression in (3), we obtain:

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

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

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