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Higher Costs for Higher Profits:
A General Assessment and an Application to Environmental Regulations *

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Abstract

We study the effect of a shock on firms' costs in a general setting by considering both perfect and imperfect competition and a general cost function. We show that, counterintuitively, firms' profits may increase with cost increases. We generalize Seade's (1985) results by considering the adaptation of firms' technological process. We find an additional effect that we call "technology effect," and which is determined by the extent to which firms' marginal and average costs differ as a result of a shock. This effect is broken down into two components: the "indirect technology effect," which is related to the elasticity of the demand slope, and the "direct technology effect," which is solely related to technology.

We apply this framework to environmental regulations, which provide a good context in which to examine technological process adaptation because they push firms to use abatement technologies and to modify their production processes. We introduce an explicit abatement cost function that is sufficiently flexible to represent the various types of abatement technologies that are found in the literature: end-of-pipe technology, process-integrated technology, and cleaner production (or fuel switching). We show that end-of-pipe abatement technologies induce a positive direct technology effect, that process integrated abatement technologies induce a negative technology effect, and that cleaner production induces a null technology effect.

JEL Classification: L13, Q53, Q58.

Key words: Cournot oligopoly, Perfect competition, Cost increase, Tax on emissions, Environmental standards, Abatement technologies.

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1 Introduction

Industrial activity is structurally affected by shocks, such as an increase in the price of an input or the implementation of a regulation. Firms react to shocks by modifying their strategies or adapting their utilization of technologies. The common intuition is that profits will decrease as a result of an increase in costs, and various policy implications are based on this intuition. However, several regulatory experiments, such as the implementation of environmental regulations in the electricity sector, have induced a profit increase. Accordingly, determining the conditions under which cost increases may be profitable and the resulting implications for policy is crucial.

In the short run (with a fixed number of firms), positive profits arise from market power or increasing returns to scale. Two independent streams of literature assess the positive effect of a shock on profits by focusing on only one of these two origins of profit. Seade (1985)[31] first established that an increase in firms' constant marginal cost can, counterintuitively, increase their profits when firms compete *à la* Cournot if the slope of the demand function is sufficiently elastic. Indeed, in such a case, the shock helps firms to coordinate to increase their products' prices, and if the slope of the demand function is sufficiently elastic, the price increase outweighs with the reduction in production, leading to a profit increase. Second, several papers show how, under perfect competition and inelastic demand, the change in the cost function due to a shock can increase profits. Nelson (1957)[24] shows that an increase in costs can increase profits in a competitive industry. Salop and Scheffman (1987)[29] and Fuess and Loewenstein (1991)[12] provide other examples in which firms' profits increase as cost curves become steeper.

The first contribution of this paper is to unify these two streams of literature and to propose a general model for assessing the effect of cost increases on profits. Indeed, we determine the conditions under which shocks may be profitable for general demand and cost functions. To do so, we linearize costs by considering equilibrium marginal costs. The condition for the profit-increasing effect, which is the same as that found in the Cournot framework by Seade (1985)[31], includes an additional effect that captures the adaptation of a technological process . We call this effect the technology effect, which is determined by the extent to which firms' marginal and average costs differ as a result of a shock. This "technology effect" is further broken down into two components: the "indirect technology effect," which is related to the elasticity of the demand slope, and the "direct technology effect," which is solely related to the technology. For example, the profits realized by electricity producers during the first phase of the EU-ETS result from a positive technology effect. In an electricity system in which marginal units are more polluting than submarginal units, the direct technology effect is the profit obtained by submarginal "clean" technologies.

The second contribution of this paper is to apply these results to environmental regulations. From a firm's point of view, an environmental regulation, which can take several forms (standards, taxes, quotas, tradable quotas), places a constraint on the use of one of its inputs, a pollutant effluent, which has a subsequent impact on its cost. The political feasibility of an environmental regulation depends on how various economic agents and, particularly, firms are affected. The lobbying capacity of firms explains the specific attention on their profits . Firms may either block a regulation or obtain compensation through free allocations or tax recycling to mitigate the (intuitively) negative impact on their profits. A sufficient understanding of the mechanisms underlying the impact of environmental regulations on firms' profits could facilitate the implementation of environmental regulations and limit such transfers. Moreover, from a theoretical point-of-view, environmental regulations provide a good context in which to examine technological process adaptation, as environmental regulations push firms to use abatement technologies and to modify their production processes. Several types of abatement technologies exist; for instance, firms can reduce emissions by using carbon storage and capture filters or by increasing their energy efficiency. Furthermore, environmental regulations are primarily implemented in oligopolistic sectors, such as the electricity, steel, or cement sectors.

We apply the framework in analyzing environmental regulations. We introduce pollutant emissions and the possibility for firms to reduce their emission rate. The technology effect is related to the interplay between the abatement and production cost, that is, whether an increase in production increases or reduces the marginal abatement cost. Two policy instruments are considered: a tax and a standard (a constraint on firms' emission intensity). Finally, we introduce an explicit abatement cost function that is sufficiently flexible to represent the various types of abatement technologies found in the literature. We consider three archetypal cases: end-of-pipe technology, process-integrated technology, and cleaner production (or fuel switching). We show that end-of-pipe abatement technologies induce a positive direct technology effect, that process-integrated abatement technologies induce a negative technology effect, and that cleaner production induces a null technology effect.

The remainder of the paper is structured as follows: We begin by reviewing the related literature in Section 2. Section 3 proposes a general model for assessing the effect of cost increases on profits. We first introduce the model, then present the effect of a shock on firms' profits, and, finally, describe the technology effect, which is broken down into a direct and an indirect technology effect. Section 4 illustrates the technology effect for several environmental regulatory instruments and various abatement technologies. Section 5 concludes the paper.

2 Relation to the Literature

This paper is related to three strands of literature. The first strand focuses on the counterintuitive profit-increasing effect of a unit cost increase. Since the seminal work of Seade (1985)[31], a body of industrial organization literature has developed on the effect of cost shocks when firms compete *à la* Cournot. Kimmel (1992)[17] focuses on asymmetric marginal costs but identical shocks, and Salant and Shaffer (1993)[28] assume identical (ex-ante) firms but asymmetric shocks. Interestingly, in the environmental economics literature, Kotchen and Salant (2011)[18] obtain results similar to those of Seade (1985)[31] when analyzing the regulation of a common-pool resource and the possible positive effects on firms' profits. In these articles, costs are assumed to be linear (constant returns to scale), and the shock is a uniform increase in each firm's marginal cost, similar to a tax on its output. By contrast, we consider increasing returns to scale and a shock that depends on the quantity produced, which allows firms to adapt their production processes to the change in their environment-or, more precisely, the change in regulation.

The second strand of literature focuses on returns to scale and assumes perfect competition only. Nelson (1957)[24] shows that an increase in costs can increase profits in a competitive industry. Salop and Scheffman (1987)[29] and Fuess and Loewenstein (1991)[12] provide other examples in which firms' profits increase as cost curves become steeper. However, some more recent and applied studies show how, under perfect competition and inelastic demand, the change in the cost function due to a shock can increase firms' profits. Indeed, in the electricity sector, the demand for electricity is inelastic in the short term. Moreover, the implementation of the EU-ETS in Europe has affected more marginal units than submarginal units (nuclear plants were not affected, whereas coal plants were affected considerably). We explicitly show the effect of modifying costs on profits under perfect and Cournot competition.

Third, this paper is also related to the strand of literature on the effect of environmental regulations on profits. Two recent contributions on the effect of environmental regulations in imperfectly competitive industries build on the work developed in the industrial organization literature. Hepburn et al. (2012)[14] determine neutral-profit allowances and show that implementing pollution permits may increase firms' profits when the demand curvature is quite large. They assume that firms are asymmetric with respect to both marginal costs and pollution intensity; however, they do not consider the effect of implementing pollution permits on firms' profits when individual firms can modify their emission intensity or use abatement technologies. Christin et al. (2013)[8] analyze the design of emission permits and show that the effect of a permit price increase on firms' profits depends on the type of abatement technologies that are available. They consider initially constant marginal costs of production and compare two specific abatement technologies (end-of-pipe and process integrated). They show that when environmental regulations are tightened, profits are more likely to increase with an end-of-pipe regulation. We generalize their results by considering a more general framework and an explicit abatement cost function that is sufficiently flexible to represent the various types of abatement technologies that are found in the literature. We then disentangle the various effects.

3 A General Assessment on the Profit-altering Effect of Cost Increases

3.1 The model

Consider a homogeneous good market with an inverse demand function $P(Q)$, where Q is the total quantity produced. The inverse demand function is twice differentiable, positive or null, and strictly decreasing when it is positive, and $P(0) = 0$. Let $E = P''Q/P'$ be the elasticity of the demand slope. Suppose that there are n firms indexed $i = 1..n$, which produce the homogeneous good. The quantity produced by firm $i = 1..n$ is denoted by q_i. The cost of production of firm i is $C_i(q_i, r)$, where r represents a shock. The function C_i is assumed to be strictly increasing and convex with respect to q_i and is assumed to be increasing with the regulatory variable. Assume that firms simultaneously choose their production to maximize their profit. Competition may be either pure and perfect or *à la* Cournot. We assume that $E > -1$, that is,

$$P''(Q) + QP' < 0 \tag{1}$$

This assumption implies that the marginal profit of a firm is decreasing with respect to the production of its rival.[1] Together with the convexity of costs, this assumption ensures that there is a unique Cournot-Nash equilibrium (Novshek (1985)[25] and Amir, 1996[2]). Let $(q_i(r))_i = 1..n$ be the equilibrium production quantities. We assume that these quantities are all strictly positive in all of the cases considered. Thus, all firms are active at the equilibrium.

The effect of the shock on marginal costs. Let $c_i(r)$ be the equilibrium marginal cost for any r:

$$c_i(r) = \frac{\partial C_i}{\partial q_i}(q_i(r), r). \tag{2}$$

Moreover, let γ_i be the effect of r on the marginal cost of firm i, and let $\gamma = \frac{1}{n}\sum \gamma_i$ be the average of the effect of r on the marginal cost for all firms. The effect of the regulation on the marginal cost is equal to:

$$\gamma_i = \frac{\partial^2 C_i}{\partial r \partial q_i} + \frac{\partial^2 C_i}{\partial q_i^2} q_i'.$$

The effect of the shock on the marginal cost comprises the increase in the marginal cost due to the shock directly and the effect via the change in production. The second effect is related to the convexity of the cost with respect to production. For instance, if firm i's production decreases, it is negative.

[1]For $Q > 0$, this assumption implies that $P'(Q) + qP''(Q) < 0$ for all $q \in [0, Q]$, because $P' > 0$.

Firms' profits. The profit of firm i is:

$$\pi_i(q_i, q_{-i}, r) = P(q_i + q_{-i})q_i - C_i(q_i, r). \tag{3}$$

To disentangle the effect of a change in r on the market equilibrium from its effect on firms' costs, we exploit the fact that the equilibrium quantities are determined by the marginal cost and not the total cost with perfect and Cournot competition. Firm i's profit can be written as follows:

$$\pi_i = [P(Q) - c_i(r)]\, q_i + [c_i(r)q_i - C_i(q_i, r)]\,. \tag{4}$$

The profit per output comprises the mark-up and the difference between the marginal cost and the average cost. Let us note that the decomposition of firms' profits is based on the fact that the equilibrium quantities can be expressed as a function of the marginal cost with Cournot and perfect competition. More precisely, the equilibrium quantities $q_i^*(r)$ with costs $(C_i(q_i, r))_{i=1..n}$ are equal to those with constant marginal costs $c_i(r)$, i.e., with the costs $(c_i(r)q_i)_{i=1..n}$. [2]

3.2 The decomposition of the profit-altering effect of cost increases

The previous formulation (4) of firms' profits enables us to isolate two effects of the change from the shock: one effect is related to firms' market power and is present with imperfect competition only, and the second effect is present with both imperfect and perfect competition. With Cournot competition, the two terms of (4) can be analyzed separately, and the calculations of Kimmel (1992)[17] can be reproduced. Let us present these calculations. Each firm chooses its production by maximizing its profit. The equilibrium quantities satisfy the first-order conditions:

$$P + P'q_i = c_i(r). \tag{5}$$

Taking the derivative of this equation with respect to r, we find a relationship between the change in the production of firm i and the change in the total production $Q(r) = \sum q_i(r)$:

$$P'q_i' = \gamma_i - [1 + Es_i]P'Q', \text{ for } i = 1, .., n. \tag{6}$$

Summing these equations (6), we obtain an equation deriving the change in the aggregate production:

[2] If one writes $(x_i(g_1, ..., g_n))_{i=1..n}$, the unique equilibrium quantities with constant marginal costs g_i for each $i = 1..n$, the $c_i(r)$ are the unique solutions of $C_q(x_i(c_1, ..., c_n), r) = c_i$ for $i = 1..n$. The corresponding quantities $x_i(c_1(r)..c_n(r))$ are the unique solutions of the Cournot game with cost $C_i(q_i, r)$. This reasoning is used by Van Long and Soubeyran (2000)[36] to provide a new proof of the existence and uniqueness of Cournot.

$$P'Q' = n\gamma/[n+1+E]. \tag{7}$$

The overall effect of a small change of r on a firm's profit, according to the envelop theorem, is:

$$\frac{\partial \pi_i}{\partial r} = q_i\left[P'\left(Q' - q_i'\right) - \gamma_i\right] + [\gamma_i q_i - \frac{\partial C_i}{\partial r}].$$

Introducing successively (6) and (7) in the previous equation, we obtain:

$$\begin{aligned}
\frac{\partial \pi_i}{\partial r} &= q_i\left[P'Q' + (1+Es_i)P'Q' - 2\gamma_i\right] + [\gamma_i q_i - \frac{\partial C_i}{\partial r}] && (8)\\
&= q_i\left[P'Q' + (1+Es_i)P'Q' - 2\gamma\right] + 2q_i(\gamma - \gamma_i) + [\gamma_i q_i - \frac{\partial C_i}{\partial r}] && (9)\\
&= \frac{P'q_iQ'}{n}\left[E(ns_i - 2) - 2\right] + 2q_i(\gamma - \gamma_i) + q_i\gamma_i - \frac{\partial C_i}{\partial r}. && (10)
\end{aligned}$$

The effect of the shock on firms' profits is presented in the following proposition:

Proposition 1. *In the case of a competition á la Cournot, the profit of firm $i = 1..n$ increases with r if and only if:*

$$\frac{\gamma}{n+1+E}\left[E\left(ns_i - 2\right) - 2\right] + 2\left(\gamma - \gamma_i\right) + \left[\gamma_i - \frac{\partial C_i}{\partial r}\frac{1}{q_i^*}\right] > 0. \tag{11}$$

Proof. From (10) and by replacing $P'Q'$ with the right-hand side of (7) and taking into account that $q_i > 0$, we find that $\frac{\partial \pi_i}{\partial r} > 0$ if and only if (11) is satisfied. □

In the case of Cournot competition, three effects are at stake. The first two effects are similar to those found by Kimmel (1992)[17]. The third effect is the primary contribution of our paper. The first effect depends on the characteristics of the demand function and on the market shares. Consider for a moment symmetric firms. This effect is positive if $E < -2$. If the demand slope is sufficiently elastic, an increase in the marginal cost induces an increase in the mark-up that prevails over the decrease in production. In such a case, the introduction of a shock increases firms' profits because it partly corrects for the lack of coordination among them. This effect is null if demand is linear. If the demand is iso-elastic, this effect is positive if and only if the elasticity of the demand is low. However, in most cases and in the present work, E is assumed to be larger than -1, and the effect of an industry wide common shock on a firm's profit is negative. With heterogeneous firms, the heterogeneity intervenes via the market share s_i, and whether larger firms are affected to a greater extent than small firms by a common increase in marginal costs will depend on the sign of E. For instance, if P is concave, E is positive, and a common shock on a heterogeneous oligopoly could increase large firms' profits and decrease small firms' profits. The second term represents the effect of the asymmetry of the shock. If the marginal cost of a firm is less affected than that of other firms, the effect for this firm is positive because the production of other firms decreases to a greater extent than its production. For instance, if only a subset of firms is regulated by a tax on emissions, the profit of unregulated firms increases. The third bracketed term in equation (11) results from the adaptation of the process production. This term represents the difference between the marginal and average effects of the shock on firms' costs. In such a case, firms' profits may increase or decrease as a result of the tax or standard. We investigate this effect, which we call the technology effect, further. This effect arises from the characteristics of the technology, which have been induced by the shock. If competition is perfect, the market price is equal to the marginal cost of all of the firms and the shock induces the technology effect only. The following proposition determines the technology effect on profits in the case of perfect competition:

Proposition 2. *In the case of perfect competition, the profit of firm $i = 1..n$ increases with r if and only if:*

$$\gamma_i - \frac{\partial C_i}{\partial r}\frac{1}{q_i^*} > 0. \tag{12}$$

Proof. With perfect competition, $p(Q(r)) = c_i(r)$ for all i. Therefore, the first term in (3) is null and, the derivative of the profit of firm i, given by (3) is:

$$\frac{\partial \pi_i}{\partial r} = \left[\gamma_i - \frac{\partial c_i}{\partial r}\right] q_i + \left[c_i(r) - \frac{\partial C_i}{\partial q_i}\right] q_i'$$

The second term is null by the definition (2) of $c_i(r)$. □

Profits may increase with a shock even under perfect competition. This result is similar to those of Salop and Scheffman (1987)[29] and Fuess and Loewenstein (1991)[12]. The result solely depends on the technology effect. Notice that, under price competition with differentiated goods, the technology effect would have been similar but the competition effect would have been different.[3]

3.3 The "technology effect"

At this stage, the technology effect is the difference between the effect of the shock on firms' marginal cost and its average effect on firms' cost (and not its effect on firms' average cost). We decompose the technology effect according to the independency or lack of independency regarding the effect of the shock on firms' output. The technology effect may be then divided as:

$$\underbrace{\left[\frac{\partial^2 C_i}{\partial r \partial q_i} - \frac{\partial C_i}{\partial r}\frac{1}{q_i^*}\right]}_{Direct\quad effect} + \underbrace{\left[\frac{\partial^2 C_i}{\partial q_i^2}\frac{dq_i^*}{dr}\right]}_{Indirect\quad effect}. \tag{13}$$

[3]See Anderson et al. (2001) [1], who study the effect of 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.

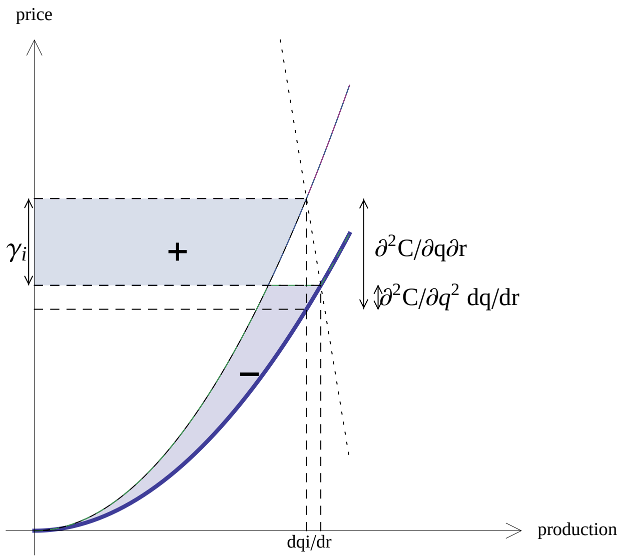

Figure 1: Illustration of a positive technology effect under perfect competition.

Let the first part of the equation be denoted as the direct technology effect, which is related to the adaptation of the technology process. We call the second term the indirect technology effect, which is related to the convexity of cost with respect to output and the adjustment of the firm's production. For the sake of clarity, we illustrate a positive technology effect under perfect competition in Figure 1; both the direct and indirect technology effects are presented. We consider a modification of the marginal cost function and assume that the marginal cost becomes steeper. For any firm with positive production, the marginal cost after the shock is higher than without the shock. In Figure 1, the blue curb is the initial marginal cost, and the black curb represents the marginal cost induced by the shock.

Since the equilibrium marginal cost increases, the equilibrium price is higher and the total production is lower after the shock.

3.3.1 The "direct technology effect"

The direct effect is related to the specificities of firms' induced technology, not firms' adjustment of production. This effect corresponds to the effect of the shock on firms' profit if the demand function were perfectly inelastic. Figure 2 shows this effect. To understand the intuition of the direct technology effect, consider for a moment that the increase in the equilibrium marginal cost results from a tax on output and that demand is inelastic. Under perfect competition, a tax on output has no effect on profits. Indeed, the marginal cost function is then relocated up to a distance of γ_i from the initial function. Thus, the gain due to the price increase (purple surface in Figure 2a) is equal to the loss due to the cost increase (green surface in Figure 2b).

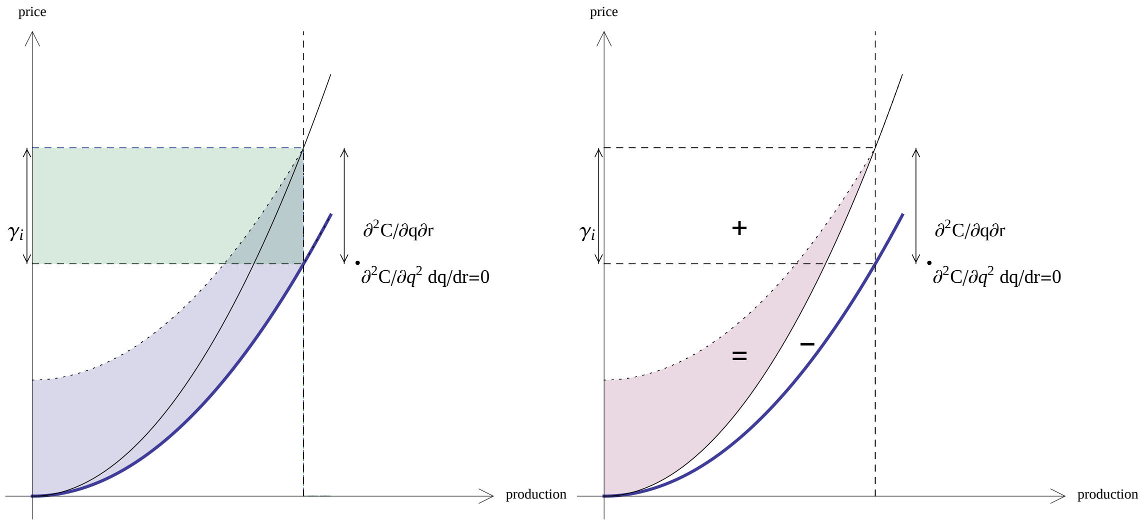

Figure 2: Illustration and decomposition of a positive direct technology effect under perfect competition.

The direct effect is the difference between both surfaces. The effect is then null in the case of a tax on output and inelastic demand. Let us now consider the case in which a shock alters the marginal cost, as in Figure 1. Thus, Figure 2b shows that the direct effect is positive if the shock has a nonuniform effect on the marginal cost, because the marginal cost function is altered by the adaptation of the technological process. In our illustrated case, the gains due to the price increase are higher than the losses due to the cost increase. In other words, a positive direct technology effect occurs because the marginal cost function becomes steeper as a result of the shock and does not relocate up to a distance a γ_i from the initial function.

3.3.2 The "indirect technology effect"

The indirect technology effect is associated with the adjustment of a firm's production. This effect is related to the shape of the demand function and constitutes a bridge between the technology effect, the effect of competition, and the market structure. Let us consider symmetric firms and drop the subscript i to reduce the complexity of the expression: $C_i(q_i, r) = C(q_j, r)$, for all i. Under perfect competition, the equilibrium individual output is the solution of $P(nq) = \partial C/\partial q$, and the change in production is:

$$\frac{dq}{dr} = -\frac{\partial^2 C/\partial q \partial r}{\partial^2 C/\partial q^2 - nP'}; \tag{14}$$

so the indirect cost effect is:

$$\frac{\partial^2 C}{\partial q^2}\frac{dq}{dr} = -\frac{\partial^2 C}{\partial q \partial r}\left[1 - \frac{nP'}{\partial^2 C/\partial q^2}\right]^{-1}. \tag{15}$$

The steeper the price function is, the smaller the change in production is, as shown in Figure 4. With Cournot competition, the situation is relatively similar except that the price function should be replaced by the individual marginal profit: $P + P'q_i$.

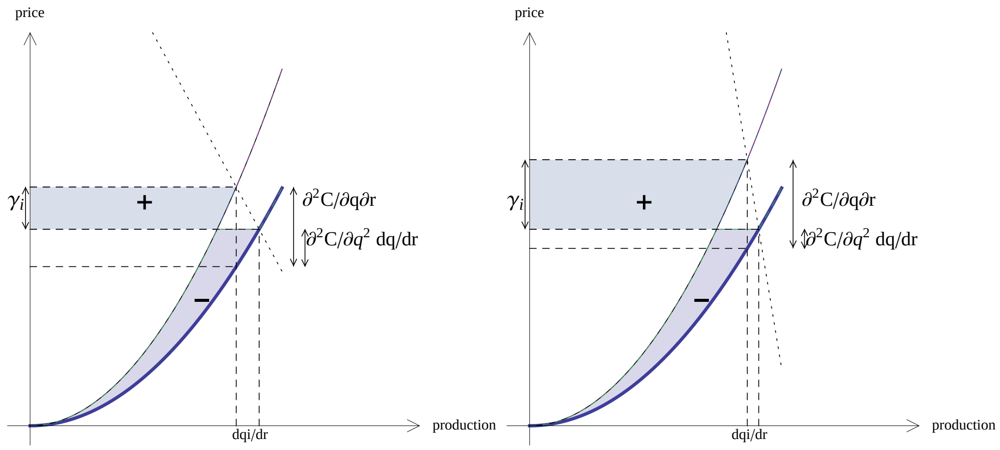

Figure 3: Illustration of the technology effect under perfect competition according to the slope of the demand function. The demand function is more inelastic in the second graphic than in the first one, and the indirect effect is diminished. Thus, the steeper the price function is, the smaller the change of production is.

The change in production is inversely related to the function $-[(n+1)P' + nP''q_i] = -P'((n+1)+E)$ and is increasing with respect to the slope of the price function and the elasticity of this slope.

Let us analyze the case of asymmetric firms. Under perfect competition, the previous results are still valid at the sectoral level; for any shock r, the sector is similar to a single price-taking firm with the cost $C(q,r) = \min\{\sum_i C_i(q_i,r) u.c. \sum q_i \leq q\}$. Equation (14) describes the change in the aggregate sectoral production. However, this aggregate change in production is not equally shared among the firms in the sector, and change in the *allocation* of production among them occurs. This reallocation of production results from the relative changes in marginal costs that followed the shock.

The change in an individual firm's production can be broken down into two parts: one part is proportional to the aggregate change in production, and the second part is related to the reallocation of production among the firms. Even if demand is inelastic and the aggregate production is constant, the change in firms' relative marginal costs affects the allocation of the aggregate production. The first part is related to the price function, whereas the second part is not. At the industry level, the reallocation effects compensate for one another (cf. appendix 4 for a formal presentation).

With asymmetric firms and Cournot competition, the analysis is more complicated, and describing the effects that are precisely at stake under these conditions is beyond the scope of this paper. Indeed, the complications arising from Cournot competition are related to the productive inefficiency of a Cournot oligopoly, that is, the inefficient allocation among firms of the aggregate equilibrium production. The allocation of the aggregate production depends on the allocation of costs and the price function. Therefore, the change in aggregate production is not simply related to the change in the aggregate marginal cost but rather depends on the allocation of production facilities among firms. Furthermore, the reallocation of the aggregate production among firms could not be disentangled from the aggregate change in production and depends on the price function, not merely the change in relative marginal costs.

3.3.3 The overall "technology effect"

The total technology effect comprises the direct and indirect technology effects, and we analyze the sum of these effects. With perfect competition, the total technology effect corresponds to the overall effect of the shock. With Cournot competition, an additional effect should be added. As we previously noticed, if the shock is a tax on the output, the direct effect is null, and the indirect effect is the unique technology effect.[4] We can now analyze the total technology effect with the general formulation $C(q, r)$. We focus first on the case of perfect competition. The following proposition determines the condition under which the total effect is positive.

Proposition 3. *With perfect competition and symmetric firms, $c_i = C$, the overall technology effect is positive or null if and only if:*

$$\frac{\partial^2 C}{\partial r \partial q} - \frac{\partial C}{\partial r}\frac{1}{q_i} \geq \frac{\partial^2 C}{\partial q^2}\frac{1}{q_i}\frac{\partial C}{\partial r}\frac{1}{-nP'}. \tag{16}$$

The output decreases following the shock, and the indirect effect is negative; the effect is increasingly negative as the price function flattens. Therefore, if the price function is sufficiently flat, i.e., the demand is sufficiently elastic, this effect can compensate for the direct cost effect. Conversely, if the direct cost effect is positive, a linear demand function $p(Q) = a - bQ$ can always be parameterized so that the indirect effect is sufficiently small to ensure that the overall effect of the shock on firms' profit is positive. Proposition 3 provides the threshold slope of the price function to ensure that overall effect of the shock on firms' profit is positive . This threshold is inversely related to the direct technology effect and proportional to the slope of the production marginal cost. This slope, together with the slope of the price function, determines the sensitivity of firms' production to a change in firms' marginal cost. With Cournot competition and symmetric firms, a similar proposition could be obtained by replacing nP' by $P'[n + 1) + E$, since the adjustment of firms' production is related to both the slope of the price function and the elasticity of this slope. Furthermore, with Cournot competition, the negative effect due to the reduction in mark-up should be added to analyze the overall effect.

Proposition 4. *With Cournot competition and symmetric firms, $C_i = C$,*

- *the overall technology effect is positive or null if and only if:*

$$\frac{\partial^2 C}{\partial r \partial q} - \frac{\partial C}{\partial r}\frac{1}{q_i^*} \geq \frac{\partial^2 C}{\partial q^2}\frac{\partial C}{\partial r}\frac{1}{q_i}\frac{1}{-P'[(n+1)+E]}, \tag{17}$$

[4] If $C(q, r) = rq + c(q)$, then $\partial C/\partial r = q$, and sothus, $q\partial^2 C/\partial r \partial q = \partial C/\partial r$.

- *and the overall effect on profit is positive or null if and only if:*

$$\frac{\partial^2 C}{\partial r \partial q} - \frac{\partial C}{\partial r}\frac{1}{q_i} \geq \frac{\partial^2 C}{\partial q^2}\frac{\partial C}{\partial r}\frac{1}{q_i}\frac{1}{-P'[(n+1)+E]} + \frac{E+2}{n+1+E}\frac{\partial C}{\partial r \partial q}. \tag{18}$$

As noted previously, the output decreases following the shock, and the indirect effect is negative. The effect described by Seade is also negative with symmetric firms. With a monopoly, condition (18) is never satisfied. More important, with both perfect and imperfect competition, the overall effect is positive only if the direct technology effect is positive.

4 Application to Environmental Regulations

We apply the previous analysis to environmental regulations, which provide a good context in which to examine technological process adaptation, as environmental regulations push firms to use abatement technologies and to modify their production processes. Several types of abatement technologies exist; for instance, firms can reduce emissions by using carbon storage and capture filters or by increasing their energy efficiency. Moreover, from a firm's point of view, an environmental regulation, which can take several forms (standards, taxes, quotas, tradable quotas), places a constraint on the use of one of its inputs, a pollutant effluent, which has a subsequent impact on its cost.

To apply our analysis to environmental regulations, we specify the cost function of firms. Producers' choice of pollution abatement can be represented in several ways. In particular, either relative abatement, i.e., the reduction of emissions per output, or absolute abatement, i.e., the reduction of the total quantity of emissions, can be considered. We consider first relative abatement, but we later consider absolute abatement.

Let μ_0 be a baseline emission rate, and assume that the cost of producing q is related to the emission rate μ. We denote this cost by $\Gamma(q, \mu)$.

4.1 Application to various environmental regulatory instruments

Until now, we have considered a shock r. Here, we illustrate our results in the case of either a tax on emissions or an environmental standard.

Standard. The regulation places a constraint on the emission intensity of firms' production processes. To ensure that costs are increasing with the stringency of the regulatory variable, we assume that $r = \mu_0 - \mu$ is a standard for the reduction of firms' environmental performance. The cost of a firm's production may then be formulated as follows:

$$C(q, r) = \Gamma(q, \mu_0 - r). \tag{19}$$

Tax on emissions. Assume the tax on emissions to be $t = r$. The firm chooses the emission rate based on its production and the tax. The cost of a firm's production may be formulated as follows:

$$C(q, r) = \min_{\mu} \ r\mu q + \Gamma(q, \mu). \tag{20}$$

From now on, we illustrate the direct technology effect according to the various regulatory instruments. The following lemma determines the conditions under which the direct effect is positive:

Lemma 1. *With a standard or a tax, the direct technology effect is positive if and only if:*

$$\frac{1}{q}\frac{\partial \Gamma}{\partial \mu} - \frac{\partial^2 \Gamma}{\partial \mu \partial q} > 0. \tag{21}$$

With both regulatory instruments, the emission rate is reduced: with a standard, it is directly set by the regulation, whereas with a tax, it is endogenously chosen by the firm. In both cases, the sign of the direct technology effect depends on the difference between the effect of an increase in the emission rate on a firm's marginal cost and the average of its effect on the firm's cost. With a standard, the result is a direct application of the definition of the direct technology effect with the cost function (19). With a tax on emissions, the direct effect of the tax on cost is equal to the quantity of emissions, according to Shephard's Lemma; thus, the direct technology effect is the derivative of the emission rate with respect to production. If the emission rate is increasing with respect to production, then an increase of the tax may increase profits. The condition (21) ensures that the emission intensity is increasing with respect to output.

4.2 Application to various abatement technologies

To illustrate the technology effect with various abatement technologies, consider the following explicit representation:

$$\Gamma(\mu, q) = f(q) + (\mu_0 - \mu)^{\alpha} q^{\beta}, \tag{22}$$

where $\beta \geq 0$ and $\alpha > 1$. The total cost may be divided into two parts: (i) the cost that depends on the production $f(q)$ only and (ii) the cost that depends on the reduction in the polluting factor and production. The first part ensures the convexity of the cost function but does not intervene in the direct cost effect. The second part is the *abatement cost*, which is the additional cost required to reduce the emission rate of $(\mu_0 - \mu)$. The two parameters α and β are the elasticities of the abatement cost according to the reduction in the polluting factor and production, respectively, and are important for assessing the sign of the direct cost effect. The problem may be rewritten in terms of absolute abatement. Let $\Delta(k, q)$ be the cost to jointly produce q and reduce emissions by an amount k. The absolute abatement k is relative to a baseline emission level without regulation. If there is no regulation, the cost is $\Delta(0, q)$. Let us assume that in the case of no regulation, with $k = 0$, the emission rate is constant with respect to q and is denoted by μ_0 so $k = (\mu_0 - \mu)q$. The two formulations, in relative terms with Γ or absolute terms with Δ, are formally equivalent, and the two costs are equal: $\Delta(k, q) = \Gamma(\mu_0 - k/q, q)$. Then, the cost Δ is:

$$\Delta(k, q) = f(q) + k^{\alpha} q^{\beta - \alpha}. \tag{23}$$

β may be either larger or smaller than α. In the latter case, an increase in production reduces the absolute abatement cost, and reducing pollution is cheaper when more pollution is produced; this assumption is natural. This formulation allows us to calculate the marginal abatement curve (MAC), which is the derivative of the previous function according to the abatement k. The MAC is then equal to:

$$MAC = \alpha \frac{k^{\alpha-1}}{q^{\alpha-\beta}} \tag{24}$$

The MAC increases with absolute abatement and may decrease or increase with production. Now, we can analyze the primary abatement technologies. In the economics literature, the two extreme cases of abatement technologies are end-of-pipe and process-integrated abatement (see Requate (2005)[27]). However, some variations from these extreme cases exist. Let us focus on three abatement technologies, which are presented in Table 1:

(i) **End-of-pipe** abatement occurs after the process of production. For instance, firms may install filters to reduce emissions. However, this abatement technology does not modify the production process. Therefore, the marginal production cost should be independent of the relative abatement. Moreover, the MAC should be independent of production. Thus, end-of-pipe abatement can be modeled with equality of both elasticities: $\beta = \alpha > 1$:

$$\Gamma = f(q) + [(\mu_0 - \mu)q]^{\alpha}.$$

(ii) **Process-integrated** abatement or an environmental investment corresponds to a fixed cost to reduce the polluting factor. Thus, the marginal production cost in terms of relative abatement should be constant. This abatement technology can be modeled as $\beta = 0$ and $\alpha > 1$. The use of this abatement technology could be interpreted as an investment $(\mu_0 - \mu)^{\alpha}$, as it reduces the polluting factor:

$$\Gamma = f(q) + (\mu_0 - \mu)^{\alpha}.$$

(iii) **Cleaner production**, as examined in Fisher (2001), or fuel switching modifies both the polluting factor and the marginal cost of production. For instance, an electricity company may switch between gas and coal. Gas is less polluting but more expensive. In this case, the cleaner a technology is, the higher its marginal cost is. Cleaner production technology can be modeled as $\beta = 1$ and $\alpha > 1$:

Abatement technologies	Modelling assumptions	Marginal cost of production	Cost in function of abatment k	MAC
End-of-pipe abatement	$\beta = \alpha$	$f'(q) + \alpha(\mu_0 - \mu)^\alpha q^{\alpha-1}$	$\Gamma(k) = f(q) + k^\alpha$	$\alpha k^{\alpha-1}$
Process integrated abatement	$\beta = 0$	$f'(q)$	$\Gamma(k) = f(q) + (\frac{k}{q})^\alpha$	$\alpha \frac{k^{\alpha-1}}{q^\alpha}$
Cleaner production	$\beta = 1$	$f'(q) + (\mu_0 - \mu)^\alpha$	$\Gamma(k) = f(q) + \frac{k^\alpha}{q^{\alpha-1}}$	$\alpha(\frac{k}{q})^{\alpha-1}$

Figure 4: Classification of the abatement technologies.

$$\Gamma = f(q) + (\mu_0 - \mu)^\alpha q.$$

We now illustrate the direct technology effect according to the type of abatement technology used. The sign of the direct technology effect, under the formulation (22) of the cost, is given by the following corollary:

Corollary 1. *When the cost function is given by (22), with either a standard or a tax, the direct technology effect is positive if and only if $\beta > 1$.*

The result is surprisingly simple. As noted in Lemma 1, with both instruments, the sign of the direct technology effect is determined by the difference between the effect of a reduction in the emission rate on a firm's marginal cost and its average effect the firm's cost. When $\beta = 1$, these two effects are equal because the abatement cost for a given emission intensity is proportional to production. When $\beta > 1$, the part of the cost due to the abatement increases at a higher rate than does production, and the direct technology effect is thus positive. The results are summarized in the Table 2. When the technology is end-of-pipe, the technology effect is positive. However, with cleaner production, the direct technology effect is null, and with process-integrated abatement, the direct technology effect is negative.

We now illustrate the overall technology effect with the following lemma. :

Corollary 2. *With perfect competition, if the cost is given by (22),*

- *if $\beta \leq 1$, firms' profit decreases as the regulatory strength r increases.*
- *if $\beta > 1$, firms' profit increases with a standard if:*

$$-nP' \geq \left[f'' + \beta(\beta - 1)(\mu_0 - \mu)^\alpha q^{\beta-2}\right] \frac{1}{\beta - 1}. \tag{25}$$

Abatement technologies	References	Modelling assumptions	Direct technology effect
End-of-pipe abatement	Christin & al (2013)[8] Montero (2002)[23]	$\beta = \alpha$	> 0
Process integrated abatement	Christin & al (2011)[8] Requate (2005)[27] Amir & Nannerup(2005)[3] Hepburn & al (2012)[14] Ulph (1997)[35]	$\beta = 0$	< 0
Cleaner production	Fisher (2001)[11] Meunier & Ponssard (2010)[22] Quirion (2007)[26]	$\beta = 1$	$= 0$

Figure 5: Classification of the abatement technologies and sign of the direct technology effect.

and firms' profit increases with a tax if:

$$-nP' \geq \left[f'' + \frac{\alpha - \beta}{\alpha - 1}(\beta - 1)(\mu_0 - \mu)^\alpha q^{\beta - 2} \right] \frac{\alpha - 1}{\beta - 1} \frac{\mu}{\mu_0 - \mu}. \tag{26}$$

With either a standard or a tax, the threshold slope of the price function is positively related to $f''(q)$, which represents the slope of the marginal production cost net of the abatement cost. In both cases, the slope of the total marginal cost (the first factor of the right-hand sides of inequalities (17) and (18)) is the sum of f'' and a second term related to the abatement cost. With a standard, this second term is positive and is the second-order derivative of the relative abatement cost with respect to q. With a tax, the second term is different because the emission rate is endogenous. With an endogenous emission rate, the slope of the marginal cost is lower than with a fixed emission rate ($(\alpha - \beta)/(\alpha - 1)$, which is lower than β if $\beta > 1$). Thus, the second component is negative if $\beta < \alpha$.

4.3 Policy implications

Several policy implications can be drawn from the application of our analysis to environmental regulations. The political feasibility of an environmental regulation depends on how various economic agents and, particularly, firms are affected. The lobbying capacity of firms explains the specific attention on their profits . Even if firms do not block the implementation of an environmental regulation, they can lobby to obtain compensation for the effects of the regulation. Indeed, firms often accept a regulation because they are granted free allocations or allowed to use tax recycling to mitigate the (intuitively) negative impact of the regulation on their profits. The funding left to compensate the consumers of the pollutant good, who are negatively affected through an increase in the price of the pollutant good, depends on regulators' ex-ante appreciation of the effect of the regulation on firms' profits. Moreover, regulators should consider the available abatement technologies, market structure, and demand characteristics when making policy regarding subsidies. Therefore, such policy should be sector based and may be determined on a geographical scale. To conclude, a better understanding of the profit-altering effect of environmental regulations would facilitate the implementation of environmental regulations and possibly alleviate the burden of environmental regulations on consumers.

Finally, the application in this paper offers new insight for the literature on voluntary agreements. Firms may decide to implement a regulatory instrument themselves to reduce emissions. Two strands of the literature on voluntary agreements focus on (i) the characteristics of demand and (ii) the threat of regulation. First, several articles examine green consumption and use models of product differentiation (Arora et Gangopadhyay (1995)[5] and Besley et Ghatak (2007)[6]). Second, firms may anticipate regulation and thus make voluntary agreements. Voluntary agreements are made when they are less costly than the regulations that would have otherwise been implemented (Manzini et Mariotti (2003),[19] Segerson et Miceli (1998)[32], Glachant (2007) [13], Maxwell et al. (2000)[20] and Heyes (2005)[15]). This article shows that even without green consumption or a regulatory threat, voluntary agreements may be made. If an environmental regulation is profitable, firms have an incentive to promote voluntary agreements. In other words, voluntary agreements may help firms to coordinate in order to jointly decrease emissions and increase profits. Competition authorities must then closely monitor voluntary agreements.

5 Conclusion

This study has examined the effects of a shock on firms' costs in a general setting with both perfect and imperfect competition and a general cost function. The effect of such a shock was found to differ from the effect of a tax on output because of a "direct technology effect," which arises from the difference between the effect of the shock on marginal costs and the average effect of the shock.

This analysis has been used to consider the profitability of environmental regulations and the role played by the type of abatement technology. Abatement technologies allow firms to modify the emission rate of their production processes, and their ability and incentive to do so depend on the quantity of emissions produced. The interplay between the production process and the abatement cost determines the sign of this effect and the potential profitability of the regulation. Archetypal cases of abatement technologies have been presented and studied with a flexible specification.

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6 Appendix

Proof of Proposition 2

With perfect competition, firms are price takers and the equilibrium productions $q_i(r)$ are the solutions of the n equations: $P(\sum_i q_i(r))) = \frac{\partial C_i}{\partial q}(q_i, r)$. Let us denote $c_i(r) = \frac{\partial C_i}{\partial q}(q_i(r), r)$. With perfect competition these are all equal to $P(\sum_i q_i(r))$. The first term of the profit (4) is null, and the effect of a marginal increase of r on the second term is $\gamma_i q_i + c_i(r) q^{i\prime}(r) - \frac{\partial C_i}{\partial r}(q_i, r) - \frac{\partial C_i}{\partial q_i}(q_i, r) q^{i\prime}$ which is $\gamma_i \frac{\partial C_i}{\partial r}(q_i, r)$.

Illustration of technology effect under Cournot competition

Asymmetric firms

With perfect competition let consider the sectoral production cost:

$$\mathcal{C}(Q, r) = \min \left\{ \sum_i C_i(q_i, r) / \sum_i q_i = Q \right\} \tag{27}$$

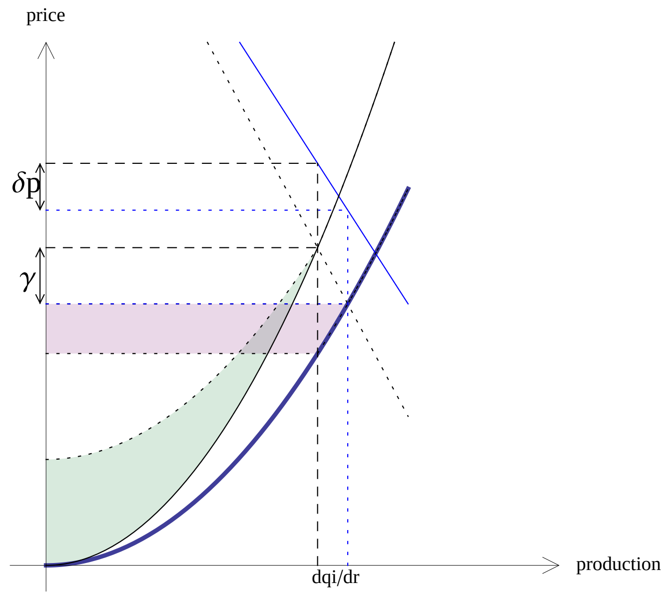

Figure 6: Illustration of a positive technology effect under Cournot competition.

Let us denote $(\phi_i(Q,r))_i$ the solution of the minimization problem, this allocation satisfies the n equations:

$$\forall i \in 2, n, \frac{\partial C_i}{\partial q}(\phi_i, r) = \frac{\partial C_1}{\partial q}(\phi_1, r), \sum_i \phi_i = Q.$$

First, the aggregate costs first order derivatives are simply related to the individual firms ones. The marginal aggregate cost is equal to the individual ones: $\forall i, \frac{\partial \mathcal{C}}{\partial Q}(Q,r) = \frac{\partial C_i}{\partial q}(f_i, r)$. The effect of a change of r on the aggregate cost is the sum of its effect on individual firms: $\frac{\partial \mathcal{C}}{\partial r}(Q,r) = \sum_i \frac{\partial \mathcal{C}}{\partial r}(\phi_i, r)$.

Second, the second order derivatives $\frac{\partial^2 \mathcal{C}}{\partial Q^2}$ and $\frac{\partial^2 \mathcal{C}}{\partial Q \partial r}$ could also be expressed in terms of individual ones. Taking the derivative of $\frac{\partial C_i}{\partial Q}(f_i, r)$ with respect to Q gives: $\frac{\partial^2 \mathcal{C}}{\partial Q^2}(Q,r) = \frac{\partial C_i}{\partial q^2}(\phi_i, r)\frac{\partial \phi_i}{\partial Q}$, and summing over all i,

$$\frac{\partial^2 \mathcal{C}}{\partial Q^2}(Q,r) = \left(\sum 1/\frac{\partial^2 C_i}{\partial q^2}\right)^{-1}.$$

And concerning the effect of r,

$$\frac{\partial^2 \mathcal{C}}{\partial Q \partial r}(Q,r) = \sum_i \frac{\partial^2 C_i}{\partial q \partial r}\frac{\partial \phi_i}{\partial Q} = \frac{\partial^2 C}{\partial Q^2}\sum_i \frac{\partial^2 C_i}{\partial q \partial r}/\frac{\partial^2 C_i}{\partial q^2}.$$

Third, the derivatives of ϕ_i are

$$\frac{\partial \phi_i}{\partial Q} = \frac{\partial^2 \mathcal{C}}{\partial Q^2}/\frac{\partial^2 C_i}{\partial q^2}, \text{ and } \frac{\partial \phi_i}{\partial r}(Q,r) = \left(\frac{\partial^2 \mathcal{C}}{\partial Q \partial r} - \frac{\partial^2 C_i}{\partial q \partial r}\right)/\frac{\partial^2 C_i}{\partial q^2}.$$

For any r, the market equilibrium can be described in two steps. The aggregate production satisfies the market clearing equation: $P(Q(r)) = \frac{\partial \mathcal{C}}{\partial q}(Q(r), r)$. And the individual productions correspond to the efficient allocation among firms of this quantity: $q_i(r) = \phi_i(Q(r), r)$.

At the aggregate level, taking the derivative of the market clearing equation:

$$Q'(r) = -\frac{\partial^2 \mathcal{C}}{\partial q \partial r} / \left(\frac{\partial^2 \mathcal{C}}{\partial q \partial q} - P' \right).$$

And at the individual level:

$$q_i'(r) = \frac{\partial \phi_i}{\partial Q} Q' + \frac{\partial \phi_i}{\partial r}.$$

The second term is the reallocation effect, it is independent of the demand function and related to cost characteristics.

Proof of Proposition 3

We drop the subscript i for ease of exposition in this proof. The individual production is q and the aggregate one $Q = nq$. At equilibrium $p(nq) = \partial C / \partial q$. From Proposition 1, an increase of r increases profit if and only if:

$$\frac{\partial^2 C}{\partial q^2} \frac{dq}{dr} + \left[\frac{\partial C^2}{\partial q \partial r} - \frac{1}{q} \frac{\partial C}{\partial r} \right] > 0.$$

Then injecting the expression of dq/dr gives

$$\frac{\partial C^2}{\partial q \partial r} - \frac{1}{q} \frac{\partial C}{\partial r} > \frac{\partial^2 C / \partial r \partial q}{1 - nP' / (\partial^2 C / \partial q^2)},$$

then

$$\frac{-nP'}{\partial^2 C / \partial q^2} > \left[\frac{\partial C^2}{\partial q \partial r} - \frac{1}{q} \frac{\partial C}{\partial r} \right]^{-1} \left[\frac{\partial^2 C}{\partial r \partial q} - \left(\frac{\partial C^2}{\partial q \partial r} - \frac{1}{q} \frac{\partial C}{\partial r} \right) \right].$$

The Proposition 3 follows.

Proof of Proposition 4

With Cournot competition and symmetric firms, the individual production is the unique solution of

$$P(nq) + P'(nq).q = \frac{\partial C(q, r)}{\partial q} \tag{28}$$

the calculations done with perfect competition could be reproduced but $P(Q)$ should be replaced by $P(Q) + P'(Q)Q/n$, differentiating the latter gives:

$$P' \frac{n+1}{n} + P'' \frac{Q}{n} = \frac{P'}{n} [n + 1 + E].$$

and replacing P'/n by the above expression in (16) gives (17).

Concerning the overall effect some more calculations are required. Starting from equation (11), the overall effect is positive if:

$$-\gamma\frac{E+2}{n+1+E}+\left[\gamma-\frac{\partial C}{\partial r}\frac{1}{q}\right]\geq 0$$

The effect of r on the individual production is:

$$q'=\frac{\partial^2 C/\partial r\partial q}{\partial^2 C/\partial q^2-(n+1+E).P'} \tag{29}$$

Therefore:

$$\left[\gamma-\frac{\partial C}{\partial r}\frac{1}{q}\right]=\left\{-\frac{\partial^2 C}{\partial q^2}\frac{\partial C}{\partial r}\frac{1}{q}-P'(n+1+E)\left[\frac{\partial^2 C}{\partial q\partial r}-\frac{\partial C}{\partial r}\frac{1}{q}\right]\right\}\left[\frac{\partial^2 C}{\partial q^2}-P'(n+1+E)\right]^{-1} \tag{30}$$

and

$$-\gamma\frac{E+2}{n+1+E}=\frac{E+2}{n+1+E}\left[\frac{\partial^2 C}{\partial q\partial r}(-P'(n+1+E)\right]\left[\frac{\partial^2 C}{\partial q^2}-P'(n+1+E)\right]^{-1} \tag{31}$$

Injecting (30) and (**??**) into (29) gives (18).

Proof of Lemma 1

Let $\Gamma_i(q_i,\mu)$ denotes the cost to produce q with an emission rate μ.

If the regulator fixes a standard, he fixes the emission rates μ, and the regulation is represented by μ_0-r, where μ_0 is the average, across firms, of the emission rate when there is no regulation. The production cost of a firm in that case is

$$C_i(q_i,r)=\Gamma_i(q_i,\mu_0-r).$$

The direct technology effect is:

$$\frac{\partial^2 C_i}{\partial q\partial r}-\frac{\partial C_i}{\partial r}q_i=-\frac{\partial^2\Gamma_i}{\partial q\partial\mu}+\frac{\partial\Gamma_i}{\partial\mu}\frac{1}{q_i}.$$

Therefore, the direct technology effect is positive if and only if

$$-\frac{\partial^2\Gamma_i}{\partial q\partial\mu}q_i\geq-\frac{\partial\Gamma_i}{\partial\mu}.$$

If the regulator fixes a tax r on emissions the production cost of firm i is:

$$C_i(q_i,r)=\min_{\mu} r\mu q_i+\Gamma_i(q_i,\mu).$$

And the emission rate that minimizes the firm cost for a production q_i is $\mu_i(q_i, r)$ the solution of

$$rq = -\frac{\partial \Gamma_i}{\partial \mu}(q_i, \mu_i). \tag{32}$$

The derivatives of C_i with respect to the tax is the quantity of emissions: $\partial C_i/\partial r = \mu_i(q_i, r)q_i$, so, the cross derivative is $\partial^2 C_i/\partial q \partial r = \mu_i + \partial \mu_i/\partial q$, and the direct technology effect is

$$\frac{\partial^2 C_i}{\partial q \partial r} - \frac{\partial C_i}{\partial r}\frac{1}{q_i} = \frac{\partial \mu_i}{\partial q}.$$

Then, from (32),

$$\frac{\partial \mu_i}{\partial q} = -(r + \frac{\partial^2 \Gamma_i}{\partial q \partial \mu})/\frac{\partial^2 \Gamma_i}{\partial \mu \partial \mu}.$$

Replacing r with the equation (32), the direct technology effect is

$$\frac{\partial^2 C_i}{\partial q \partial r} - \frac{\partial C_i}{\partial r}\frac{1}{q_i} = \left(\frac{\partial \Gamma^2}{\partial q \partial \mu} - \frac{1}{q}\frac{\partial \Gamma}{\partial \mu}\right)\frac{1}{\partial^2 \Gamma/\partial \mu^2} \tag{33}$$

and using the fact that $\partial^2 \Gamma_i/\partial \mu^2 > 0$, the direct technology effect is positive if and only is:

$$-\frac{\partial^2 \Gamma_i}{\partial q \partial \mu} q \geq -\frac{\partial \Gamma}{\partial \mu}.$$

Proof of Corollary 1

If the cost function is given by (22), the derivatives are:

$$\frac{\partial \Gamma}{\partial q} = f' + \beta(\mu_0 - \mu)^\alpha q^{\beta-1}, \text{ and } \frac{\partial \Gamma}{\partial \mu} = -\alpha(\mu_0 - \mu)^{\alpha-1} q^\beta;$$

and the second order derivatives:

$$\frac{\partial^2 \Gamma}{\partial q \partial \mu} = -\alpha\beta(\mu_0 - \mu)^{\alpha-1} q^{\beta-1}.$$

The direct technology effect has the sign of $-q\partial^2\Gamma/\partial q \partial \mu + \partial \Gamma/\partial \mu = \alpha(\beta - 1)(\mu_0 - \mu)^{\alpha-1} q^\beta$. The direct technology effect is strictly positive if $\beta > 1$. It is null if $\beta = 1$. Finally, if $\beta < 1$, the direct technology effect strictly negative.

Proof of Corollary 2

The first part of the Corollary 2 is straightforward because the indirect technology effect is always negative.

To prove the second part, we determine the derivatives of the cost with both a standard and a tax.

- With a standard, the cost is $C(q,r) = f(q) + r^\alpha q^\beta$, therefore

$$\frac{\partial C}{\partial r} = \alpha r^{\alpha-1} q^\beta, \frac{\partial^2 C}{\partial q \partial r} = \alpha \beta r^{\alpha-1} q^{\beta-1}, \frac{\partial C^2}{\partial q^2} = f'' + \beta(\beta-1) r^\alpha q^{\beta-2};$$

plugging these expressions into the right hand side of the inequality (16) of Proposition 3 gives the threshold:

$$\left[f'' + \beta(\beta-1) r^\alpha q^{\beta-1}\right] \frac{1}{\beta-1}.$$

- With a tax, the cost is given by (20). The first order derivatives are $\partial C/\partial r = \mu q$ and $\partial C/\partial q = f' + t\mu + \beta(\mu_0 - \mu)^\alpha q^{\beta-1}$ and the second order derivatives:

$$\frac{\partial^2 C_i}{\partial q \partial r} = \mu_i + \frac{\partial \mu_i}{\partial q}$$

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