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Abstract

The present paper addresses two policy objectives that the environmental regulator aims to accomplish: to implement a market for permits and make regulation acceptable for businesses. Profit-neutral permit allocations are defined as the number of permits that the regulator should give for free so that profits after regulation (i.e. profits that the firm realizes in the market for products plus the value of the allowances granted for free) are equal to profits before regulation. The paper demonstrates that a low number of free allowances is sufficient to meet these two goals. Moreover, even when the reduction is high, the regulator can fully offset losses if the concerned sectors are not in a monopoly context. The suggested model is developed by assuming that firms compete "à la Cournot", use polluting technologies and the demand function is iso-elastic. It is then illustrated by the first two phases of the EU Emissions Trading System.

Keywords: Pollution permits, Cournot oligopoly, EU-ETS.

Classification JEL : F18 ; H2 ; L13; L51; Q2.

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1 Introduction

Since 2005, the EU has set up the European Emission Trading Scheme (EU-ETS), a large cap and trade system to enforce its international commitments to reducing CO2 emissions. The first two phases (2005-2007 and 2008-2012) were characterized by the distribution of free allocations, the use of grand-fathering allocations and a weak percentage of emission reduction. These mechanisms induced an increase in profits but also generated competitive losses and leakage - i.e. the substitution of emissions from environmentally regulated countries to countries without effective environmental policies. In light of these results, the EU decided to revise the allocation rules for its third phase (2013-2020). While abandoning grand-fathering allocations in favor of innovative measures of distribution linked with production capacities, the EU has nevertheless kept the same percentage of emission reduction by fear that increasing exigencies in terms of emission reduction would not have been accepted by firms. This positioning is highly problematic since it has been proven that emission reductions must be of a drastic nature to respond to climate change issues (IPCC (2014) [11]). A key question that the EU therefore must tackle is to find a way to make more stringent environmental policies acceptable to firms.

Indeed, it appears crucial to secure firms' acceptance of environmental regulation to preempt them from lobbying against their application or limit their enforcement. Here, the regulator faces a participation constraint with the need to induce firms to support environmental regulation by protecting their profits but also needs ensuring the finality of regulation, i.e. effective emission reduction. To reconcile acceptability for the businesses concerned with the strengthening of EU environmental policy, a different approach could involve retaining grandfathering while also introducing higher emission reductions.

Implementing pollution permits means imposing price on emissions so that emitting pollution becomes costly. As a result, firms pass-through the marginal cost increase to their products' prices, while production is reduced. Profits ordinarily decrease with the implementation of pollution permits. However, grandfathering (being a lump-sum transfer from the regulator to firms) could therefore be used to offset losses in profits.

The criterion applied to determine the conditions whereby firms will not oppose regulation is profit-neutral permit allocations. Profit-neutral permit allocations are defined as the number of permits the regulator should give for free so that profits after regulation (ie. profits that the firm realizes in the market for products plus the value of the allowances granted for free) are equal to profits before regulation. Profit-neutral allowances should be understood as an upper bound. Indeed, granting more allowances induces an increase in profits relative to the case without regulation while the product price increases. This situation may appear unfair since firms benefit from regulation while consumers are worse off. This paper aims to determine the maximum amount of permits to grant for free while satisfying the participation constraint. To do so, it analyzes the relation between the profit-neutral permit allocations and the emission reduction in a partial equilibrium framework.

The EU-ETS covers oligopolistic sectors (such as cement, electricity and steel) concerning more than three thousand firms.[1] However, some firms predominate in the market for permits, but the three biggest emitting firms - RWE, E.ON and Vattenfall - represent respectively only 7.1%, 4.7 % and 4.2% of the total amount of emissions. Even power companies are not big enough to manipulate alone the permit price.[2] Hence it is assumed that firms are price-takers in the market for permits even if they are price-makers in the markets for products. The paper, considering a Cournot oligopoly subject to a market for permits, assesses the conditions under which the regulator can offset losses in profits.

Hintermann (2013) [10] demonstrates that the pass-through may be higher than 100% for the electricity sector, which justifies the use of an isoelastic demand function. Indeed, only both an isoelastic function and weak elasticity may induce pass-through higher than 100%. The paper also considers that the regulator reduces emissions by applying a reducing factor, such that the total amount of emissions after regulation is equal to the initial emissions multiplied by the reducing factor. A low value of the reducing factor denotes an important reduction while a high value will amount to a weak reduction. This is the approach used by policy makers, who first determine the percentage of emission reduction and then set pollution

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

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

caps. The paper further assumes that firms can only abate pollution emissions by reducing production. The aim of the paper is to determine an upper bound for the required number of free allowances which offset losses in profits. If abatement technology is available, firms will reduce their quantities less and will not suffer so much from the introduction of environmental regulation. This assumption is discussed further in the paper (section 4.4).

Five major theoretical findings result from the study. First, the paper analyses in which cases free allowances are not required on the ground of profit neutrality. When demand is isoelastic and the elasticity of demand is weak, profits increase with the permit price since the pass-through is higher than 100%. In such a case, the profit-neutral percentage of permits is determined according to the percentage of emission reduction. The paper shows that the number of free allowances required to neutralize profits decreases with the number of firms. Indeed, profit-neutral allowances depend on two effects: first, the gain due to the lump-sum transfer from the regulator to firms and second the modification of profits due to the introduction of pollution permits. The first effect does not depend on market structures while the total losses in profits decrease with the number of firms.

These results are consistent with Hepburn et al (2013)[8] who examine the impact of pollution permits on equilibrium emissions, output, price, market concentration, and profits in a generalized Cournot model. They identify a formula for the number of emission permits that have to be freely allocated to firms to neutralize the impact on profits of pollution permits and show that it is lower than the Herfindahl index. Considering an exogenous permits price, the authors also demonstrate that in some cases free allowances are not required on the ground of profit neutrality. The present paper is complementary to Hepburn et al (2013)[8] since it endogenizes the permit price and analyzes the profit-neutral policy according to the level of emission reduction.

The second contribution of this paper relatively to Hepburn et al (2013)[8] is to highlight the constraint met by the regulator: the number of free allowances should be lower than the number of permits put into circulation.[3] If not, the permit price would be equal to zero. Hepburn et al (2013)[8] find that, on the basis of profit-neutrality, an industry may receive

[3]This condition is equivalent to the percentage of permits lower than one hundred percent.

more permits than it needs, but do not identify in which cases it occurs since they assume an exogenous permit price. In the present paper, it is shown that the regulator cannot offset the firms' losses in case of either a monopoly or a duopoly with high reductions. To go further, the level of reduction that a regulator could set when his goal is to offset losses in profits in order to obtain the firms' assent is determined. A crucial policy implication can be induced from this finding: the regulator may implement more stringent regulations even when the main constraint is firms' participation.

Third, the paper reconciles efficiency with acceptability - two streams of literature that are usually analyzed separately - by offering a unique analysis of profit-neutral allocations under optimal regulation. It assesses the percentage of emission reduction that maximizes welfare (social surplus minus environmental damage) and analyzes under what conditions the regulator can both offset losses in profits and implement the optimal policy. As in the case of an exogenous percentage of emission reduction, the paper shows that acceptability is not reachable in the case of monopoly. In addition, the more firms there are, the higher will be the marginal damage under which the regulator will be able both to implement the optimal percentage of emission reduction and offset losses in profits.

Fourth, in the case of international competition, unilaterally implementing pollution permits induces a loss of competitiveness and generates leakage. The paper establishes what percentage of reduction of the total amount of emissions is feasible, i.e. until what percentage the regulation does not push domestic firms out of the market. Then it focuses on the feasible cases and analyzes whether offsetting losses in profits is possible. The paper suggests that if elasticity is sufficiently weak (which is the case in the steel and cement sectors), the regulator can offset losses in profits by giving allowances for free. Another major finding is that if it is possible to offset losses in profits for a certain level of reduction, it will always be possible to offset losses in profits for a more stringent and feasible regulation.

Finally, extending the analysis to a market for permits covering several sectors, the paper assesses how different sectors are altered by the implementation of pollution permits. This is the first study in the literature, except Nicolai & Zamorano (2014)[16], to consider both several sectors and a percentage of reduction instead of fixing a pollution cap. It is found that the distribution of the emission reductions between sectors depends on the relative magnitude of both elasticities of demand and the ratios of marginal cost over emission intensity. Consider for instance two sectors. When the two elasticities of demand are the same, the sector which has the lowest ratio of marginal cost over emission intensity reduces in proportion to the level of emissions. The intuition is as follows: the higher the initial pollution is, the higher the cost to reduce the first emission will be. For the same reason, when the two ratios are equal, the sector with the higher elasticity reduces in proportion with emissions. This finding allows the gap between the partial equilibrium results and the numerical illustration to be bridged.

The paper also illustrates the overall findings with the first two phases of the EU-ETS, considering three main sectors: electricity, steel and cement. The latter two are exposed to international competition while the first is not. The framework retained here allows two different ways of offsetting losses in profits to be considered: uniform and sector-based distribution of free allowances, as successively chosen by the EU. In the first two phases of the EU-ETS, the distribution of permits was uniform among sectors whereas the third phase introduced a distinction amongst sectors and, for instance, permits in the electricity sector were auctioned. The results are as follows: first, if the regulator uses a uniform policy of distribution (the same grandfathering rate), 20% of permits would be necessary. These figures, which are far from the 99% of permits given for free during the first period, show that the lobbying power of firms is high in Europe. Indeed, the difference between the percentage retained by the EU and the percentage which offsets losses in profits represents the fraction of permits that the regulator gives without any justification on the ground of profit neutrality, and is thus a good indicator of lobbying power. This illustration is consistent with the literature showing that in Europe no more than 50% of permits given for free is enough to obtain profit neutrality (Demailly & Quirion (2006)[3], Bovenberg & Goulder (2001)[2], Grubb & Neuhoff (2006)[7]).[4] The present paper differs from these previous studies in that it assesses sector based distribution with a high percentage of emission reduction. Hence, it shows that if the policy of distributing free allowances was sector-based, 10% of permits would have been sufficient to offset firms' losses

[4]Goulder & al(2010)[6] consider that giving 20% is enough to neutralize the profits of all US industries.

during the first two phases of the EU-ETS. In such a case, the required number of permits is extremely low. It can be deduced from this figure that the lobbying power is even greater. Moreover, it can be shown that in cases under which the total level of emissions is reduced by 10% and 20%, the percentage of total allowances that the regulator should give uniformly for free is respectively equal to 23% and 28%, which therefore increases the percentage of emission reduction and keeps the regulation acceptable for firms.

The remainder of the paper is structured as followed. Section 2 presents the modeling assumptions. Section 3 focuses on a single sector not exposed to international competition. Section 4 analyzes the robustness of the model, extends the paper to several sectors, and considers successively the presence of international competition, the possibility to abate emissions and optimal regulation. Section 5 applies the findings to the first two phases of the EU-ETS. Section 6 concludes.

2 The Model

The present section introduces the model.

Firms. There are n symmetric firms competing in a market and producing a homogenous good. The production technology is polluting. Let c be the marginal cost and assume that the emissions intensity is equal to f. In other words, one unit of production generates f units of pollution. Firms cannot abate emissions except by reducing production. The emission intensity indicates how polluting a sector is. Firms compete "a la Cournot", simultaneously choosing their quantity to maximize profits.

Consumers. Assume an iso-elastic demand function. Let β be the elasticity of the demand. Firms face a demand given by:

$$P(Q) = \alpha Q^{-\frac{1}{\beta}} \quad with \quad Q = \Sigma_{i=1}^{n} q_i, \tag{1}$$

where α is the market size.

Assumption 1. $\beta > 1/n$. Assumption 1 states that elasticity is higher than $\frac{1}{n}$ and it is shown below that this ensures the existence of the equilibrium.

Moreover, in order to be realistic enough, assume that the elasticity of demand is lower than 10. Note that an iso-elastic demand function has an interesting and crucial property for the issue of how profits are altered by the implementation of a regulation. A constant elasticity demand ensures the potential profit-increasing effect of a cost increase, which appears in the general demand framework. This potential profit-increasing effect cannot occur with linear demand. Policy makers ordinarily use linear demand, which prevents them from considering this potential profit-increasing effect that has generated a major strand of the IO literature.[5]

Regulation. In order to cut down pollution, the regulator implements a market for permits. A firm has to own a permit in order to pollute one unit. Firms are price-takers in the market for permits. The permit price is denoted by σ and clears when the supply equals the demand. Total emissions, when the permit price is equal to σ, are equal to $fQ(\sigma)$. The goal of the regulator is to reduce emissions with a reducing factor z, such that

$$fQ(\sigma) = zfQ(0), \tag{2}$$

where $0 < z < 1$. The emissions before the regulation are denoted by $Q(0)$. Note that low values of z denote high emission reductions. The number of permits put into circulation is equal to $zfQ(0)$.

3 Profit-neutral allocations

The regulator distributes free allowances ε_i to firm i and auctions the remaining permits. Profits may be written as the sum of the profits in the market for products and the gain due to free allowances.

$$\pi_i(\sigma) = (p(Q) - c - f\sigma)\, q_i + \varepsilon_i \sigma.$$

[5] See a survey of this literature in Meunier & Nicolaï (2013) [14].

Since allowances are grandfathered, they are only a lump-sum transfer from the regulator to the firms and they do not affect the firms' decisions. However, free allowances do increase the firms' profits. Let us then define the profit-neutral allowances.

Definition 1. *The profit-neutral allowances ϵ_i^N are defined as the number of free allowances that would level out the firms' profits with or without environmental regulation: $\pi_i(0) = \pi_i(\sigma) + \epsilon_i^N \sigma$.*

First, it is shown that the effect of the implementation of a market for permits on profits is of second order whereas the effect of free allowances on profit is of first order. Secondly, the number of profit-neutral allowances, i.e. the number of free allowances that would level out the firms' profits with or without the environmental regulation, is determined.

Let us first deal with profit in the market for products. The perceived marginal cost is equal to the sum of the marginal cost of production and the permit price weighted by emission intensity. At symmetric equilibrium, all firms produce the same. The quantities produced, the product price and the mark-up rate are given by:

$$q_i(\sigma) = \frac{1}{n}\left(\frac{\alpha(\beta - 1/n)}{\beta(c + f\sigma)}\right)^{\beta}, \qquad p(\sigma) = \frac{c + f\sigma}{1 - 1/(n\beta)}, \qquad \frac{p(\sigma) - c - f\sigma}{c + f\sigma} = \frac{1}{n\beta - 1}.$$

Quantity decreases with the permit price, emission intensity and the marginal cost. Furthermore, the pass-through decreases with the number of firms and elasticity. When elasticity is sufficiently high ($\beta > 1$), production increases with demand elasticity while the price decreases with the latter. When elasticity increases, firms reduce the price of products since consumer demand decreases and consequently firms increase production.

The profit of firm i is given by:

$$\pi_i(\sigma) = \left(\frac{1}{n}\right)^{\beta+1}\left(\frac{\alpha}{\beta}\right)^{\beta}\left(\frac{n\beta - 1}{c + f\sigma}\right)^{\beta-1}. \tag{3}$$

The profit of firm i increases with the permit price when the elasticity of demand is weak (< 1), and decreases otherwise. This result will be explained once the equilibirum permit price has been determined.

The equilibrium on the market for permits is now introduced. The aggregate demand for permits is equal to the total amount of permits firms need and that have not been granted for free, that is, $fQ(\sigma) - \Sigma_{i=1}^{n}\varepsilon_i$. The total supply is the number of permits that the regulator is ready to sell, that is, $zQ(0) - \Sigma_{i=1}^{n}\varepsilon_i$. Thus, the perfectly competitive permits market clears when supply equals demand, or:

$$fQ(\sigma) - \Sigma_{i=1}^{n}\varepsilon_i = zfQ(0) - \Sigma_{i=1}^{n}\varepsilon_i \Leftrightarrow fQ(\sigma) = zfQ(0).$$

Note that the permit price is independent of the way permits are distributed. Free allowances decrease supply and the demand in the same way. Thus, grandfathered free allowances modify neither the firms' decisions, nor the equilibrium permit price.

Lemma 1. *The equilibrium permit price does not depend on the market structure and increases with the marginal cost and the reducing factor. It also decreases with emission intensity and is equal to:*

$$\sigma = (z^{-\frac{1}{\beta}} - 1)\frac{c}{f}. \tag{4}$$

The permit price decreases with the reducing factor z and increases with the marginal cost. Note that reducing total production by a factor z is equivalent to implementing a marginal cost equal to $z^{-\frac{1}{\beta}}$ multiplied by the initial marginal cost.[6] The permit price is equal to the difference between this targeted marginal cost and the initial marginal cost.

Another interpretation is that firms choose the level of reduction of production in order to equalize the permit price and the marginal abatement cost.[7] The marginal abatement cost is equal to $(z^{-\frac{1}{\beta}} - 1)\frac{c}{f}$. A rise of z denotes that the environmental policy is less stringent and induces an increase in supply. A rise of the marginal cost generates a lower initial production. The lower the initial quantity is, the higher the cost to reduce one unit will be. For the same reasons, the permit price increases with demand elasticity since initial production decreases

[6]The demand function is equal to $P(Q) = \alpha Q^{-\frac{1}{\beta}}$. Thus, in order to reduce production until $zQ(0)$ the price of products should be multiplied by $z^{-\frac{1}{\beta}}$. Since the product price is linear with the marginal cost, the latter sould be equal to $z^{-\frac{1}{\beta}}$ multiplied by the initial marginal cost.

[7]Since there is no abatement technology, the abatement cost is the cost to reduce production.

with the latter. The higher production is, the lower will be the cost of abating the first unit. When emission intensity increases or the marginal cost of production increases, emissions increase. Furthermore, the higher initial emissions are, the lower will be the cost of abating the first unit.

The permit price does not depend on the market structure since the reduction in production is relative and firms are symmetric. If a cap is implemented instead of a reducing factor, the permit price would depend on market structures. Note that the individual gain of firms due to free allowances does not depend on the number of firms. Profits may then be determined and written as a function of the reducing factor:

$$\pi_i(z) = \left(\frac{1}{n}\right)^{\beta+1} \left(\frac{\alpha}{\beta}\right)^{\beta} (n\beta - 1)^{\beta-1} \left(z^{-\frac{1}{\beta}} c\right)^{1-\beta}. \tag{5}$$

The following Lemma indicates how profits are altered by the implementation of a market for permits.

Lemma 2. *The effect on profits of the introduction of a market for permits depends on both elasticity of demand and the market structure:*

(i) Profits decrease with the reducing factor when the elasticity of demand is weak (< 1), and increase otherwise.

(ii) When elasticity of demand is high (> 1), losses in profits for a firm decrease with the number of firms and are proportional to $1/n^2$.

(iii) When elasticity of demand is high (> 1), total losses in profits decrease with the number of firms and are proportional to $1/n$.

Point (i) states that reducing total production with a reducing factor z is equivalent to multiplying profits by $z^{1-\frac{1}{\beta}}$. Profits increase when demand elasticity is weak (< 1), and decrease otherwise. This phenomenon is well known from Seade (1985)[19]: when elasticity is sufficiently low, implementing a tax on production leads to increasing profits.[8] The permit

[8] According to Seade (1985)[19], profits increase when the elasticity of the slope of demand is higher than two if marginal cost is constant. Note that the elasticity of the slope of demand is constant with an iso-elastic demand function and equal to the inverse of the elasticity.

price helps firms to coordinate so as to decrease production and consequently boost the product price. This case corresponds to a passthrough higher than 100%. In such a case, free allowances should not be given on the ground of profit neutrality.

Point (ii) states that when the elasticity of demand is sufficiently high (> 1), profits decrease if competition is imperfect. Free allowances are then required to offset losses. For instance, under perfect competition, profits are equal to zero. In the case of a monopoly, profit decreases with the implementation of the market for permits. Losses in profits for a firm decrease with the number of firms. The larger the number of firms, the lower individual profits will be. Moreover, the losses will be higher all the more so as the sum of initial profits is high.

Point (iii) states that total losses in profits decrease with the number of firms. Such a result is well known in the literature and explains why firms have incentives to enter into cartels. Indeed, the sum of profits decreases with the number of firms and the losses will be higher all the more so as initial profits are high.

Now, consider the case in which the elasticity of demand is sufficiently high ($\beta > 1$). In other words, let us focus on the case whereby profits decrease with the permit price. Profit-neutral allowances, which level out the firms' profits with or without environmental regulation(ϵ_i^N), are given by:

$$\begin{aligned}\epsilon_i^N &= \frac{f}{(n\beta - 1)} \left(\frac{1 - z^{1-1/\beta}}{z^{-1/\beta} - 1} \right) q_i(0) \\ &= f(\frac{1}{n})^{\beta+1}(\frac{\alpha}{\beta})^{\beta}(n\beta - 1)^{\beta-1} \left(\frac{1 - z^{1-1/\beta}}{z^{-1/\beta} - 1} \right) c^{-\beta}.\end{aligned}$$

Profit-neutral allowances decrease with the number of firms. Indeed, profit-neutral allowances depend on two effects; (i) the gain due to the lump-sum transfer from the regulator to firms and (ii) the modification of profits due to the introduction of pollution permits. The first effect does not depend on market structures while total losses in profits decrease with the number of firms. Moreover, neutral profit allowances increase with the initial level of production and consequently with initial emissions. The higher individual production is, the higher individual profit will be as also the higher the losses induced by implementation of the market for permits. Profit-neutral allowances decrease with the reducing factor. An increase in the reducing factor implies a decrease in the permit price and a reduction of losses in profits.

Let us then define the profit-neutral ratio of free allowances and the profit-neutral grand-fathering rate.

Definition 2. *The profit-neutral ratio of free allowances is defined as the profit neutral allowances over permits, i.e.* $\gamma_p = \frac{n\epsilon_i^N}{fQ(\sigma)}$.[9] *The profit-neutral grand-fathering rate is defined as the profit neutral allowances over initial emissions, i.e.* $\gamma_{gf} = \frac{n\epsilon_i^N}{fQ(0)}$.[10]

The characteristics of the profit-neutral policy are given by the following proposition.

Proposition 1. *If elasticity is high (> 1), in order to keep profits at their levels without regulation, the ratio of free allowances over permits (γ_p) and the grandfathering rate (γ_{gf}), are given by:*

$$\gamma_p = \frac{1}{n\beta - 1}\left(\frac{z^{-1} - 1}{z^{-\frac{1}{\beta}} - 1} - 1\right), \qquad \gamma_{gf} = \frac{1}{(n\beta - 1)}\left(\frac{1 - z^{1-1/\beta}}{z^{-1/\beta} - 1}\right).$$

Let us first deal with the required ratio of free allowances over permits. The profit-neutral percentage of permits decreases with the reducing factor, $\frac{\partial \gamma_p}{\partial z} < 0$. A rise in the reducing factor denotes that environmental policy is less stringent and consequently the permit price is lower. The ratio of free allowances over permits should be higher to offset losses.

Figure 1 represents the percentage of free allowances to give for free to offset losses in profits according to the percentage of emission reduction and the number of firms, for an elasticity of demand equal to 2. Note that the percentage of free allowances diminishes rapidly with the number of firms.

As with the required percentage of permits, the profit-neutral grandfathering rate decreases with the number of firms. However, note that the profit-neutral grand-fathering rate increases with the reducing factor,

$$\frac{\partial \gamma_{gf}}{\partial z} = \gamma_p + z\frac{\partial \gamma_p}{\partial z} > 0.$$

[9] The percentage of permits freely given which neutralizes profits is equal to 100 multiplied by γ_p.

[10] Since firms are symmetric, $\gamma_{gf} = \frac{\epsilon_i^N}{fq_i(0)}$ and $\gamma_p = \frac{\epsilon_i^N}{fq_i(\sigma)}$.

The profit-neutral grandfathering rate is equal to the reducing factor multiplied by the ratio of free allowances over permits that offsets losses. Thus, two effects should be considered when the regulator increases the reducing-factor: (i) increasing the reducing factor induces an increase in the number of permits and consequently an increase in the grandfathering rate ($\gamma_p \frac{\partial z}{\partial z} > 0$), (ii) increasing the reducing factor induces a decrease of losses in profits and consequently a decrease in the percentage of permits to be given for free ($z \frac{\partial \gamma_p}{\partial z} < 0$). The first effect is of the first order while the second is of the second order. For this reason, profit-neutral allowances increase with the reducing factor, since they are equal to the initial production multiplied by the profit-neutral grandfathering rate.

The grandfathering rate should be lower than the reducing factor and the ratio of free allowances over permits (γ_p) should be lower than one. Otherwise, firms will receive more free allowances than there are permits in circulation. In such a case, firms have no incentive to reduce pollution and the permit price will be equal to zero. Both conditions are obviously equivalent.[11] When the constraint is not respected, the regulator cannot fully offset losses. The conditions under which compensation is possible are now determined. From the previous results, the following proposition is deduced:

Proposition 2. *Let $\overline{z}(\beta, n)$ be the reducing factor that the regulator can reach giving all permits for free and neutralizing profits. For each (z, β, n), if $z < \overline{z}(\beta, n)$, offsetting is not possible. The threshold, for $\beta < 10$ is such that:*

(i) $\frac{\partial \overline{z}}{\partial \beta} > 0$ *and* $\frac{\partial \overline{z}}{\partial n} < 0$.

(ii) When n=1, $\overline{z}(\beta, 1) > 1$.

(iii) When n=2, $0.3 > \overline{z}(\beta, 2)$.

(iv) When $n > 2$, $\overline{z}(\beta, n) < 0.2$.

The regulator cannot offset the losses generated by the implementation of a market for permits in the case of a monopoly. The losses suffered by a monopoly are too significant to

[11] In fact, $\frac{\varepsilon_i}{q_i(0)} < z \Leftrightarrow \frac{\varepsilon_i}{q_i(\sigma)} < 1$.

be compensated. This result is coherent with Hepburn, Quah & Ritz (2013)[8], who consider the case of the monopoly and also show that it receives more free allowances than it needs permits. The threshold $\overline{z}(\beta, n)$ decreases with the number of firms. For instance, in the case of a duopoly, for very high reductions in emissions, the regulator cannot fully compensate firms. From a policy point of view, this proposition is crucial. Even when the reduction is high, the regulator can only offset losses fully when the sectors are not in a monopoly or a duopoly context. Thus, the regulator may be more ambitious when he chooses the reducing factor even if he wants to obtain the firms' assent.

Recall that the first two phases of EU-ETS were characterized by all allowances being given for free to firms. Let then $z_{\pi_{FA}} = \frac{\pi(\sigma)+q_i f \sigma}{\pi(0)}$ be the profit-altering factor when all permits are given for free. This is equal to:

$$z_{\pi_{FA}} = z(1 + n\beta(z^{-1/\beta} - 1)).$$

From the previous equation, the following proposition is deduced.

Proposition 3. *The profit-altering factor, when all permits are given for free, increases with the number of firms.*

As previously, this result derives from the two effects that are at stake; The effect on profits (negative in most cases) decreases with the number of firms while the gain due to free allowances does not depend on the market structure. Moreover, the more competitive firms are, the lower will be the profit before implementation. Sijm, Neuhoff & Chen (2006)[20], Grubb & Neuhoff (2006)[7] and Demailly & Quirion (2006)[2] show that implementation of the EU-ETS has induced a profit increasing effect. According to them, this phenomenon comes from passthrough and the gain due to free allowances. This strand of literature focuses on absolute profit increase while this paper is concerned with relative profit increase. Thus, this result is complementary to this theory and Proposition 3 shows that the role of the market structure is crucial to explain the relative increase in profits; The competitive sectors benefit proportionately more than the others do.

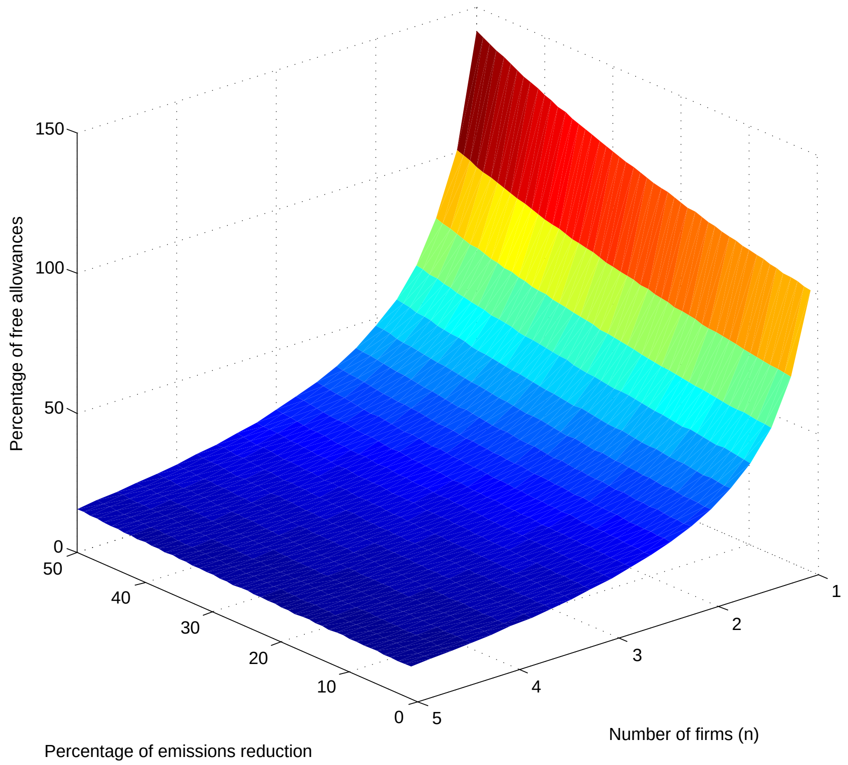

Figure 1: The percentage of free allowances over permits for $\beta = 2$.

4 Extensions

The main assumptions of the paper are: a single sector, absence of international competition, no abatement technology and an exogenous factor of emission reduction. In this section, these four assumptions are relaxed and the robustness of the previous results is analyzed.

4.1 Multi-sector market for permits

In what follows two sectors called A and B covered by the same market for permits are considered. Inside each sector, all firms are symmetric. A sector j is characterized by elasticity β_j, size of demand α_j, marginal cost c_j, number of firms n_j and emission intensity f_j. The goal of the regulator is now assumed to be to reduce global emissions by a factor z, such that $f_A Q_A(\sigma) + f_B Q_B(\sigma) = z\,(f_A Q_A(0) + f_B Q_B(0))$. Firms are price-takers in the market for permits. Firms take into account the permit price σ as exogenous. The effective marginal cost is equal to the sum of the marginal cost of production and the permit price weighted by emission intensity. Let $z_A = \frac{Q_A(\sigma)}{Q_A(0)}$ and $z_B = \frac{Q_B(\sigma)}{Q_B(0)}$ be respectively the induced emission-reducing factors of sector A and sector B.

At the symmetric equilibrium, as in Section 3, the quantities of a firm i of sector j produced and the product price for the same sector are given by:

$$q_{ij}(\sigma) = \frac{1}{n_j}\left(\frac{\alpha_j(\beta_j - 1/n_j)}{\beta_j(c + f_j\sigma)}\right)^{\beta_j}, \qquad p_j(\sigma) = \frac{c_j + f_j\sigma}{1 - 1/(n_j\beta_j)}. \tag{6}$$

On the market for permits, the aggregate demand for permits is equal to the total number of permits firms need and that have not been granted for free. Thus, the perfectly competitive permits market clears when supply equals demand, or:

$$\begin{aligned} & f_A Q_A(\sigma) + f_B Q_B(\sigma) = z\,(f_A Q_A(0) + f_B Q_B(0)) \\ & \Rightarrow f_A Q_A(0) * (z_A - z) + f_B Q_B(0) * (z_B - z) = 0. \end{aligned}$$

From the previous equation, remark that one reducing factor is obviously lower than the whole economy reducing factor whereas the other is higher. Moreover, as in Section 3, the permit price is independent of the ways permits are distributed. The approach here is different from the previous section. The goal is not to determine the permit price but to determine the sector-based reductions in each sector. The latter for the sector j is given by:

$$z_j = \frac{Q_j(\sigma)}{Q_j(0)} = \left(\frac{1}{\frac{f_j}{c_j}\sigma + 1}\right)^{\beta_j}.$$

Firms choose the level of reduction of production in order to equalize the permit price and the marginal abatement cost.[12] The marginal abatement cost is equal to $(z_j^{-\frac{1}{\beta_j}} - 1)\frac{c_i}{f_j}$. However, all firms make decisions based on the same permit price. Indeed, the goal of a market for permits is that firms may trade permits until they equalize the marginal abatement costs. Therefore, each reducing factor may be rewritten as a function of the second one.

$$\sigma = (z_A^{-\frac{1}{\beta_A}} - 1)\frac{c_A}{f_A} = (z_B^{-\frac{1}{\beta_B}} - 1)\frac{c_B}{f_B} \Rightarrow z_B = ((z_A^{-\frac{1}{\beta_A}} - 1)\frac{c_A f_B}{c_B f_A} + 1)^{-\beta_B}.$$

From the previous results, the following proposition is deduced.

Proposition 4. *When $\beta_A = \beta_B$, $c_A = c_B$ and $f_A = f_B$,*

$$\frac{\partial z_A}{\partial \beta_A} < 0, \qquad \frac{\partial z_A}{\partial c_A} > 0, \qquad \frac{\partial z_A}{\partial f_A} < 0.$$

Since there is no abatement technology, a multi-sector market for permits is equivalent to several independent markets for permits with different reducing factors. When both elasticities are the same, the sector which has the lowest ratio of marginal cost over emission intensity reduces proportionately the more emissions. The intuition is as follows. The higher the initial pollution is, the higher will be the cost to reduce the first emission. For the same reason, when both ratios are the same, the sector which has the higher elasticity proportionately reduces more emissions.

To come back to the profit-neutral allocation issue, it is possible to give more free allowances than permits to a monopoly if the other sectors are oligopolistic and if the number of initial

[12]Since there is no abatement technology, the abatement cost is the cost to reduce production.

emissions in the other sectors is sufficiently high. However, if all sectors are characterized by a monopoly, it will be impossible to offset losses in profits. Moreover, a uniform distribution (the same grandfathering rate) generates transfer across sectors, from the more polluting to the less polluting. This point will be illustrated in Section 5 .

4.2 International competition and unilateral regulation

Assume two geographical areas H and F. Trade between the two zones is permitted, and there is no trade barrier. However, transportation from one area to another is costly. Firms bear a unit transportation cost denoted by τ. Assume that there are $n = n^H + n^F$ firms producing a homogenous good, where n^{BH} and n^{BF} are, respectively, the number of domestic and foreign firms. To reduce pollution, the regulator implements a market for permits in the domestic area. Assume that the demand function is still isoelastic and that $\beta > \frac{1}{n_H+n_F}$. As previously, this assumption ensures the existence of an equilibrium. For the sake of simplcity, assume that emission intensity is equal to one.

The regulator reduces global emissions by a factor z. This approach is close to reality where scientists detail from which percentage the emissions should drop in order to avoid irreversibily damaging the environment. This allows it to be determined under what conditions a country may reach acceptability and world-wide objectives. Finally, to what extent international competition prevents the regulator from offsetting of losses in profits is analyzed.

Domestic firms should own pollution permits to produce, while foreign firms are not subject to this regulation. The individual quantities produced by domestic and foreign firms are given in equilibrium by:

$$\begin{aligned} q_{i,H} =& (\frac{\alpha}{\beta})^\beta \frac{((n_F+n_H)\beta-1)^\beta}{(n_H(c+\sigma)+n_F\tau)^{\beta+1}} \left(\beta n_F\tau + (1-n_F\beta)(c+\sigma)\right), \\ q_{i,F} =& (\frac{\alpha}{\beta})^\beta \frac{((n_F+n_H)\beta-1)^\beta}{(n_H(c+\sigma)+n_F\tau)^{\beta+1}} \left(\beta n_H(c+\sigma) + (1-n_H\beta)\tau\right). \end{aligned}$$

Obviously, domestic production decreases with the permit price while foreign production increases. The implementation of pollution permits induces an increase in foreign emissions.

Now consider the equilibrium on the market for permits. The perfectly competitive permits market is such that total emissions are equal to z times initial total emissions, i.e. $Q_H(\sigma) + Q_F(\sigma) = z(Q_H^{\varnothing} + Q_F^{\varnothing})$. The following lemma determines and analyzes the equilibrium permit price.

Lemma 3. *The permit price decreases with the number of domestic firms and increases with the foreign market structure. The permit price is equal to*

$$\sigma = (z^{-\frac{1}{\beta}} - 1)(c + \frac{n_F}{n_H}\tau).$$

The main difference with the result of the equilibrium permit price in Section 3 is that the permit price depends on domestic and foreign market structures. The higher the number of domestic firms, the lower the permit price will be. The higher the number of foreign firms, the higher the permit price will be. Indeed, initial production in the domestic area depends positively on the number of foreign firms and negatively on the number of domestic firms. As previously, the higher the initial production is, the higher will be the equilibrium permit price.

The percentage of reduction that the regulator should apply in the domestic area in order to reduce emissions by a factor z is determined. Let $z_H = \frac{Q_H(\sigma)}{Q_H(0)}$ be the emission-reducing factor of the domestic quantities. This is given by:

$$z_H = z\left(1 - \frac{1}{n_H}\frac{((n_F + n_H)\beta - 1)}{(\frac{1}{n_F} - \beta)\frac{c}{\tau} + \beta}(1 - z^{\frac{1}{\beta}})\right).$$

The emission-reducing factor, that the regulator implements to decrease total emissions by a factor z, decreases with the number of foreign firms and increases with the number of domestic firms. Indeed, the more domestic firms there are, the less the permit price and then the higher the domestic emission reducing factor will be. Moreover, the more foreign firms there are, the higher the permit price and also the lower the domestic emission reducing factor will be.

Obviously the emission-reducing factor should be positive and we define the thresold $\tilde{z}_H$, such that $z > \tilde{z}_H$ implies $z_H > 0$. This threshold is given by:

$$\tilde{z}_H = \left(1 - \frac{n_H(\frac{1}{n_F} - \beta)\frac{c}{\tau} + \beta)}{(n_F + n_H)\beta - 1)}\right)^{\beta}.$$

The regulator cannot reduce total emissions by a factor z lower than $\bar{z}_H$. Let us assume in the following that $z > \tilde{z}_H$. The threshold decreases with the number of foreign firms. If $\beta < \frac{1}{n_F}$, the threshold decreases with the marginal cost and increases with the transportation cost. Otherwise, the threshold increases with the marginal cost and decreases with the transportation cost.

The existence of international trade, in addition to penalizing countries through the implementation of permit markets, led to a shift in pollution from one area to another. This carbon leakage, or "leakage," is defined by the UNFCCC[13] as the increase in emissions in countries that did not ratify Annex B of the Kyoto Protocol. Carbon leakage can be interpreted in the short run as a substitution between local and foreign production. Let $z_F = \frac{Q_F(\sigma)}{Q_F(0)}$ be the leakage factor, which is equal to:

$$z_F = z\left(1 + \frac{1}{n_H}\frac{((n_F + n_H)\beta - 1)}{\beta\frac{c}{\tau} + \frac{1}{n_H} - \beta}(1 - z^{\frac{1}{\beta}})\right).$$

The leakage factor increases with the number of foreign firms. Indeed, the more firms there are, the less individual foreign production and the more the increase of total foreign production will be. When the transport cost is higher than the domestic marginal cost of production, the leakage factor will increase with the number of domestic firms. As previously, the less individual foreign production is and the higher leakage will be.

Let $z_{\pi_i} = \frac{\pi_i(\sigma)}{\pi_i(0)}$ be the profit-altering factor of the area j. This i is equal to:

$$z_{\pi_i} = z^{-1-\frac{1}{\beta}} z_i^2. \tag{7}$$

The relative modification of domestic profits depends on the elasticity of demand and the

[13]The United Nations Framework Convention on Climate Change (UNFCCC or FCCC).

domestic emission-reducing factor. From equation (7), the conditions under which environmental regulation leads to a profit-increasing effect for domestic firms are given by the following lemma.

Lemma 4. *There is one threshold β_H with $\beta_H < 1$ such that:*

(i) If $\beta < \beta_H$, then domestic firms benefit from environmental regulation. On the ground of the profits neutrality criterion, no free allowances should be given.

(ii) If $\beta > \beta_H$, the profits of domestic firms decrease. On the ground of the profits neutrality criterion, free allowances should be given to domestic firms.

The condition for an increase in profits without free allowances is more constraining in the case of international competition. Indeed, even when elasticity is weak, foreign firms capture a part of demand resulting from the product price increase. The elasticity which ensures a profit-increasing effect of the implementation of pollution permits is obviously weaker than the one in a closed economy. The profit-neutral allowances for a domestic firm (ϵ_{iH}) are given by:

$$\begin{aligned}
\epsilon_{iH} &= \frac{1}{(n_H+n_F)\beta-1}\left((q_{iH}(\sigma=0)-q_{iH}(\sigma))\frac{\beta n_F\tau+(1-n_F\beta)c}{\sigma}-(1-n_F\beta)q_{iH}(\sigma)\right), \\
&= \frac{q_{iH}(\sigma)}{(n_H+n_F)\beta-1}\left((z_H^{-1}-1)\frac{\beta n_F\tau+(1-n_F\beta)c}{\sigma}-(1-n_F\beta)\right), \\
&= \frac{q_{iH}(\sigma)}{(n_H+n_F)\beta-1}\left(\frac{(z_H^{-1}-1)}{(z^{-\frac{1}{\beta}}-1)}\frac{\beta n_F\tau+(1-n_F\beta)c}{c+\frac{n_F}{n_H}\tau}-(1-n_F\beta)\right).
\end{aligned}$$

It is immediately apparent that the share of permits that the regulator grants for free (denoted by (γ_{pH}) is equal to:

$$\gamma_{pH} = \frac{1}{(n_H+n_F)\beta-1}\left(\frac{(z_H^{-1}-1)}{(z^{-\frac{1}{\beta}}-1)}\frac{\beta n_F\tau+(1-n_F\beta)c}{c+\frac{n_F}{n_H}\tau}-(1-n_F\beta)\right). \tag{8}$$

The profit-neutral allowances are lower than the total number of permits if and only if

$$\frac{(z_H^{-1}-1)}{(z^{-\frac{1}{\beta}}-1)} < \frac{(1-n_F\beta)((n_H+n_F)\beta-1)(c+\frac{n_F}{n_H}\tau)}{\beta n_F\tau+(1-n_F\beta)c}. \tag{9}$$

From equation (23), the following proposition is deduced.

Proposition 5. *The exposure to international competition makes the conditions under which the offseting is possible more stringent.*

(i) The regulator can fully offset losses in profits if and only if $\beta < \frac{1}{n_F}$.

(iii) If the regulator can offset losses in profits for a certain value of $\bar{z}$, *it is always possible to offset losses in profits for a more stringent regulation (*$\forall z$, *such that* $\tilde{z}_H < z < \bar{z}$*).*

This result shows that if elasticity is sufficiently weak, the regulator can offset losses in profits by giving allowances for free. Section 5 illustrates this result and shows that sectors such as steel and cement satisfy this condition. The bad news is that the regulator cannot offset losses in profits in sectors exposed to international competition and whose elasticity of demand is higher than one. However, the good news is that if it is possible to offset losses in profits for a certain level of reduction, it will always be possible to offset losses in profits for a more stringent and feasible regulation.

4.3 Abatement technologies

Section 3 shows that even without abatement technology, the profit neutrality criterion requires few permits. This analysis assumes a lack of abatement technologies. When abatement is available, profits without abatement are ordinarily lower than profits with abatement. However, different abatement technologies exist. I focus on two cases: end-of pipe abatement and cleaner production.

Following Christin et al (2013), consider the case of end-of-pipe abatement, which includes capture and storage systems, pollution filters and clean development mechanisms. Firms reduce emissions once goods are produced. Therefore, abatement decisions are independent from production decisions. Firms abate if and only it is profitable. Thus, end-of-pipe abatement may be considered to be a firms' second activity, producing permits. In such a case, profits with abatement are compulsorily higher than without. The results found previously are then an upper-bound for offsetting.

Consider now cleaner production. Firms may then use an abatement technology to reduce emissions changing both emission intensity and marginal cost of production. In that case, the cleaner a technology is, the higher will be its marginal cost. As in Nicolai & Zamorano (2014)[16], assume that the unit cost of production and abatement for a firm i is equal to:

$$c_i(f_i) + \frac{\gamma}{2}(f_0 - f_i)^2, \tag{10}$$

where f_i is the resulting emission intensity of firm i, f_0 is the business-as-usual emission intensity and γ the cost parameter of abatement. The left side of the above expression represents the marginal cost $c_i(f_i)$ of production and the right one is the unit cost related to abatement. Assumptions of isoelastic demand function and symmetry are retained.

The profit of a firm i may be written as follows:

$$\pi_i(q_i, f_i) = P(Q)q_i - \left(f_i\sigma + c_i(f_i) + \frac{\gamma}{2}(f_0 - f_i)^2\right) q_i. \tag{11}$$

Indeed, firms buy permits ($f_i q_i \sigma$) and bear the cost of production and abatement (($c_i(f_i) + \frac{\gamma}{2}(f_0 - f_i)^2)q_i$)) while they earn the revenue from sales ($P(Q)q_i$). The first order conditions of profits satisfy

$$P(Q) + P'j(Q)q_i = f_i\sigma + c_i(f_i) + \frac{\gamma}{2}(f_0 - f_i)^2. \tag{12}$$

Derivating the First Order Condition with respect to σ gives:

$$P'q_i' = f_i - [1 - (1 + \frac{1}{\beta})\frac{1}{n}]P'Q'. \tag{13}$$

By summing the First Order Conditions, we obtain:

$$nP + P'Q = \sum_i \left(f_i\sigma + c_i(f_i) + \frac{\gamma}{2}(f_0 - f_i)^2\right). \tag{14}$$

Taking the derivative of this equation with respect to σ gives:

$$P'Q' = nf_i/(n - 1/\beta). \tag{15}$$

Since we focus on the effect of permits price on the firms' profits, I analyze the derivative of the function π_i with respect to σ, and we obtain:

$$\frac{\partial \pi_i}{\partial \sigma} = q_i[P'(Q' - q_i')] - f_i. \tag{16}$$

Replacing (13) and (15) on (16) gives:

$$\frac{\partial \pi_i}{\partial \sigma} = q_i f_i \left[\frac{1-\beta}{n\beta - 1}\right]. \tag{17}$$

Profits increase with the permit price when demand elasticity is weak (< 1), and decrease otherwise. This profit increase is exactly the same as in the case without abatement techologies in Section 3. The value of the free allowances ($\varepsilon^N \sigma$) which offset losses in profits under cleaner production is, approximately, the same as without abatement technologies. Indeed, by definition, $\varepsilon^N \sigma = \pi_i(0) - \pi_i(\sigma)$. At the first order, the approximation of $\pi_i(0) - \pi_i(\sigma)$ is $\frac{\partial \pi_i}{\partial \sigma}$. Moreover, equation (17) indicates that the profit increase is exactly the same as in the case without abatement technologies. Thus, the paper's results seem to provide a good approximation of the offsetting losses in profits in the case of cleaner production.

4.4 Optimal regulation

Until now, the paper has focused on an exogenous factor of reduction. Let us now analyze how to endogenize emission reduction to make it welfare-optimal. We consider a linear damage function of pollution, where λ is the marginal damage. The regulator takes into account the firms' profits (π), the net consumers' surplus (CS), the environmental damage (λE) and the value of the permits sold ($E\sigma$). The social welfare function is then defined as:

$$W = CS + \Sigma_{i=1}^{n} \pi_i - \lambda E + \sigma E.$$

Profits are equal to the sales minus the production costs and the costs to purchase permits. Thus, the welfare is the sum of the gross consumers' surplus minus the production costs and the environmental damages and may be rewritten as:

$$W = \int_0^{Q^*} P(Q)dQ - cQ^* - \lambda Q^*$$

Since production depends on the reducing factor, we can then rewrite welfare as a function of the reducing factor z:

$$W = \int_0^{zQ(0)} \alpha Q^{-1/\beta} dQ - czQ(0) - z\lambda Q(0)$$

By maximizing welfare according to the reducing factor, we deduce the optimal reducing factor, which is equal to:

$$z^{opt} = (\frac{\alpha}{c+\lambda})^{\beta} \frac{1}{Q(0)} \tag{18}$$

$$= (\frac{\alpha}{c+\lambda})^{\beta} \left(\frac{\beta c}{\alpha(\beta - 1/n)}\right)^{\beta} \tag{19}$$

$$= \left((1 + \frac{\lambda}{c})(1 - 1/(n\beta))\right)^{-\beta} \tag{20}$$

The optimal factor of reduction depends on the marginal damage, the number of firms, the marginal cost of production and the elasticity of demand. When marginal damage increases, obviously the optimal reducing factor decreases. Indeed, if pollution becomes more harmful, it is optimal to further reduce pollution. When the number of firms increases, the optimal reducing factor decreases. The higher the number of firms is, the lower will be the distortion in the demand side. Moreover, the reduction of environmental externality induces an increase in the exercise of market power. Indeed, to reduce market power, the regulator should subsidize production and then set a lower factor of reduction as in the case without imperfect competition. When the marginal cost of production increases, the optimal reducing factor increases. A low marginal cost of production corresponds to high initial pollution. Therefore, optimally the regulator should make environmental regulation more stringent when the marginal cost of production increases.

From equation (4) and equation (20), the optimal permit price is given by:

$$\sigma^{opt} = \lambda(1 - 1/(n\beta)) - c/(n\beta)$$

The optimal permit price increases with the marginal damage, the number of firms and the elasticity of demand while it decreases with the unit production cost. When the elasticity of demand is high and the unit cost low, initial production will be high, requiring a high permit price to reduce the induced damage. The following lemma compares the optimal pollution permit price with the Pigovian tax, i.e., the marginal damage.

Lemma 5. *The optimal permit price is lower than the marginal damage.*

This result is standard and well known in the literature.[14] Under perfect competition, the optimal permit price is equal to the Pigovian tax. However, under imperfect competition, the regulator should implement a lower permit price to decrease the market power of firms in the market for products.

From equation (20), Proposition 2 can be rewritten and the conditions under which the regulator implements the optimal reducing factor and makes environmental policy acceptable to firms can be determined.

Proposition 6. *Let $\overline{\lambda}(\beta, n)$ be the marginal damage under which the regulator can implement the optimal reduction of emissions and offset losses in profits. For each (λ, β, n), if $\lambda > \overline{\lambda}(\beta, n)$, offsetting will be impossible. The threshold, for $\beta < 10$, is given by:*

(i) When n=1, $\overline{\lambda}(\beta, 1) < 0$.

(ii) When n=2, $\overline{\lambda}(\beta, 2) = \frac{1}{1-1/(2\beta)}((0.3)^{-1/\beta} - 1)c$.

(iii) When $n > 2$, $\overline{\lambda}(\beta, n) = \frac{1}{1-1/(n\beta)}((0.2)^{-1/\beta} - 1)c$.

As in the case of an exogenous reducing factor, acceptability is not reachable in the case of monopoly. The more firms there are, the higher the marginal damage under which the

[14] For instance, Barnett (1980) showed that the optimal tax or permits price is lower than the marginal damage in the presence of market-power.

regulator can implement the optimal reduction of emissions and may offset losses in profits will be. This proposition reconciles efficiency with acceptability.

5 Discussion, illustration and policy implications

The present section discusses this paper's relevance in view of the free allowances distributed in Europe.

5.1 Summary of the EU free allowances process

The EU free allowances process is exhaustively detailed in Ellerman et al (2010)[5]. In the two first phases (2005-2007 and 2008-2012), all sectors were treated uniformly and approximately all permits given for free. However, in the third phase (2013-2020), sectors were differentiated and auctioning was introduced.

Phase 1 (2005-2007) and phase 2 (2008-2012) During these two periods, distribution of permits was decentralized. Each member state was allowed to auction up to 5 per cent of their totals in the first periods and up to 10 per cent in the second. In other words, the minimum of free allowances for the two phases was 95% and 90% respectively. Note that in the second phase, eight countries auctioned permits. Germany distributed 91% of permits for free. According to Ellerman et al(2010)[5] 99.87% and 97% of permits in Europe were granted for free respectively for phases 1 and 2. The distribution of permits was uniform across sectors and grandfathered.

Phase 3 (2013-2020) During the third phase, distribution of permits was centralized and each member state had to respect the ETS Directive approved in December 2008. Three categories of sectors were considered. The power sector was to receive no free allowances as from 2013. Sensitive sectors, such as cement and steel, which face a significant risk of carbon leakage could receive free allowances of up to 100 per cent of their needs. Note that, while all permits were previously grandfathered, a new mechanism for allocation came into effect in

2013; it combined an ex-ante lump-sum transfer based on historic output (and multiplied by a benchmark) with an ex-post adjustment of this lump-sum according to rules related to actual capacity and activity level. Other sectors received a free allocation of 80% of their share of the cap in 2013, to be reduced by ten percentage points each year so that free allocation would be phased out in 2020.

Conclusion The two main differences between the two first phases and the third one related to the degree of centralization and the treatment by sectors. Indeed, distribution was uniform in the two first periods and differentiated across sectors in the third phase. However, grandfathering rates were very high for the two first phases and for the sensitive sectors in the third one. In addition, up to 80% of permits at the start of the third phase were high. The difference between sectors in the third phase may be explained by the presence of international competition.

The following illustration has three goals; (i) to show that during the first two phases of the EU-ETS, few permits were required, (ii) to compare uniform and sector-based policies and (iii) to determine the percentage of free allowances to be granted for free according to the profit-neutral criterion for higher emission reductions.

5.2 Illustration for cement, electricity and steel in the EU-ETS

Three sectors are considered: electricity, cement ans steel. All the parameter values are provided in Table 1.[15]

First some information as to the method and data used for the illustration:

- The electricity sector is not exposed to international competition while the two other sectors are. Thus, for the steel and cement sectors, as in section 4.2, I consider two countries, home (H) and foreign (F). Home represents the European area and F the rest of the world. However, for the electricity sector, the framework retained in Section 3 is used.

[15] This calibration is close to the calibration used for a different context in Nicolai & Zamorano (2014)[16]. In this latter, the effect of output-based allocation on profits is analyzed.

Table 1: Data for the parameters and calibration of the model

Sectors Unit	**Electricity** MWh	**Steel** tonne	**Cement** tonne
Market Size (α)	3600	200	250
	Meunier & Ponssard (2012)[13]		
Elasticity (β)	0,4	0,6	0,5
	Hepburn et al. (2013)[8]		Computation
Price (p) €	47	313	64
	Reinaud (2004)[2]		
Unit cost (c^H) €	37	247	46,8
	Ministry of the Economy (2003)[15]	Reinaud (2004)[2]	
BAU emission intensity (μ_0) tCO2/unit	0.37	1.3	0.7
	Knetter (2007)[?]	Meunier & Ponssard (2012)[13]	
Impact over unit cost (c') €	0,5	4,5	1,5
	Meunier & Ponssard (2012)[13]		
Cost's parameter of abatement (γ) $€/tCO2^2$	1017	115	315
	Computation		
Transportation cost τ €		31	25
		Meunier & Ponssard(2012)[13]	Computation
Foreign unit cost c^F €		247	35
		Reinaud (2004)[2]	Meunier & Ponssard (2012)[13]
Market structure	$n = \frac{1}{\beta(1-c/p)}$	$n^{BF} = 1$ & $n^{BH} = \frac{P^B(1-\beta)+\beta(c^F+\tau)}{\beta^B(P^B-c^H)}$	
	12	7	8

- Firms may use an abatement technology to reduce emissions. Thus, firms may reduce emissions by reducing production and abating emissions. The specifications of section 4.4 are adopted, such that the unit cost of production and abatement for a firm i is equal to:

$$c_i(f_i) + \frac{\gamma}{2}(f_0 - f_i)^2,$$

where f_i is the resulting emission intensity of firm i, f_0 is the business-as-usual emission intensity and γ the abatement cost parameter.

- Production and abatement are calculated in the two cases of exposure and non-exposure to international competition. The analytical results are given in Tables 3 and 4.

- Electricity generation requires the use of more diverse technologies than in other industries. Thus, Demailly & Quirion (2008)[4] use average values for this sector. However, they consider competition to be perfect and assume that prices are equal to unit production costs. 47 euros/MWh is retained as the price of electricity. However, for the cost of electricity, the cost determined by the Ministery of Economy in France for some coal plants is retained, i.e. equal to 37. A average cost is not retained but rather the cost of an intermediate technology, that of the combined gas cycle.

- Steel production is heterogenous and Reinaud (2004)[18] distinguishes the BOF and EAF routes for steel making. Demailly & Quirion (2008)[4] aggregate the data by summing them, weighted by their shares in total production capacity of EU and non-EU countries.

- Elasticities (absolute value) correspond to values over the short-term for observed prices, with the understanding that these elasticities are difficult to estimate in practice. According to Hepburn et al (2013)[8], electricity and steel have respectively a demand elasticity equal to 0.4 and 0.6. There is no consensus on the demand elasticities for cement and the average between those determined by Hepburn et al (2013)[8] and Meunier et Ponssard (2012)[13] is taken, equal to 0.5.

- In order to determine the abatement cost parameter in each sector, the optimal emission intensity is calculated; the two values for emission intensity calculated by Meunier & Ponssard (2012)[13] for $\sigma = 0$ and $\sigma = 30$ are used. The value of the abatement cost parameter is determined by making a linear interpolation.[16]

- Market structures are determined indirectly from market prices (BAU) and unit costs by reversing the Cournot solution in a context without regulation and abatement costs (i.e., the number of firms is adjusted to match observed prices and does not correspond to the number of firms observed). For electicity production, the number of firms is calculated such that $n = 1/\beta(1 - c/p)$, and we round off to the higher unit. However, for the two other sectors, $n^H = [(p(1-\beta) + \beta(c^F)]/\beta(p - c^H)$ is calculated, when $n^F = 1$. In the simulation, the set of foreign firms are considered as if they were a single exporter.

- In the cement industry, the value of transportation costs is crucial and presents a significant variation due to geographical characteristics and the way cement is transported (road versus sea transportation). There is no consensus on the transportation cost for the cement industry, and we take the average between those determined by the Boston Consulting Group (2012)[1] and Meunier & Ponssard (2012)[13], which is equal to 25.

- It is assumed that emissions are reduced by five, ten and twenty per cent. The first case illustrates emission reduction for the first two phases of EU-ETS. The other cases are useful to illustrate that even with greater reduction, the percentage of permits to be allocated to firms to offset losses in profits is low.

Without free allowances First of all, the case under which emissions are reduced by 5% is focused on, corresponding to the first two phases of EU-ETS. The permit price is equal to $\sigma = 4$, which is quite close to the permit price observed in 2012 under the EU-ETS.

The main feature is that efforts to reduce emissions are clearly different between sectors. Moreover, the trade-off between output reduction and abatement varies also among them.

[16] The cost parameter for abatement is determined by the inverse of the pollution factor solution, i.e., we fix γ according to the values observed from $f_i^j(\sigma = 30)$, $f_0^j(\sigma = 0)$ and the marginal cost in each sector. By Meunier & Ponssard (2011)[13]: $f_0^e(\sigma = 0) = 0,37$, $f_i^e(\sigma = 30) = 0,34$, $f_0^s(\sigma = 0) = 1,3$, $f_i^s(\sigma = 30) = 1$, $f_0^c(\sigma = 0) = 0,7$ and $f_i^c(\sigma = 30) = 0,6$.

Implementation of the market for permits Reduction of total emissions	-5%	-10%	-20%
Permit price (Euros)	4	9	21
Effect on quantities			
Electricity	-1.5%	-3.3%	-7.1%
Steel	-1.9%	-4.1%	-8.4%
Cement	-4.5%	-9.5%	-18%
Effect on emission intensity			
Electricity	-1.2%	-2.5%	-5.7%
Steel	-5.6%	-9%	-17%
Cement	-2.4%	-4%	-10%
Effect on price			
Electricity	+3.4%	+8.3%	+19.7%
Steel	+2.9%	+5%	+9.24%
Cement	+5.9%	+11%	+25%
Effect on profits			
Electricity	+2.4%	+5.3%	+11.8%
Steel	-1.4%	-3.4%	-8.8%
Cement	-2.3%	-5.2%	-12%
Effect on foreign emissions			
Steel	+10,88%	+22.86%	+45.52%
Cement	+57.45%	+116.11%	+215.49%
All permits for free			
Uniform policy with the grand-fathering rate equal to z	0.95	0.9	0.8
Effect on profits			
Electricity	+16.8%	+36.08%	+75.70%
Steel	+5.66%	+11.64%	+22.54%
Cement	+12.63%	+26.67%	+54.13%
Sector-based policy that neutralizes all profits			
Profit-neutral allowances/ initial emissions (%)			
Electricity	0%	0%	0%
Steel	+19.12 %	+20.61	+ 22.43
Cement	+14.72%	+14.69	+14.51
Percentage of total allowances given for free	8.97%	9.77%	11.33%
Uniform policy which neutralizes all profits			
Grand-fathering rate applied	0.191	0.206	0.224
Effect on profits			
Electricity	+5.45%	+8.9	+34
Steel	0%	0%	0%
Cement	0%	0.7%	11%
Percentage of total allowances given for free	20.10%	22.88%	28%

Table 2: Results of the illustration.

The cement sector is the sector that proportionately reduces the output most while steel is the one that abates the most. Indeed, the lowest the cost over emission intensity ratio is that of cement while the three elasticities are quite close to each other. Section 4.1 shows that when elasticities are the same, the sector that has the lowest ratio of marginal cost over emission intensity reduces the most emissions proportionately. The main consequence of this result is that the product price of the cement sector is the one that increases the most proportionately. In other words, the consumers most negatively affected by the implementation of pollution permits are those who purchase cement.

Secondly, power companies' profits increase with the implementation of pollution permits while the two other sectors' profits decrease. This result in the power sector results from non-exposure to international competition and the low elasticity of demand. The Lemma 1 shows that profit increases when the elasticity of demand is weak (< 1). Cement is the sector most negatively affected by emission reduction.

Consider now that total emissions are reduced by 10% and 20%. Results are not qualitatively modified. As in the case of a 5% reduction, the consumers the most negatively affected by emission reduction are those who purchase cement. The price of cement increases respectively by 11% and 25%. The power sector benefits from the regulation and profits increase respectively by 11% and 25%.

All permits for free Assume that the grand-fathering rate applied is equal to the global reducing factor z. The sector that benefits the most is electricity. Profits in the electricity sector increase by 16.8%. This result is consistent with the windfall theory such that electricity benefits from the opening of the EU-ETS. Profits in the cement sector increase by 12.63% while they increase by 5.66% in the steel sector.

Let us focus on profit-neutral allowances. Two methods of distribution are compared: a uniform grandfathering rate and a sector-based grandfathering rate. The first represents the two first phases of the EU-ETS while the second corresponds to the third phase.

Sector-based profit-neutral policy The regulator allocates the adequate number of free allowances to each sector. For the power sector, no free allowances should be given. The regulator applies a grand-fathering rate equal respectively to 14.72% and 19.12%, in the cement and steel sectors. Globally, only 11% of permits are sufficient to neutralize all firms' profits. In the cases where total emissions are reduced by 10% and 20%, the percentage of total allowances that the regulator grants for free are respectively equal to 9.77% and 11.33%.

Uniform profit-neutral policy The regulator uses a uniform policy, i.e., he applies the same grandfathering rate to each sector. In other words, the regulator applies to all sectors the higher grandfathering rate determined in the sector-based profit-neutral policy case. Thus, the regulator uses the grandfathering rate applied previously to the steel sector. Losses in profits in the steel sector are offset while in the other sectors profits increase. Firms producing cement benefit in a low proportion and profits in the power sector increase by 5.45%. 20.10% of permits are required to offset losses. This figure is very low and far from the 99% of permits given for free in Europe during the two first phases. In the instances under which the total emissions are reduced by 10% and 20%, the percentages of total allowances that the regulator grants for free are respectively equal to 23% and 28%.

To conclude, this illustration shows that few permits are required when the distribution of permits is sector-based in order to offset losses. Moreover evolution of the EU free allowances process, i.e. from uniform to sector-based policy prevents the regulator from giving too many permits and thus diminishes fiscal revenue. Furthermore, the process has become more centralized and countries cannot give all for free. In a decentralized organization, countries prefer to give all for free to their own firms. For the third phase, as in our simulations, electricity producers do not receive free allowances. However, the cement and stell sectors receive all the permits they need for free. Thus, the number of permits given for free is always too high and both sectors should be differentiated. The simulations of 10% and 20% of reductions show that even with significant reductions, the percentage of permits to grant for free in order to offset losses in profits is very low.

6 Conclusion

The present paper addresses two policy objectives that the environmental regulator aims to accomplish: to implement a market for permits and make regulation acceptable for businesses. It shows that a low number of free allowances is sufficient to meet these two goals. Moreover, even when the reduction is high, the regulator can fully offset losses if the concerned sectors are not in a monopoly context. The existence of international competition is one of the main limits to offset losses in profits but when the elasticity of demand is quite low (as for the cement and steel sectors), offsetting losses in profits remains possible. The paper also shows that the inclusion of a polluting sector not exposed to international competition in the market for permits allows the regulator to offset losses in profits in the sectors exposed to international competition.

While the existing emission trading schemes have replaced the grand-fathering allocation by other methods such as output-based or capacity-based allocations, it is found that these methods lower the effective marginal production cost but cannot achieve acceptability. Furthermore, the percentage of emission reduction implemented by regulators remain the same. In light of these findings, it is argued that the use of grandfathering allocation coupled with a significant reduction of carbon emissions should be promoted.

Under a profit-neutral allocation, only consumers and the State bear the cost of environmental regulation. It is demonstrated that regulators should limit the number of free allowances to this upper bound. On the basis of comparison between distribution of free allowances and profit-neutral allocation reflecting the existing lobbying power of firms, it is shown that 10% of permits were sufficient to neutralize profits during the two first phases of EU-ETS, which is far from the 99% of permits given for free by the EU during the same period.

References

[1] Boston Consulting Group (2012), Key Arguments Justifying the European Cement Industry's Application for State Aid to Balance the Offshoring Risk Caused by the Increased of Electricity Prices Due to EU-ETS, report, January 2012.

[2] Bovenberg, A., Goulder, L. (2001), Neutralizing the Adverse Industry Impacts CO2 Abatement Policies: What does It Cost? In C.Carraro and G.Metcalf (eds), Behavioral and distributional Effects of Environmental Policy, Chicago, IL: Chicago University Press.

[3] Demailly, D. and Quirion, P. (2006), CO2 abatement, competitiveness and leakage in the European Cement Industry under the EU ETS: grandfathering versus output-based allocation. Climate Policy, 6, 93-113.

[4] Demailly, D. and Quirion, P. (2008), Changing the Allocation Rules in the EU ETS: Impact on Competitiveness and Economic Efficiency, FEEM Working Paper No. 89.2008, October.

[5] Ellerman, D., Convery, F.J. and de Perthuis, C. (2010), Pricing Carbon: The European Union Emissions Trading Scheme. Cambridge University Press.

[6] Goulder, L., Hafstead, M.A.C. and Dworsky, M. (2010), Impacts of Alternative Emissions Allowance Allocation Methods under a Federal Cap-and-Trade Program, Journal of Environmental Economics and Management 60, 161-181.

[7] Grubb, M. and Neuhoff, K. (2006), Allocation and competitiveness in the EU emissions trading scheme: policy overview, Climate Policy, 6 (1), 7-30.

[8] Hepburn, C., Quah, J. and Ritz, R. (2013), Emissions trading with profit-neutral permit allocations, Journal of Public Economics, Vol. 98, 85–99 (2013)

[9] Hintermann, B. (2011), Market Power, Permit Allocation and Efficiency in Emission Permit Markets, Environmental and Resource Economics, vol. 49(3), pages 327-349, July.

[10] Hintermann, B. (2013), Market Power in Emission Permit Markets: Theory and Evidence, CESifo Working Paper Series, CESifo Group Munich 4447, CESifo Group Munich.

[11] IPCC (2014), Climate Change 2014, Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, R.K. Pachauri and L.A. Meyer (eds.)]. IPCC, Geneva, Switzerland, 151 pp.

[12] Oxera (2004), CO_2 Emissions trading: How it will Affect UK Industry, Oxford, Oxera Consulting Ltd.

[13] Meunier, G. and Ponssard, J.P.(2012), A Sectoral Approach Balancing Global Efficiency and Equity, Environmental and Resource Economics, 2012, 53, 533-552.

[14] Meunier, G. and Nicolaï, J.Ph. (2013), Higher Costs for Higher Profits: a General Assessment and an Application to Environmental Regulations, CER-ETH Zurich working-paper.

[15] Ministere d'Economie, des Finances et de l'Industrie (2003), Coûts de référence de la production électrique, DGEMP-DIDEME, december 2003.

[16] Nicolai, J-P. and Zamorano J. (2014), "Windfall profits 2.0" during the third phase of the EU-ETS, Economics Working Paper Series of CER-ETH - Center of Economic Research at ETH Zurich, Working Paper 13/189, November 2014.

[17] Requate, T. (2005), Dynamic incentives by environmental policy instruments–a survey, Ecological Economics, 54(2-3), 175 - 195.

[18] Reinaud, J. (2004), Industrial competitiveness under the European Union Emissions Trading Scheme, IEA Information Paper (2004).

[19] Seade, J. (1985), Profitable Cost Increases and the Shifting of Taxation, unpublished University of Warwick Economic Research Paper.

[20] Sijm, J., Neuhoff, K. and Chen, Y. (2006), CO2 Cost Pass Through and Windfall Profits in the Power Sector, Climate Policy, 6, 49-72.

[21] Smale, R., Hartley, M., Hepburn, C., Ward, J. and Grubb, M. (2006) The impact of CO_2 "'emissions trading on firm profits and market prices. Climate Policy 6:29-46.

7 Appendix

Proof of Proposition 1:

The profit is equal to

$$\pi_i(\sigma) = q_i(\sigma)\frac{c+\sigma}{n\beta - 1}.$$

The profit-neutral allowances are given by $\varepsilon\sigma = \pi_i(0) - \pi_i(\sigma)$ and may be formulated as:

$$\varepsilon^N = \frac{1}{n\beta - 1}\frac{1}{\sigma}\left(q_i(0)c - q_i(\sigma)(c + f\sigma)\right).$$

Moreover, $q_i(\sigma) = zq_i(0)$ and $\sigma = (z^{-\frac{1}{\beta}} - 1)\frac{c}{f}$. The profit-neutral allowances may be written as follows:

$$\begin{aligned}
\epsilon^N &= \frac{f}{(n\beta - 1)}\left(\frac{1 - z^{1-1/\beta}}{z^{-1/\beta} - 1}\right) q_i(0) \\
&= f(\frac{1}{n})^{\beta+1}(\frac{\alpha}{\beta})^{\beta}(n\beta - 1)^{\beta-1}\left(\frac{1 - z^{1-1/\beta}}{z^{-1/\beta} - 1}\right) c^{-\beta}.
\end{aligned}$$

The grand-fathering rate($\gamma_{gf} = \frac{\epsilon}{q_i(0)}$) and the ratio of free allowances over permits ($\gamma_p = \frac{\epsilon}{q_i(\sigma)}$) which are required to offset losses are equal to:

$$\gamma_{gf} = \frac{1}{(n\beta - 1)}\left(\frac{1 - z^{1-1/\beta}}{z^{-1/\beta} - 1}\right), \qquad \gamma_p = \frac{1}{n\beta - 1}\left(\frac{z^{-1} - 1}{z^{-\frac{1}{\beta}} - 1} - 1\right). \tag{21}$$

Proof of Proposition 2

The goal of Proposition 2 is to determine when γ_p et γ_{gf} respect the constraints imposed. However, both constraints are equivalent

$$\gamma_{gf} = \frac{\varepsilon_i}{q_i(0)} < z \Leftrightarrow \gamma_p = \frac{\varepsilon_i}{q_i(\sigma)} < 1.$$

Free allowances cannot exceed the number of permits in circulation. Focus on the condition relative to γ_p: When n=1, β is higher than 1 by assumption. γ_p may then be rewritten as follows:

$$\gamma_p = \frac{1}{n\beta - 1}\Sigma_{k=1}^{\beta-1} z^{(-\frac{1}{\beta})^k}.$$

γ_p is the quotient of a sum of β terms higher than 1 over $\beta - 1$ which is higher than 1. As conclusion, if n=1, then $\gamma_p > 1$. As in the previous proof,

$$\gamma_p = \frac{1}{n\beta - 1}\left(\frac{z^{-1} - 1}{z^{-\frac{1}{\beta}} - 1} - 1\right) < 1 \Leftrightarrow \left(\frac{z^{-1} - 1}{z^{-\frac{1}{\beta}} - 1}\right) < n\beta.$$

When n=2, the constraint is given by $(\frac{z^{-1}-1}{z^{-\frac{1}{\beta}}-1}) < 2\beta$. For $\beta < 10$, this corresponds to $\bar{z} = 0.253$. When n=3, the constraint is given by $(\frac{z^{-1}-1}{z^{-\frac{1}{\beta}}-1}) < 3\beta$. For $\beta < 10$, this corresponds to $\bar{z} = 0.127$.

Since $\bar{z}$ increases with elasticity and decreases with the number of firms, it can be concluded that: when n=2, $0.3 > \overline{z}(\beta, 2)$ and when $n > 2$, $\overline{z}(\beta, n) < 0.2$.

Proof of Corollary 1

Let $z_{\pi_{FA}} = \frac{\pi(\sigma)+q_i\sigma}{\pi(0)}$ be the profit-altering factor when all permits are given for free.

The profit of firm i is equal to

$$\pi_i(\sigma) = q_i(\sigma)\frac{c + \sigma}{n\beta - 1}.$$

Then, the profit-altering factor when all permits are given for free may be formulated as:

$$\begin{aligned} z_{\pi_{FA}} &= \frac{\pi(\sigma) + q_i(\sigma)\sigma}{\pi(0)} = \frac{\frac{1}{n\beta-1}q_i(\sigma)(c+\sigma) + q_i(\sigma)\sigma}{\frac{q_i(0)c}{n\beta-1}}, \\ &= \frac{q_i(\sigma)}{q_i(0)} + \frac{n\beta q_i(\sigma)\sigma}{cq_i(0)}, \\ &= z + \frac{n\beta z\sigma}{c}, \\ &= z + n\beta z(z^{-\frac{1}{\beta}} - 1) \end{aligned}$$

To conclude, the profit-altering factor when all permits are given for free is equal to:

$$z_{\pi_{FA}} = z(1 + n\beta(z^{-1/\beta} - 1)).$$

Proof of Corollary 2

The profit of a firm i of the sector j is equal to

$$\pi_i(\sigma) = q_i(\sigma)\frac{c + f_j\sigma}{n_j\beta - 1}.$$

The profit-neutral allowances are given by $\varepsilon\sigma = \pi_i(0) - \pi_i(\sigma)$ and may be formulated as:

$$\varepsilon = \frac{1}{n\beta - 1}\frac{1}{\sigma}\left(q_i(0)c_j - q_i(\sigma)(c + f_j\sigma)\right).$$

Moreover, $q_i(\sigma) = zq_i(0)$ and $c_j + f_j\sigma = (z^{-\frac{1}{\beta}} - 1)$. Thus, the profit-neutral grandfathering rate ($\gamma_{gf} = \frac{\epsilon}{f_j q_i(0)}$) is equal to:

$$\gamma_{gf} = \frac{1}{f_j}\frac{1}{(n\beta - 1)}\left(\frac{1 - z^{1-1/\beta}}{z^{-1/\beta} - 1}\right). \tag{22}$$

Proof of Proposition 5

Assume that $z > \tilde{z}_H$. Equation (23) indicates that profit-neutral allowances are lower than the total number of permits if and only if

$$\frac{(z_H^{-1} - 1)}{(z^{-\frac{1}{\beta}} - 1)} < \frac{(1 - n_F\beta)((n_H + n_F)\beta - 1)(c + \frac{n_F}{n_H}\tau)}{\beta n_F\tau + (1 - n_F\beta)c}. \tag{23}$$

However, since z and z_H are positive and lower than one, $\frac{(z_H^{-1}-1)}{(z^{-\frac{1}{\beta}}-1)} > 0$. Then, if $\beta > \frac{1}{n_F}$, the second part of the inequality is negative. Moreover, when $\beta < \frac{1}{n_F}$, $\frac{(z_H^{-1}-1)}{(z^{-\frac{1}{\beta}}-1)}$ is an increasing function of z. Thus, since the second part of the inequality does not depend on z, then if the regulator can offset losses in profits for a certain value of $\bar{z}$, it is always possible to offset profits' losses for a more stringent regulation ($\forall z < \bar{z}$).

Quantities, Emissions and Prices used for the Calibration

Tables 4 and 5 present the individual and total quantities, the emission rates and the market prices for the exposed and non-exposed sectors. Calculations for the non-exposed sector are used in the illustration to deal with the power sector. Calculations for the non-exposed sector are used to cover the steel and cement sectors.

Table 3: Quantities, emission rate and prices in the non-exposed sector

	Non-exposed Sector
Individual Quantities	$q_i = \frac{1}{n}\left(\frac{\alpha(1-1/(n\beta))}{(c_i+f_0\sigma)+\frac{1}{2\gamma}(c_i'^2-\sigma^2)}\right)^\beta$
Emission rate	$f_i = f_0 - \frac{1}{\gamma}(c_i' + \sigma)$
Total Quantities	$Q = \left(\frac{\alpha(1-1/(n\beta))}{(c_i+f_0\sigma)+\frac{1}{2\gamma}(c_i'^2-\sigma^2)}\right)^\beta$
Price	$P_i(Q) = \frac{c_i+f_0\sigma+\frac{1}{2\gamma}(c_i'^2-\sigma^2)}{1-1/(n\beta)}$

Table 4: Quantities, emission rate and prices in the non-exposed sector

	Exposed Sector
Individual Quantities	$q_i^H = (\frac{\alpha}{\beta})^\beta \frac{((n^F+n^H)\beta-1)^\beta \left(\beta n^F(c^F+\tau)+(1-n^F\beta^B)(c^H+(f_i^H-\omega f_0^H)\sigma)\right)}{(n^H(c^H+(f_i^H-\omega f_0^H)\sigma)+n^F(c^F+\tau))^{(\beta+1)}}$ $q_i^F = (\frac{\alpha}{\beta})^\beta \frac{((n^F+n^H)\beta-1)^\beta \left(\beta n^H(c^H+(f_i^H-\omega f_0^H)\sigma)+(1-n^H\beta)(c^F+\tau)\right)}{(n^H(c^H+(f_i^H-\omega f_0^H)\sigma)+n^F(c^F+\tau))^{(\beta+1)}}$
Emission rate	$f_i^H = f_0^H - \frac{1}{\gamma}({c'}_i^H + \sigma)$ $f_0^F = f_0^H$
Total Quantities	$Q^H + Q^F = (\frac{\alpha}{\beta})^\beta \frac{((n^F+n^H)\beta-1)}{(n^H(c^H+(f^H-\omega f_0^H)\sigma)+n^F(c^F+\tau))}$
Price	$P = \beta \frac{(n^H(c^H+(f^H-\omega f_0^H)\sigma)+n^F(c^F+\tau))}{((n^F+n^H)\beta^B-1)}$

Table 5: Quantities, emission rate and prices in the exposed sector

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