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Scarcity Rents and Incentives for Price Manipulation in Emissions Permit Markets with Stackelberg Competition[1]

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ABSTRACT

Prior research has shown, on the one hand, that firms subject to a cap-and-trade system can enjoy scarcity rents and, on the other hand, that cost effectiveness in a competitive emission permit market could be affected by tacit collusion and price manipulation when the corresponding polluting product market is oligopolistic. It has also been argued that this type of collusive behavior might be responsible for the high prices of permits observed during the first phase of the EU ETS. We analyze these cross market links using a Stackelberg model to show that, under reasonable assumptions, there are no incentives to collude in order to manipulate prices up. However, incentives for manipulating the price of permits upward appear if there is an initial free allocation of permits, which is a policy argument against grandfathering and in favor of auctioning. This effect is increasing with the amount of permits allocated to the leader. The likelihood of observing price manipulation increases with those changes that tend to undermine the leader's advantage in output production or to reduce the leader's abatement cost.

JEL code: D43, L13, Q58

Key words: Emissions permits, Collusion, Market power, Duopoly, Stackelberg model.

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1. Introduction

In this paper we examine the existence of scarcity rents and incentives for firms to collude in order to inflate the price of emission permits under the assumption of a leader-follower relationship in the output market. Both scarcity rents and price manipulation have been pointed out as relevant factors in the European Union Emission Trading System (EU ETS).

The main reason why cap-and-trade (CAT) programs are so attractive and popular among economists is that they theoretically allow emissions to be reduced in a cost-effective way by means of a price system. Regardless of the initial allocation rule chosen for the permits, the cost-effectiveness property is well documented in the literature under the assumption of perfect competition (see Montgomery 1972). Unfortunately, the perfect-market assumption rarely holds in practice and the cost-effectiveness property is in fact challenged if there is market power in either the permit market, in the associated product market or in both. The literature analyzing the relationship between imperfect competition and emission permits can be divided in three different branches, depending on whether market power is introduced in the permit market, in the good market or in both simultaneously.

The first line considers market power just in the permit market. The ground-breaking paper is Hahn (1984), which, based on a static model a la Stackelberg, stated that the efficiency loss due to market power depends on the initial allocation of permits and the permit price is an increasing function of the leader's allocation. The dominant firm will manipulate the price (upwards if it is a seller and downwards if it is a buyer) unless the initial allocation equals the cost-effective one, which requires a perfectly informed regulator. Hagen & Westskog (1998) extended the Hahn setting in a dynamic two-period model and found a non-optimal distribution of abatement in an imperfectly competitive market with banking and borrowing.

A second line addresses the concurrent existence of market power in both permit and output markets. Misiolek & Elder (1989) extended Hahn's setting to the product market and concluded that a single dominant firm can manipulate the permit market to drive up the fringe firm's cost in the product market. Hinterman (2011) found that the threshold of free allocation above which a dominant firm will set the permit price above its marginal abatement costs is below its optimal emissions in a competitive market, and that overall efficiency cannot be achieved by means of permit allocation alone.

This paper fits within a third branch of research that considers market power in the product market, but not in the permit market. The reason to choose this branch is twofold. First, as noted by Montero (2009) and Muller *et al.* (2002), whereas market power among firms is very common in output markets, the existence of market power in emissions permits is more likely to appear when the relevant players are countries rather than firms or facilities.[3] In the latter case, there are normally a very large number of them, which makes it very difficult for market power to arise. It can be argued that this is the case in the EU ETS, with more than 11,000 facilities involved. Moreover, the latest steps taken by the European Commission seem to be aimed at increasing the degree of competition even more (for example, by enlarging the number of involved sectors, centralizing the allocation of permits or moving from grandfathering to auctioning). On the other hand, among the economic sectors that are subject to the EU ETS, it is rather realistic to assume that at least in some of them there is some market power in the output market (see, e.g. Smale *et al.* 2006 or Hinterman 2011).

[3] As an example regarding Annex 1 countries in the Kyoto Protocol, Russia initially received roughly a fifth of the permits and a third went to the USA. Countries with market power can easily manipulate prices up (down) through tariffs on permit exports (domestic subsidies to cleaner technologies) and also implement policies regarding the linkage between domestic and foreigner markets. See Montero (2009) or Barrett (1998) for a related discussion.

As a second reason for this line of research, the EU-ETS price shock in 2005 generated a great deal of interest in issues related to market power. Initially, the price of allowances was far in excess of expectations, but it suddenly fell in April 2006, reaching zero in mid-2007. Empirical studies have not been able to perfectly explain these excessively high price levels when the number of permits exceeded emissions in every year of the first phase (see, e.g. Ellerman *et al.* 2010). It is therefore natural to ask whether the reason for these variations in price might be linked to the output market rather than the permit market insofar as permits could somehow be used to obtain windfall profits in the output market.

In this third line, some articles have shown that perfect competition in the permit market might not be sufficient to render a cost-effective outcome if the product market is not perfectly competitive. Within the framework of a Cournot duopoly, Sartzetakis (1997) compares the efficiency of a competitive emissions market to a command-and-control regulation. Emissions trading modifies the allocation of emissions among firms and hence their production choices. Sartzetakis (2004) shows that welfare can decrease when emissions trading is allowed between asymmetric firms endowed with different abatement and production technologies. The permit price that clears the market is a weighted average of the value of emissions of firms under command and control and therefore the cost of the more inefficient firm is reduced while the cost of the more efficient one is increased when permits trading is introduced.

Meunier (2011) analyzes the efficiency of emissions permit trading between two imperfectly competitive product markets and concludes that even if the firms are price takers in the permit market, the integration of permit markets can decrease welfare because of imperfect competition in product markets. Theoretically, if markets are perfectly competitive, a unique global permit market that covers all polluting activities will be efficient to allocate an aggregate emissions level. If markets are not perfect but some firm enjoys market power instead, several permit markets may be more efficient than an integrated one.

The closest paper to ours is the one by Ehrhart *et al.* (2008), which claims that under some conditions a permit price increase leads to higher firms' profit due to a decrease in product quantities, which in turn increases the output price. This result can be seen as an important case of scarcity rents. As far as permits are a limited input, output price will reflect the scarcity value of the permits.[4] Due to the tradable nature of emission permits, some firms can take the opportunity to obtain additional revenues by selling permits. Empirical evidence suggests that this phenomenon has been rather important in the first phase of the European Union Emission Trading System (EU ETS). For example, Newell *et al.* (2013) point out that power generators extracted rents by receiving carbon allowances for free and then passing along the opportunity costs of these allowances to their customers. For an analysis of this phenomenon, see Ellerman and Joskow (2008) or Ellerman *et al.* (2010).

Ehrhart *et al.* (2008) show that under some conditions firms benefit from a higher price of permits even if they are net buyers rather than seller of permits. Although an increase in the permit price has the direct effect of increasing one's cost, seeing as it also raises the rival's cost, it can generate scarcity rents for both firms by restricting the quantity and increasing the price of output. They conclude that, under these conditions, firms have incentives to collude in order to push the price of permits upwards.

Importantly, Ehrhart *et al.* (2008) also claim that, although there is apparently no explicit market power as such in the EU ETS, there are loopholes in the trading law that allow collusive behavior among firms to manipulate the price of permits. The most

[4] See, e.g. Fullerton and Metcalf (2001) for a discussion on scarcity rents. In a perfect competition framework, Mohr and Saha (2008) claim that, via the generation of scarcity rents, a stricter environmental regulation might have a distributional impact in the sense of increasing firm's profits and passing the cost onto consumers. André *et al.* (2009) make a similar discussion in a strategic setting with quality competition.

important of these mechanisms are first, the possibility to influence the initial allocation of permits (to make it more stringent); second, the 'opt-in' rule, which enables industries not committed to participating in the permits trading system to do so voluntarily; third, the possibility to implement project-based mechanisms and pay more for these credits than they would in the market and fourth, by paying additional emissions duties. It has also been argued that price manipulation practices might be responsible for the variations in price observed during the first phase of the EU ETS. For example, Hinterman (2011) concludes that the largest electricity producers in Germany, the UK and the Nordpool market might have found it profitable to manipulate the permit price upwards and he claims that this could explain the elevated allowance price level during the first 18 months of the EU ETS.[5]

This paper addresses the question as to whether, via the generation of scarcity rents, firms' interests could be aligned to push the price of permits up (and therefore if there are incentives to collude) under Stackelberg competition in the output market. We thus investigate whether the colluding incentives reported by Ehrhart *et al.* (2008) in a symmetric scenario might still arise in a setting that is asymmetric in nature in the sense that there is a leader and a follower. This seems a relevant case to consider seeing as, in the EU ETS, there are some big leading firms together with small firms that probably act as followers. As an additional contribution of this model, it fills a gap in the literature by considering Stackelberg competition in the third line of research, among the three reported above. In fact, leader-follower competition has been addressed in the first line by Hahn (1984) and in the second one by Hinterman (2011) but, as far as we know, it has not been studied in the third line, as we do.

[5] Note, however, that Hinterman's analysis is not fully comparable to ours as he assumes explicit market power in both output and permit markets.

As in Ehrhart *et al.* (2008), we take the permit price as given and thus we do not explicitly model the permit market. Consequently, we restrict ourselves to testing the existence of incentives for collusion to manipulate the price of permits rather than modeling price manipulation itself or determining if such manipulation has taken place in practice.

We first use a general model to show that a higher permit price increases the firms' cost of purchasing permits but also restricts output and increases the output price, generating some scarcity rents. Therefore, the final effect on both the leader's and the follower's profit is ambiguous. Hence, the possibility that firms benefit from a price increase still exists as in Ehrhart *et al.* (2008), but in our case the asymmetric role of the firms means that such a possibility arises under different conditions for the leader and the follower. This introduces the possibility of one firm being interested in raising and the other in decreasing the permit price.

We subsequently proceed to explore a particular case with a separable cost function to gain more accurate insights. We start with a basic case in which both firms have the same cost function and there is no grandfathering. As a first core finding, under the reasonable assumption that the solution is interior (both firms produce, pollute and abate to some extent), we conclude that both firms face a profit function that is convex in the permit price. Moreover, within the relevant range, when the price is sufficiently low, both firms will benefit from a further price reduction, whereas for sufficiently high prices, the follower will benefit from a price increase, while the leader will still prefer the price to decrease. Hence, in the absence of grandfathering, there is no room for collusion in the latter range. This is contrary to Ehrhart *et al.* (2008), which uses a symmetric model where both firms' interests are always aligned. The implication of this finding is that the existence of leadership in output markets reduces the room for collusion in the permit market. In fact, in our specific example with a separable function, we conclude that the collusive region shrinks to the extent that it disappears.

As a first extension, we consider the possibility that some permits are distributed for free (by means of grandfathering) and conclude that this possibility opens up the way for collusion. In fact, apart from the two regions identified in the simple case, there is a third region in which both firms are interested in pushing the price up and this region becomes wider the more permits are distributed for free. This result represents an important argument against grandfathering insofar as it could introduce incentives to foster collusive behavior for price manipulation.

As a second extension, we explore the effect of asymmetries and conclude that the likelihood of facing an environment that is conductive to collusion is sensitive to the cost parameters of both firms and the allocation of free permits received by the leader, but not by the follower. In short, those parameter changes that tend to undermine the leader's advantage in output production (i.e., an increase in the leader's cost, or a decrease in the follower's cost) have the effect of making the firms more symmetric in a certain sense and hence increase the likelihood of observing collusive behavior. The opposite occurs with abatement costs: the likelihood of collusive behavior tends to decrease with the leader's abatement cost and to increase with the follower's. The reason is that, seeing as the leader produces more output than the follower, its cost is more sensitive to the permit price and thus it is more difficult for the former to benefit from such a price increase, and this is truer, the higher the leader's abatement cost. On the other hand, an increase in the follower's abatement cost reduces the possibility of its being optimal for it to pollute zero, which widens the interior solution range and hence also the scope for collusion.

Section 2 expounds the basic model. A particular abatement cost function is considered in Section 3, including the basic case and the two extensions. Concluding remarks are given in Section 4. All the mathematical proofs are gathered in the appendix.

2. The general model

Let us consider a simple duopoly Stackelberg model of a polluting industry that is subject to a tradable permit system. Firm 1 is a leader and firm 2 is a follower in the output market. Following Ehrhart *et al.* (2008), we assume no explicit market power in the permit market and thus the permit price is taken as an exogenous value. The game has three stages: in the two first stages firms sequentially decide on their output levels, x_1 and x_2, a la Stackelberg, facing the inverse demand function $P(X)$, where $X := x_1 + x_2$ and $\frac{dp}{dX} < 0$. In the third stage, they simultaneously choose their cost-minimizing emission levels, e_1 and e_2.

The cost function of firm $i \in (1, 2)$, $C_i(x_i, e_i)$, depends on output (x_i) and emissions (e_i) and is continuous and twice differentiable in both arguments with the following properties:

$$\frac{\partial C_i}{\partial x_i} > 0, \quad \frac{\partial C_i}{\partial e_i} < 0, \quad \frac{\partial^2 C_i}{\partial e_i^2} > 0, \quad \frac{\partial^2 C_i}{\partial x_i \partial e_i} < 0. \tag{1}$$

This function integrates production and abatement costs and reflects the fact that producing clean (with low emissions) is more costly than producing dirty. Each unit of emissions must be covered by an emission permit. Initially, each firm i is endowed with a given amount of permits S_i, and additionally required permits, $e_i - S_i$, can be obtained on the market at a given price, p. Considering the cost of permit purchasing, the total cost of firm i is given by

$$TC_i\left(x_i,e_i\right):=C_i\left(x_i,e_i\right)+p\left(e_i-S_i\right). \tag{2}$$

The model is solved by backward induction. In the third stage of the game, both firms decide on their emissions levels to minimize their total cost, $TC_i\left(x_i,e_i\right)$, while taking their output levels and the price of permits as given. If the solution is interior, we obtain the standard first-order condition (FOC),[6]

$$\frac{\partial C_i}{\partial e_i}+p=0, \tag{3}$$

from which we obtain each firm's demand for permits, $e_i^*\left(x_i,p\right)$.[7] Total differentiation of the FOC shows that optimal emissions are increasing in output and decreasing in the permit price:

$$\frac{\partial^2 C_i}{\partial e_i^2}de_i+\frac{\partial^2 C_i}{\partial e_i\partial x_i}dx_i=0\Rightarrow\frac{\partial e_i}{\partial x_i}=\frac{-\dfrac{\partial^2 C_i}{\partial e_i x_i}}{\dfrac{\partial^2 C_i}{\partial e_i^2}}>0, \tag{4}$$

$$\frac{\partial^2 C_i}{\partial e_i^2}de_i+dp=0\Rightarrow\frac{\partial e_i}{\partial p}=\frac{-1}{\dfrac{\partial^2 C_i}{\partial e_i^2}}<0. \tag{5}$$

Using the Envelope Theorem, we conclude that the minimized total cost function defined as

$$TC_i^*\left(x_i,p\right):=TC\left(x_i,e_i^*\left(x_i,p\right)\right)=C\left(x_i,e_i^*\left(x_i,p\right)\right)+p\left[e_i^*\left(x_i,p\right)-S_i\right] \tag{6}$$

has the following properties:

$$\partial TC_i^* \big/ \partial p=e_i^*-S_i, \tag{7}$$

$$\frac{\partial TC_i^*}{\partial x_i}=\frac{\partial C_i}{\partial x_i}+\left(\frac{\partial C_i}{\partial e_i}+p\right)\frac{\partial e_i}{\partial x_i}=\frac{\partial C_i}{\partial x_i}, \tag{8}$$

[6] The second order condition is always fulfilled due to the convexity of C_i in emissions.

[7] Throughout the paper we use asterisks to denote equilibrium values.

$$\frac{\partial^2 TC_i^*}{\partial x_i^2} = \frac{\partial^2 C_i}{\partial x_i^2} + \frac{\partial^2 C_i}{\partial x_i \partial e_i}\frac{\partial e_i}{\partial x_i} = \frac{\partial^2 C_i}{\partial x_i^2} - \frac{\left(\frac{\partial^2 C_i}{\partial x_i \partial e_i}\right)^2}{\frac{\partial^2 C_i}{\partial e_i^2}} \quad , \tag{9}$$

$$\frac{\partial^2 TC_i^*}{\partial x_i \partial p} = \frac{\partial^2 C_i}{\partial x_i \partial e_i}\frac{\partial e_i}{\partial p} = \frac{-\frac{\partial^2 C_i}{\partial x_i \partial e_i}}{\frac{\partial^2 C_i}{\partial e_i^2}} > 0 \, . \tag{10}$$

We now move on to the first and the second stages, in which the firms choose their output levels. The follower faces the following maximization problem:

$$\underset{x_2}{Max}\, \Pi_2\left(x_1, x_2, e_2^*\left(x_2, p\right), p\right) = P\left(x_1 + x_2\right)x_2 - TC_2^*\left(x_2, p\right). \tag{11}$$

The FOC of this problem is

$$P + \frac{dP}{dX}x_2 - \frac{\partial TC_2^*}{\partial x_2} = 0 \, , \tag{12}$$

which, solving for x_2, gives the reaction function of the follower, $x_2^R\left(x_1, p\right)$. Differentiating the FOC and operating, we conclude that the optimal follower's output is decreasing in the leader's output and the price of permits:

$$\frac{\partial x_2^R}{\partial x_1} = \frac{-\frac{dP}{dX}}{2\frac{dP}{dX} - \frac{\partial^2 TC_2}{\partial x_2^2}} < 0 \, , \qquad \frac{\partial x_2^R}{\partial p} = \frac{\frac{\partial^2 TC_2}{\partial x_2 \partial p}}{2\frac{dP}{dX} - \frac{\partial^2 TC_2}{\partial x_2^2}} < 0 \, . \tag{13}$$

Finally, in the first stage, the leader takes the follower's reaction function into account when maximizing its own profit. The FOC of the corresponding problem is

$$P\left(x_1 + x_2\right) + \frac{dP}{dX}x_1\left(1 + \frac{\partial x_2^R}{\partial x_1}\right) - \frac{\partial TC_1}{\partial x_1} = 0 \, , \tag{14}$$

from which we obtain the leader's optimal output as a function of the permit price, $x_1^*\left(p\right)$. By differentiating (14), we conclude that the leader's output supply is also decreasing in the price of permits:

$$\frac{dx_1^*}{dp} = \frac{\dfrac{\partial^2 TC_1^*}{\partial x_1 \partial p}}{\dfrac{dP}{dX}\left(2 + \dfrac{\partial x_2^R}{\partial x_1}\right) - \dfrac{\partial^2 TC_1^*}{\partial x_1^2}} < 0 . \tag{15}$$

Equations (13) and (15) show how the leader and the follower react to a permit price increase. While the follower only takes into account the effect of its own output variation on the output price, the leader incorporates, not only its own, but also the follower's. This tends to make the denominator smaller in absolute value and, hence, the whole value of (15) greater in absolute value.

Using the equilibrium output values we can express the profit of both firms solely as a function of the permit price: $\Pi_1^*(p)$, $\Pi_2^*(p)$. We are now ready to address the main question of this paper, namely the effect of an increase in the price of permits on firm's profit. The question is: could both firms benefit simultaneously from a price increase as predicted by Ehrhart *et al.* (2008) in a symmetric setting? The motivation behind this question is that, if the answer happens to be positive, both firms might have incentives to collude in order to manipulate the price of permits upwards. For the sake of realism, it is relevant to ask this question in a setting in which the firms play different roles regarding their market power, as this situation is commonly observed in the real world and, specifically, in the EU ETS. As in Ehrhart *et al.* (2008), we do not model explicitly price manipulation. We simply test for the existence of firms' incentives to do so.

By direct differentiation of the profit functions, and dropping the terms that cancel out due to the FOCs, we conclude that the marginal effect of the price of permits on both firms' profit has two effects: on the one hand, it drives cost up, which tends to reduce firm's profit. On the other hand, however, it also causes output to decrease and therefore the product price to increase, which is beneficial for both firms. Formally,

$$\frac{d\Pi_1^*}{dp} = \underbrace{\frac{dP}{dX}\frac{\partial x_2^R}{\partial p}x_1^*}_{SR_1} - \left(e_1^* - S_1\right), \tag{16}$$

$$\frac{d\Pi_2^*}{dp} = \underbrace{\frac{dP}{dX}\frac{dx_1^*}{dp}x_2^*}_{SR_2} - \left(e_2^* - S_2\right). \tag{17}$$

The first summand in equations (16) and (17) can be seen as the scarcity rents from the point of view of firms 1 and 2 respectively (SR_1 and SR_2), *i.e.*, the additional revenue that each firm will receive thanks to the reduction in output supply. It is interesting to note that a higher value of p causes the output of both firms to decrease but each firm can only benefit from the effect that is due to the rival's output reduction. The reason is that decreasing the own output has a positive effect (increasing the price and decreasing the cost) and a negative effect (decreasing the number of sold units) and in equilibrium both effects cancel out as both firms are at the profit maximizing output level. Note also that the effect of a price increase on the follower's output has two components: a direct one and an indirect one through the leader's output. Formally, $\frac{dx_2^*}{dp} = \frac{\partial x_2^R}{\partial p} + \frac{\partial x_2^R}{\partial x_1}\frac{dx_1^*}{dp}$. Nevertheless, the latter effect is already accounted for in the leader's optimizing process and hence only the former matter to determine the leader's scarcity rent.

Direct comparison of (16) and (17) shows that $SR_1 \geq SR_2 \Leftrightarrow \varepsilon_{x_2^R, p} \geq \varepsilon_{x_1^*, p}$, where $\varepsilon_{A,B}$ denotes the elasticity of A with respect to B, i.e., a firm can enjoy more scarcity rents than its rival if its rival's output is more sensitive to the permit price than its own output.

The second term in (16) and (17) is the marginal increase in cost due to a higher permit price, which simply equals each firm's purchase of permits. It determines which part of the scarcity rents is captured by each firm. In the most favorable case, if all the permits were distributed for free, $e_i^* = S_i$, then the marginal impact of p on the cost would be zero and each firm would capture the whole available scarcity rent.

The sign of both (16) and (17) is ambiguous. If the first term (the scarcity rent) dominates the first (the marginal cost) then profit will increase with the price of permits. If this occurs simultaneously for both firms, there exist incentives to collude in order to manipulate the price upward, as Ehrhart *et al.* (2008) noted in a symmetric setting. Actually, their analysis is conducted in the absence of free permits ($S_i = 0$), which is the less favorable case for the firms and they conclude that, even in this case, the net effect might be positive. According to our interpretation, the question is to determine to what extent a higher permit price generates enough scarcity rents for both firms to compensate for the higher cost of purchasing permits.

Equations (16) and (17) also show that the conditions under which a higher price is profit-enhancing are different for the leader and the follower. This is due, not only to the fact that they may have different cost structures, but also to the fact that their reactions to a price increase, given in (13) and (15), are different. This opens up the possibility of disagreement between the firms insofar as one of them is interested in a price increase and the other one in a price decrease. This is contrary to Ehrhart *et al.* (2008), in which both firms are symmetric and therefore either both firms are better-off or both are worse-off after a price increase. Hence, the introduction of asymmetry seems to reduce the scope for collusion. At this level of generality, it is not possible to gain more specific insights. For that reason, we explore a specific case in the next section.

3. A Separable Function

To gain some additional insight, we assume now a separable cost function. As is done in Ehrhart *et al.* (2008), we initially consider a basic case with no grandfathering ($S_1 = S_2 = 0$) and the same cost functions for both firms, so that the only difference between them is due to their roles as leader and follower. After studying this basic case, we first explore the effect of distributing free permits to the firms and second, the consequences of considering cost asymmetries.

3.1. Basic case

Let us assume that production and abatement costs are separable in the following way. The production cost of firm *i* is given by cx_i, so there is a constant marginal production cost equal to *c*. The (inverse) demand function for output has the linear form $P(X) = a - bX$. Each unit of output generates *r* units of pollution, where $r > 0$ is a constant coefficient of pollution intensity (the gross emissions of firm *i* are hence given by rx_i). By performing abatement activities, firms can reduce their flow of pollution. Let us denote as $q_i \geq 0$ the amount of emissions abated by firm *i*. Thus, net emissions are given by $e_i = rx_i - q_i$. Following Sarzetakis (1997), we assume the following quadratic abatement cost function, which is common to both firms:

$$AC(q_i) = q_i(d + tq_i), \tag{18}$$

where *d* and *t* are positive parameters. Adding up all the costs we have the cost function

$$TC_i(x_i, e_i) = cx_i + (rx_i - e_i)(d + t(rx_i - e_i)) + pe_i. \tag{19}$$

To ensure an interior solution, we bound the relevant parameters by including the following technical assumption:

Assumption 1: $d < p < \overline{p}$, *where* $\overline{p} := p \,/\, e_2^*(x_2^*, p) = 0$. (20)

This assumption rules out uninteresting solutions in which either of the firms produces zero, pollutes zero or abates zero. The lower bound for p prevents abatement from being negative (see Equation (22) below). To understand this result, note that d is the marginal cost of abatement at $q_i = 0$. If the price of permits is even lower than the cost of the first unit of abatement it will never be profitable for the firms to abate, as buying permits is a cheaper option. The upper bound for p is defined as that value of the permit price such that, in equilibrium, it is optimal for the follower to pollute zero.[8] The reason to include this assumption is that, in our setting, the follower's emissions is the first variable to reach a zero value as p increases and hence this is a sufficient condition to ensure a nonnegative solution.[9]

Proceeding as in the general model, we first solve the third stage, in which both firms choose their emission levels. Endowed with our specific analytical expressions, we can compute the optimal amount of emissions of firm *i* as a function of output:

$$e_i^*\left(x_i, p\right) = rx_i - \frac{p-d}{2t}, \tag{21}$$

and it is straightforward to conclude that firm *i*'s optimal abatement is

$$q_i^*\left(p\right) = \frac{p-d}{2t} > 0, \quad i = 1,2, \tag{22}$$

which, due to separability, is independent of output and, due to cost symmetry, is common for both firms. Using (21) in (19), we obtain the expression for the minimized cost function, which reveals that the marginal product cost is constant in output and increasing in permit price:

[8] The specific expression for $\overline{p}$ can be found in the appendix. Specifically, it is given by (A3) in the basic model, but takes a different form in the subsequently developed extensions.

[9] If both the follower's abatement and the follower's net emissions are nonnegative, it is straightforward to conclude that the follower's gross emissions, rx_2, are nonnegative, which implies that the follower's output is nonnegative. As we subsequently show, in equilibrium the leader always produces more and pollutes more than the follower and thus Assumption 1 ensures that all the relevant variables of the model are nonnegative in equilibrium.

$$TC_i^*\left(x_i, p\right) = x_i\left(c + pr\right) - \frac{\left(p-d\right)^2}{4t}. \tag{23}$$

We now move on to solve the two first stages, in which both firms decide on their output levels. By standard methods,[10] we obtain

$$x_1^* = \frac{a-c-rp}{2b}, \tag{24}$$

$$x_2^* = \frac{a-c-rp}{4b}. \tag{25}$$

From (24) and (25), we conclude that the leader's output is twice that of the follower's, as in the classical Stackelberg model with linear demand and constant marginal cost, both firms' output depend positively on the demand intercept, *a*, and negatively on the demand slope, *b*, and all the cost parameters *c*, *r* and *p*. The equilibrium profits can be now be written as a function of the price of permits, defined as:

$$\Pi_i^*\left(p\right) := \left[a - b\left(x_1^* + x_2^*\right)\right]x_i^* - TC_i^*\left(x_i^*, p\right). \tag{26}$$

Using our specific functions to substitute in (16) and (17) we obtain

$$\frac{\partial \Pi_i^*}{dp} = \underbrace{\frac{r}{2}x_i^*}_{SR_i} \underbrace{-rx_i^* + \frac{p-d}{2t}}_{-e_i^*}, \tag{27}$$

from which we conclude that the scarcity rent due to the rise in the permit price that accrue to firm i is given by $rx_i^*/2$. The second and the third terms in (27) determine the marginal increase in cost due to permit purchasing. The second term is gross emissions and measure how much cost would increase in the absence of abatement. Finally, the third term measures how much the firms are able to save by performing abatement activities.

[10] The follower chooses x_2 to maximize its profit while taking x_1 as given. The leader chooses x_1 to maximize its own profit taking into account the follower's reaction function.

There are some straightforward insights that we can get from equation (27). First, if the firms were not able to abate (and thus the third term would be absent), scarcity rents by themselves would never be able to compensate for the cost increase and thus firms would never benefit from a higher permit price. Second, the positive abatement effect is increasing in the price of permits, which means that the higher the permit price the more firms can gain by using abatement to adapt themselves to the market conditions.

As a third important insight, the simple form of equation (27) allows a straightforward comparison between the effects on the leader's and the follower's profit. Indeed, simple manipulation of (27), together with (24) and (25) gives

$$\frac{\partial \Pi_1^*}{dp} - \frac{\partial \Pi_2^*}{dp} = -\frac{r}{2}\left(x_1^* - x_2^*\right) = -\frac{r\left(a-c-rp\right)}{8b} < 0, \qquad (28)$$

where the inequality always holds under interior solution. Thus, we conclude that a rise in the permit price will always benefit the follower more than the leader or will harm the leader more than the follower. According to (28), the reason for this result lies in the output difference: since the leader produces more output than the follower it also pollutes more and, therefore, its cost is more sensitive to a higher permit price.

To study the effect on firms' incentives, we conduct now a more detailed study of the profit functions. For notational convenience, we denote as $\hat{p}_i$ the value of the permit price that minimizes firm *i*'s profit. Formally,

$$\hat{p}_i := \arg\min_p \Pi_i^*\left(p\right) \quad i = 1,2. \qquad (29)$$

Lemma 1 and Proposition 1 show the main results of this part of the paper. Lemma 1 determines the shape of the equilibrium profit functions in terms of the permit price and Proposition 1 splits the relevant range in two regions with different consequences for the firms' interests regarding the evolution of p.

LEMMA 1

$\Pi_1^*(p)$ *and* $\Pi_2^*(p)$ are strictly convex functions of p with $d < \hat{p}_2 < \hat{p}_1 = \overline{p}$. ■

PROPOSITION 1

If $d < p < \hat{p}_2$*, a price decrease will make the profit of both firms increase. If* $\hat{p}_2 < p < \overline{p}$*, a price increase will decrease the leader's profit and increase the follower's profit.* ■

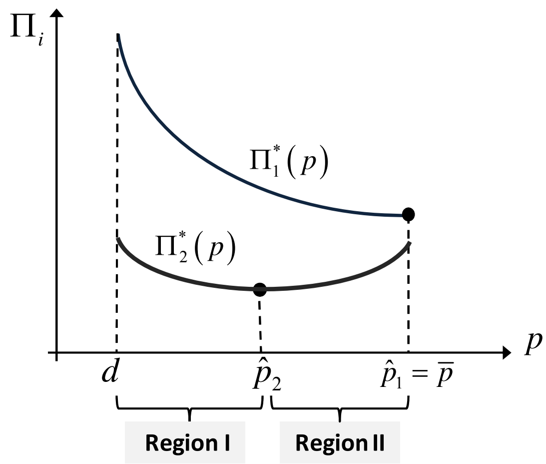

FIGURE 1: Equilibrium profits as a function of *p* (basic case)

The results in Lemma 1 and Proposition 1 are shown in Figure 1. There are two important facts worth highlighting in this figure. First, profits are strictly convex in p with a minimum at $\hat{p}_i$ (for i=1, 2). As it can be concluded from equation (27), the convex shape of the profit functions is a direct implication of the firm's reaction to a price increase by abating more and purchasing fewer permits.

The second insight from Figure 1 is that the minima of the profit functions are unambiguously ordered such that $\hat{p}_2 < \hat{p}_1$; i.e., the follower reaches a minimum for a lower price than the leader. Hence, we have that, if $p < \hat{p}_2$, both firms are situated in the decreasing part of their profit functions, which implies that their profit will increase if the permit price decreases. If, instead, $\hat{p}_2 < p < \hat{p}_1$, the follower is situated in the increasing part (and so will benefit from a price increase), whereas the leader is still in the decreasing part (and therefore will still prefer the price to decrease). As we can conclude form our previous discussion, the reason why firm 2's profit reaches a minimum before firm 1's is that, being a Stackelberg follower, it is optimal for firm 2 to produce less than firm 1 and therefore to pollute less. This implies that the direct effect of a price increase on its cost is less pronounced that it is for the leader.

Apparently, if $p > \hat{p}_1$, the leader enters the increasing part of its profit function and both firms will benefit from a higher price. Under our specification, however, we have that $\hat{p}_1 = \overline{p}$; i.e., the minimum of the leader's profit function is reached precisely at the highest value of the price that is compatible with an interior solution (specifically, (21) renders $e_2 < 0$ for any $p > \hat{p}_1$) and hence there is no feasible range under which both firms will benefit from a price increase.

Regarding the existence of incentives for collusion, the main consequence of Lemma 1 and Proposition 1 is that, in our example, there is a range within which both firms are interested in decreasing the price but, unlike the symmetric case developed by Ehrhart *el al.* (2008), it is never the case that both firms simultaneously profit from a price increase. Therefore, they never have incentives to collude in order to push the price up. Moreover, there is a range of disagreement within which the interests of both firms diverge, which can never occur in the symmetric case.

In this example, we have shown how asymmetry between firms (in the form of a leader-follower relationship) reduces the likelihood of collusive behavior to such an extent that they disappear. In the next subsections, we show two generalizations of this example in which the result is not so extreme in the sense that the likelihood of collusion, though smaller than in a purely symmetric setting, does not fully disappear.

3.2. Grandfathering

In the basic case, for the sake of comparability with Ehrhart *et al.* (2008), we have assumed that firms do not have any initial allocation of permits and therefore have to buy all the permits they need on the market. In reality, it is common for the participants in CAP systems to receive some permits for free by means of a grandfathering scheme. In fact, as is discussed for example in Alvarez and André (2014), grandfathering has traditionally been the most widespread method used to distribute permits.

We now extend our setting to consider the possibility that some permits are initially distributed with no cost for the firms via a grandfathering scheme.[11] Hence, firms need only buy those permits that exceed their initial allocation and, moreover, they have the option to sell permits if they pollute less than their initial allocation.

Let us consider that both firms receive an equal allocation of free permits, S, and denote as y_i the amount of permits that firm i buys (if $y_i > 0$) or sells (if $y_i < 0$) on the market, which can be calculated as the difference between net emissions and the allocation of permits:

$$y_i = e_i - S = rx_i - q_i - S, \tag{30}$$

from which we have that $e_i = y_i + S$; i.e., the net emissions of a firm must be covered by permits that either come from its free allocation or are bought on the market. Therefore, firm i's total cost function is now given by the expression

$$TC_i\left(x_i, y_i\right) = cx_i + \left(rx_i - y_i - S\right)\left(d + t\left(rx_i - y_i - S\right)\right) + py_i, \tag{31}$$

which can be written in terms of output and net emissions as

$$TC_i\left(x_i, e_i\right) = cx_i + \left(rx_i - e_i\right)\left(d + t\left(rx_i - e_i\right)\right) + p\left(e_i - S\right). \tag{32}$$

[11] Actually, the fact that permits are distributed for free is not crucial for our results. The only important assumption is that firms enjoy an exogenously given amount of permits.

Solving the third stage of the game, we conclude that the optimal levels of emissions and abatement for each firm are still given by (21) and (22), respectively, and it is straightforward to obtain the optimal traded permits and the corresponding minimized cost function:

$$y_i^*\left(x_i, p\right) = \frac{d-p}{2t} + rx_i - S\ , \tag{33}$$

$$TC_i^*\left(x_i, p\right) = x_i\left(c+pr\right) - \frac{\left(p-d\right)^2}{4t} - pS\ , \tag{34}$$

where separability entails that the minimized cost function has the same structure as in the basic case, except for the fact that the initial permit endowment appears as a reduction in the cost. Regarding the sensitivity of profits to the permit price, as we know from equations (16) and (17), the inclusion of grandfathering does not affect the overall value of scarcity rents, but it modifies the cost term and thus has an impact on the part of the scarcity rents that each firm is able to capture in equilibrium.

Lemma 2 and Proposition 2 are the main results of this part of the paper. We still use the notation introduced in (29) to refer to the value of the permit price that minimizes each profit function. For notational convenience, we also define the following threshold value for S:

$$\tilde{S} := \frac{r\left(a-c-dr\right)}{8b}. \tag{35}$$

LEMMA 2

When both firms are initially endowed with the same free allocation of permits, S, the equilibrium profit functions for both firms are strictly convex with a unique minimum each at $\hat{p}_i$ for $i=1,2$, with $\frac{\partial \hat{p}_i}{\partial S} < 0$. Moreover, we have the following ordering:

a) If $S < \tilde{S}$, then $d < \hat{p}_2 < \hat{p}_1 < \overline{p}$.

b) If $\tilde{S} < S < 2\tilde{S}$*, then* $\hat{p}_2 < d < \hat{p}_1 < \overline{p}$.

c) If $S > 2\tilde{S}$*, then* $\hat{p}_2 < \hat{p}_1 < d < \overline{p}$. ■

PROPOSITION 2

When both firms are initially endowed with a free allocation of permits, the following results hold:

a) If $S < \tilde{S}$*, the relevant range of values for* p *has three regions: In region I, defined by* $d < p < \hat{p}_2$*, both firms become better off when p decreases. In region II, defined by* $\hat{p}_2 < p < \hat{p}_1$*, the leader becomes better off when p decreases and the follower becomes better off when p increases. In region III, defined by* $\hat{p}_1 < p < \overline{p}$*, both firms become better off when* p *increases.*

b) If $\tilde{S} < S < 2\tilde{S}$*, region I disappears and region II is delimited by* $d < p < \hat{p}_1$.

c) If $S > 2\tilde{S}$*, regions I and II disappear and region III is defined by the entire feasible range,* $[d, \overline{p}]$. ■

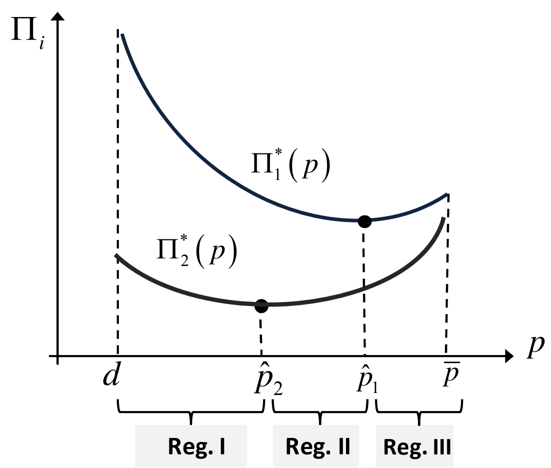

FIGURE 2: Equilibrium profits as a function of *p* (basic case)

The consequences of Lemma 2 and Proposition 2 are the following. The profit of both firms is still strictly convex in the price of permits, with a minimum at $\hat{p}_i$, i =1, 2. When grandfathering is introduced, the values of the permit price at which the minima are reached, $\hat{p}_1$ *and* $\hat{p}_2$, shift to the left and do so to a greater extent the higher the value of S. This shift implies that, for each firm, there is a wider range of the permit price such that it becomes better-off when the price increases. The reason is that the existence of free permits makes permit purchasing less costly for firms. Moreover, it opens the way for obtaining positive revenues by selling some permits.

More importantly, the inclusion of grandfathering opens up the possibility of collusion. Let us focus first on case *a*) (with $S < \tilde{S}$). We have now three regions instead of two, as shown in Figure 2. In region III, to the right of $\hat{p}_1$, both firms benefit from a price increase, while the solution is still interior ($e_1, e_2 > 0$). The technical reason why this new region arises is that the direct effect of a price increase on cost is now less pronounced, as the firms have to buy fewer permits and thus they can capture a higher part of the scarcity rents. Furthermore, if the price is high enough, it can also be the case that it is profitable for the firms to sell part of their free endowment instead of buying additional permits, which provides a new opportunity to increase profits. Nevertheless, it can be shown that at $\hat{p}_1$ we have $y_1 > 0$; i.e., at the point where the leader starts finding it profitable to increase the price, it is still a net buyer of permits and hence the profit-enhancing effect is not yet due to selling permits.

Moreover, if the initial allocation of permits is large enough, it could be the case that region I disappears, which implies that the follower is always interested in increasing the price of permits (case *b* in Lemma 2 and Proposition 2), or even that both regions I and II disappear, which implies that both the leader and the follower are always interested in manipulating the price upward. This is the most favorable case for collusion.

The focus of this paper is on region III, given that this is the only region within which firms can find it profitable to collude in order to push the price up. One natural question is how large this region is, or, in other words, how likely it is to fall within this region. To answer this question, we focus on case *a*) ($S < \tilde{S}$), which is perhaps the most realistic. The discussion of the other two cases is more straightforward. Region III is thus delimited by two threshold values for *p*. First, $\hat{p}_1$, which is the price above which it is profitable, not only for the follower, but also for the leader to push the price up. The second threshold is the upper bound, $\overline{p}$, which is the highest value of the price compatible with an interior solution. The size of region III is thus given by the difference between these two thresholds:

$$\overline{p} - \hat{p}_1 = \frac{4btS}{2b + tr^2}, \tag{36}$$

which depends positively on the number of free permits as well as the slope of the demand curve, *b*, and the abatement cost parameter *t*, whereas it depends negatively on the emissions intensity parameter, *r*.

3.3. Asymmetric cost

In the previous subsections we have assumed both firms to be fully symmetric in terms of cost functions and also, in the case of grandfathering, of free permit endowment. There are two reasons for making this assumption. The first is for the sake of simplicity. The second is to focus on the leader-follower relationship as the (only) source of asymmetry between firms. As a sensitivity analysis, in this subsection we consider the possibility that firms are asymmetric in terms of cost and/or initial permit endowment and explore the effect of these asymmetries on the likelihood of generating a propitious environment for collusive behavior. In other words, we explore the effect of different parameters on the size of region III as defined in the previous subsection.

To account for cost asymmetry, we denote the production cost of firm *i* as $c_i x_i$, where c_i is a firm-specific unit cost parameter. Seeing as we have postulated that firm 1 is a leader and firm 2 is a follower in the output market, it is natural to conjecture that $c_1 < c_2$; i.e., the position of the leader might well be due to the fact that it enjoys a cost advantage. However, nothing prevents us from considering the opposite case as a theoretical possibility. Analogously, firm *i*'s abatement cost function is given by:

$$AC_i\left(q_i\right) = q_i\left(d_i + t_i q_i\right), \qquad i = 1, 2. \tag{37}$$

Finally, each firm might receive an initial free endowment of permits, S_i, which is not necessarily constant across firms. Proceeding as in the basic case, we conclude that the optimal amounts of emissions, abatement and purchase of permits for each firm in the third stage are given, respectively, by[12]

$$e_i^*\left(x_i, p\right) = \frac{d_i - p}{2t_i} + rx_i, \tag{38}$$

$$q_i^*\left(p\right) = \frac{p - d_i}{2t_i}, \tag{39}$$

$$y_i^*\left(x_i, p\right) = rx_i - \frac{p - d_i}{2t} - S_i, \tag{40}$$

and, moving on to the first and second stages, we can compute the equilibrium levels of output:

$$x_1^* = \frac{a + c_2 - 2c_1 - rp}{2b}, \tag{41}$$

$$x_2^* = \frac{a + 2c_1 - 3c_2 - rp}{4b}. \tag{42}$$

[12] Unlike the other parameters, we assume that the emissions intensity parameter, *r*, is common to both firms; i.e., $r_1 = r_2 = r$. There are two pragmatic reasons for this simplification. First, the sensitivity analysis results related to these parameters are unclear and so we do not gain any valuable insight by exploring them. Second, the sign of some equilibrium values for some of the key variables are affected by the terms $2r_1 - r_2$ and/or $3r_1 - 2r_2$ and this fact forces us to keep the asymmetry between these parameters bounded so as to avoid meaningless results.

To investigate the likelihood of observing collusive behavior, we proceed by analyzing the effect of different parameters on the size of region III. In the previous subsection we concluded that, simply by introducing a constant initial allocation of permits, three different cases arise. Now, due to the larger number of varying parameters, by choosing the right combination of these parameters we could generate almost any imaginable case. Hence, we need to bound the range of possibilities in some way so as to avoid, on the one hand, meaningless results (such as negative output, negative abatement or negative emissions) and, on the other, a qualitative change in the nature of the solution. For this reason, we introduce the following assumptions in this subsection:

Assumption 1': $d_1, d_2 < p < \overline{p}$, *where* $\overline{p}$ is defined in (20).

Assumption 2: $e_1 > e_2$.

Assumption 3: $\hat{p}_2 < \hat{p}_1$.

The two first assumptions ensure nonnegative values for all the relevant variables. The idea is that the leader will still be the one who produces a larger amount of output and a larger amount of emissions. Hence, the follower will still be the one who finds it profitable to pollute zero for a lower value of p and such a value determines the upper bound for the range that is compatible with an interior solution, $\overline{p}$. If this is the case, it is natural to accept that Assumption 3 also holds; i.e., it is easier for the follower than it is for the leader to benefit from a price increase.

Under these assumptions, region III is still delimited by $\hat{p}_1$ and $\overline{p}$ and hence its size increases if $\overline{p}$ increases and/or $\hat{p}_1$ decreases. Proposition 3 summarizes how the size of this region depends on the parameters of the model. Table 1 presents a taxonomy of all the relevant effects.

PROPOSITION 3

The size of region III is increasing in the following cases:

a) *If the leader's marginal production cost,* c_1, *increases or the follower's marginal production cost,* c_2, *decreases.*

b) *If the parameter of the linear term in the abatement cost function decreases for the leader* (d_1) *or increases for the follower* (d_2).

c) *If the parameter of the quadratic term in the leader's abatement cost function,* t_1, *decreases* (*provided the number of free permits is moderate*) *or the equivalent follower's parameter,* t_2, *increases.*

d) *If the number of free permits received by the leader,* S_1, *is increasing regardless of the free permits received by the follower.* ■

Effects on thresholds	***Changes in model parameters***							
	c_1	***c_2***	***d_1***	***d_2***	***t_1***	***t_2***	***S_1***	***S_2***
$\Delta\overline{p}$	+	-	0	+	0	+	0	0
$\Delta\hat{p}_1$	-	+	+	0	+ (*)	0	-	0
$\Delta\left(\overline{p}-\hat{p}_1\right)$	+	-	-	+	- (*)	+	+	0

Table 1. Summary of sensitivity analysis results.

(*) For a moderate value of S_1.

Regarding point a) in Proposition 3, increasing the leader's production cost or reducing the follower's cost tends to erode the leader's advantage with respect to the follower, which has the effect of making the firms more symmetric in terms of their position in the market. The more symmetric the firms are, the more aligned their interests will be and hence it is more likely for them to find it profitable to collude. Table 1 shows that increasing c_1 has a twofold effect. On the one hand, $\overline{p}$ grows because the output of the follower increases, which makes it less likely for firm 2 to decide not to emit at all (in other words, the range of prices under which there is an interior solution widens). On the other hand, $\hat{p}_1$ decreases, as, due to the higher cost, firm 1 tends to produce less and to emit less and hence its total cost will be less sensitive to an increase in the price of permits. Both of these effects tend to enlarge the collusion region. Just the opposite occurs when c_2 increases. Firm 1 tends to produce more and pollute more and hence its cost becomes more sensitive to an increase in the price of permits (which increases the value of $\hat{p}_1$), whereas the follower tends to produce less and to reach the point where it finds it profitable to stop polluting ($\overline{p}$ decreases) sooner, which reduces the size of the collusion region.

As to the parameters of the abatement cost function (d_i and t_i), notice that, due to separability, each firm's parameters are only relevant for the own firm, but not for its rival. Both the linear and the quadratic term of firm 2 are irrelevant in determining the value of $\hat{p}_1$. However, increasing either of them makes the follower's abatement cost increase, which in turn makes it less likely to reach the point where it decides to pollute zero. In other words, it enlarges the relevant feasible range. The corresponding parameters for firm 1 are immaterial in determining the value of $\overline{p}$, their only relevant effect being on $\hat{p}_1$. Assuming a moderate value of the leader's initial endowment of permits, any increase in d_1 and t_1 makes the leader's abatement cost higher, which makes firm 1 become more sensitive to increases in the price of permits.

Finally, the initial allocation of permits is irrelevant for the upper bound of p, as it represents simply a fixed term in the cost (and the profit) function and so the optimal decisions are not affected. The value of a firm's profits is affected by its own endowment (not the rival's) and hence only S_1 is relevant in determining the size of region III. When the leader's free endowment increases, its cost becomes less sensitive to an increase in the price of permits and it will hence be more receptive to the idea of pushing the price up, thereby increasing the likelihood of observing collusive behavior.

4. Conclusions and policy implications

We have explored the possibility that two firms that compete a la Stackelberg in the output market and are subject to a CAT system could have incentives to manipulate the price of permits upward and increase their profits. We do so within a framework similar to that proposed by Ehrhart *et al.* (2008), with the difference that these authors restrict their study to symmetric situations, whereas we explore a situation that is asymmetric in nature. We also include a reading of their results in terms of scarcity rents generation. The main research question is whether the incentives for this type of collusive behavior still exist in a situation in which some firm has a dominant position and the other or others act as followers.

We have shown in a general model that the effect of a permit price increase on the firms' profit has an ambiguous sign as it has two effects: on the one hand, it raises cost but, on the other hand, it creates scarcity rents, of which each firm can only benefit from that part that is due to the rival's output reduction. This ambiguity opens the way for firms to benefit from a price increase and the possibility of colluding in order to manipulate the price upward. However, the asymmetric role of each firm means that the conditions under which a price is profit-enhancing are different for each of them.

Under a separable cost function, we first show that the profit functions are strictly convex in the permit price and secondly that the minima of the profit functions are different for both firms, which creates a region of disagreement within which the leader prefers the price to go down, whereas the follower prefers it to go up. This situation is ruled out in Ehrhart *et al.* (2008) by construction, as the interests of fully symmetric firms are always aligned.

The main message is that a leader-follower relationship in the output market reduces the scope for collusion to manipulate the price of permits upward. Actually, in a standard separable case with symmetric costs functions, if no free permits are distributed among the firms, the region within which there are incentives to collude shrinks to the extent of disappearing. The main policy implication of this finding is that a situation of market power in the product market can preclude the existence of incentives for collusion in the permit market.

Another central policy implication of our research is that distributing some permits for free (e.g. by means of grandfathering) allows the firms to capture a larger share of the scarcity rents and thus opens up the possibility for collusive behavior. The greater the number of permits distributed by a non-market scheme, particularly to firms that enjoy market power, the more incentives there are for collusion. The European Union is reducing the use of grandfathering and increasing the use of auctioning to distribute emission permits. The 2008 revised European Emission Trading Directive established the mandate that auctioning of allowances is to be the default method for allocating allowances as a fundamental change for the third trading period, starting in 2013. The arguments put forward by the European Commission (EC) to support the introduction of auctions are that auctioning "best ensures the efficiency, transparency and simplicity of the system, creates the greatest incentives for investment in a low-carbon economy and eliminates windfall profits".[13] Our results suggest an additional argument

[13] See http://ec.europa.eu/clima/policies/ets/cap/auctioning/faq_en.htm, section "Why are allowances being auctioned?". Alvarez and André (2014) present a discussion on the efficiency argument.

to reduce the use of grandfathering (and arguably to increase the use of auctioning), as it might introduce incentives for price manipulation.

Our final insight is that the likelihood of firms finding collusion profitable is very sensitive to the cost asymmetries between them. In general terms, the more asymmetric the firms are, the more difficult collusion becomes. Moreover, if a grandfathering scheme exists, the more permits are allocated to firms enjoying market power, the more likely collusion becomes.

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APPENDIX

Proof of Lemma 1

Using (24) and (25) in (21), we obtain the equilibrium values for emissions:

$$e_1^*\left(x_1^*, p\right) = \frac{db + rt\left(a-c\right) - p\left(b+tr^2\right)}{2bt}, \tag{A1}$$

$$e_2^*\left(x_2^*, p\right) = \frac{2bd + tr\left(a-c\right) - p\left(2b+tr^2\right)}{4bt}, \tag{A2}$$

and using the definition given in (20), we compute the value of $\overline{p}$ by equating (A2) to zero:

$$e_2^*\left(x_2^*, p\right) = 0 \Rightarrow p = \overline{p} = \frac{2bd + rt\left(a-c\right)}{2b+tr^2}. \tag{A3}$$

Using (24) and (25) in the inverse demand expression $P\left(X\right) = a - bX$, we get the equilibrium price of output: $P = \frac{a+3\left(c+pr\right)}{4}$. Using the equilibrium expressions for x_1, x_2, e_1, e_2 and P together with (19), we obtain the expressions for the equilibrium profits of both firms:

$$\Pi_1^*\left(p\right) = \frac{t\left(a-c-pr\right)^2 + 2b\left(p-d\right)^2}{8bt},$$

$$\Pi_2^*\left(p\right) = \frac{t\left(a-c-pr\right)^2 + 4b\left(p-d\right)^2}{16bt}.$$

Differentiating twice with respect to p, we conclude that the second derivative of both functions is positive and thus both of them are strictly convex in p. By inspection of the first derivative and bearing in mind (A3), we conclude that Π_1 has a minimum at $p = \hat{p}_1 = \overline{p}$, which implies that Π_1 is decreasing in p for all the feasible values of p below $\overline{p}$. We similarly conclude that Π_2 has a minimum at $\hat{p}_2 := \frac{tr(a-c)+4bd}{4b+tr^2}$, which implies that Π_2 is decreasing in p for $p < \overline{p}_2$ and increasing for $p > \overline{p}_2$.

The last step is to check that the thresholds are ordered in the right way. By direct comparison, we conclude that

$$d < \hat{p}_2 < \overline{p} \Leftrightarrow a - c > dr.$$

To prove that the last inequality is true, using (22) and the definition of abatement ($q_i = rx_i - e_i$), we conclude that, within the relevant range, $x_2 > \frac{e_2}{r} > 0$. Using the expression for x_2^* given in (25), we conclude that $x_2 > 0$ implies $a - c > rp$, and that this inequality, together with $d < p$ (Assumption 1), implies $a - c > dr$. QED.

Proof of Proposition 1

The result follows straightforwardly from Lemma 1: the relevant range for p *is* delimited by d and $\overline{p}$. As Π_2^* is strictly convex and reaches a minimum at $\hat{p}_2$, we conclude that it is strictly decreasing between d and $\hat{p}_2$ and strictly increasing between $\hat{p}_2$ and $\overline{p}$. As Π_1^* is strictly convex and reaches a minimum at $\hat{p}_1 = \overline{p}$, it is strictly decreasing between d and $\overline{p}$. This completes the proof. QED.

Proof of Lemma 2

As the expressions for e_i (i=1,2) are the same as in the basic case and the minimized cost function (34) is the same as (23), except for a constant term, it immediately follows that the expressions for x_i (i=1,2) are also the same as in the basic case. Using these values, we get the equilibrium profits of both firms

$$\Pi_1^*(p) = P(x_1^* + x_2^*)x_1^* - TC_1^*(x_1^*, p) = \frac{t(a-c-pr)^2 + 2b(p-d)^2 + 8btpS}{8bt},$$
$$\Pi_2^*(p) = P(x_1^* + x_2^*)x_2^* - TC_2^*(x_2^*, p) = \frac{t(a-c-pr)^2 + 4b(p-d)^2 + 16btpS}{16bt}.$$

The second derivative reveals that these functions are still strictly convex. Differentiating them with respect to p, we conclude that they have respective minima at

$$Arg \min_p \Pi_1^*(p) \equiv \hat{p}_1 = \frac{rt(a-c) + 2bd - 4btS}{2b + tr^2},$$
$$Arg \min_p \Pi_2^*(p) \equiv \hat{p}_2 = \frac{rt(a-c) + 4bd - 8btS}{4b + tr^2},$$

and it follows straightforwardly that both $\hat{p}_1$ and $\hat{p}_2$ depend negatively on S.

Regarding the order of the thresholds, by direct comparison we conclude that $\hat{p}_1 > \hat{p}_2 \Leftrightarrow 2brt(a-c-dr+2rSt) > 0$; however, in the proof of Proposition 1 we have proved $a-c-dr \geq 0$, which ensures that $\hat{p}_1 > \hat{p}_2$. Moreover, using (A3) we also conclude that $\overline{p} = \hat{p}_1 + \frac{4btS}{2b+tr^2} > \hat{p}_1$. Hence, we have that $\hat{p}_2 < \hat{p}_1 < \overline{p}$. To determine the relative position of d, let us first recall that, from Lemma 1, we know that $d < \overline{p}$ and hence we only have to check whether d is below $\hat{p}_2$, in the interval $(\hat{p}_2, \hat{p}_1)$ or in the interval $(\hat{p}_1, \overline{p})$. By direct comparison, we conclude the following:

$$\hat{p}_1 > d \Leftrightarrow S < \frac{r(a-c-dr)}{4b} = 2\tilde{S}, \quad \text{(A4)}$$

$$\hat{p}_2 > d \Leftrightarrow S < \frac{r(a-c-rd)}{8b} = \tilde{S} \ . \qquad \text{(A5)}$$

This completes the proof. QED.

Proof of Proposition 2

Let us first consider statement a). The results in regions I and II follow from Lemma 2 according to a similar reasoning to that used in the proof of Proposition 1. In region III, between $\hat{p}_1$ and $\overline{p}$, it is straightforward to conclude that both $\Pi_1^*(p)$ and $\Pi_2^*(p)$ are strictly increasing in p. Statements b) and c) follow straightforwardly from (A4), (A5) and Assumption 1. QED.

Proof of Proposition 3

Using (41) and (42) in (38), we obtain the equilibrium values for emissions:

$$e_1^*\left(x_1^*, p\right) = \frac{b(d_1 - p) + t_1 r\left[a + c_2 - 2c_1 - rp\right]}{2bt_1},$$

$$e_2^*\left(x_2^*, p\right) = \frac{2b(d_2 - p) + rt_2\left(a + 2c_1 - 3c_2 - rp\right)}{4bt_2}.$$

By imposing the non-negativity conditions on the follower's emissions, we obtain the upper bound value for the permit price, $\overline{p}$ in this case:

$$e_2^* \geq 0 \Leftrightarrow p \leq \overline{p} = \frac{2bd_2 + rt_2\left(a - 3c_2 + 2c_1\right)}{2b + r^2 t_2}. \qquad \text{(A6)}$$

By substitution of the relevant variables in the profit function, we obtain the expression for the leader's profit function in terms of the model parameters:

$$\Pi_1^*(p) = \frac{\left[a + c_2 - 2c_1 - rp\right]^2}{8b} + \frac{\left(p - d_1\right)^2}{4t_1} + pS_1$$

Differentiating with respect to p , we obtain

$$\frac{\partial \Pi_1^*}{\partial p} = \frac{2b\left(p-d_1\right)+4bt_1S_1-rt_1\left[a+c_2-2c_1-rp\right]}{4bt_1}$$

and, by equating this derivative to zero, we get the minimum value of p such that the leader finds it profitable to push the price up, $\hat{p}_1$:

$$\frac{\partial \Pi_1^*}{\partial p} \geq 0 \Leftrightarrow p \geq \frac{rt_1\left(a+c_2-2c_1\right)+2bd_1-4bt_1S_1}{r^2t_1+2b} = \hat{p}_1. \quad \text{(A7)}$$

By direct differentiation of the values of $\overline{p}$ and $\hat{p}_1$, we obtain the results in the proposition:

$$\frac{\partial \overline{p}}{\partial c_1} = \frac{2rt_2}{2b+r^2t_2} > 0\,; \qquad \frac{\partial \hat{p}_1}{\partial c_1} = \frac{-2rt_1}{2b+rt_1} < 0\,;$$

$$\frac{\partial \overline{p}}{\partial c_2} = \frac{-3rt_2}{2b+r^2t_2} < 0\,; \qquad \frac{\partial \hat{p}_1}{\partial c_2} = \frac{rt_1}{2b+rt_1} > 0\,;$$

$$\frac{\partial \overline{p}}{\partial d_1} = 0\,; \qquad \frac{\partial \hat{p}_1}{\partial d_1} = \frac{2b}{2b+rt_1} > 0\,;$$

$$\frac{\partial \overline{p}}{\partial d_2} = \frac{2b}{2b+r^2t_2} > 0\,; \qquad \frac{\partial \hat{p}_1}{\partial d_2} = 0\,;$$

$$\frac{\partial \overline{p}}{\partial S_1} = \frac{\partial \overline{p}}{\partial S_2} = 0\,;$$

$$\frac{\partial \hat{p}_1}{\partial S_1} = \frac{-4bt_1}{2b+rt_1} < 0\,; \qquad \frac{\partial \hat{p}_1}{\partial S_2} = 0\,;$$

$$\frac{\partial \hat{p}_1}{\partial t_1} = \frac{2br\left(a+c_2-2c_1-d_1r\right)-8b^2S_1}{\left[r^2t_1+2b\right]} \leq 0 \Leftrightarrow S_1 \leq \frac{r\left(a+c_2-2c_1-d_1r\right)}{4b};$$

$$\frac{\partial \overline{p}}{\partial t_2} = \frac{2br\left[a-3c_2+2c_1-rd_2\right]}{\left(2b+r^2t_2\right)^2} > 0,$$

where, in an interior solution, the numerator of the last expression must be positive for the follower's output to be positive. QED.