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Market Power and Windfall Profits in Emission Permit Markets

Beat Hintermann

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ETH
Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich

CEPE
Zurichbergstrasse 18 (ZUE E)
CH-8032 Zurich
www.cepe.ethz.ch

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Abstract

Market power in permit markets has been examined in some detail following the seminal work of Hahn (1984), but the effect of free allocation on price manipulation with market power in both output and permit market has not specifically been addressed. I show that in this case, the threshold of free allocation above which a dominant firm will increase the permit price is below its optimal emissions in a competitive market and that by means of permit allocation alone, overall efficiency cannot be achieved. In addition to being of general economic interest, this issue is relevant in the context of the EUETS. I find that the largest German, UK and Nordpool power generators received free allowances in excess of the derived threshold. Conditional on having price-setting power in both the electricity and permit markets, these firms would have found it profitable to manipulate the permit price upwards.

Keywords: Market power, emissions permit markets, air pollution, EU ETS, CO2, electricity generation, permit allocation, windfall profits, cost pass-through.

JEL codes: D42-43, L11-13, L94, Q52-54.

1. Introduction

During the first 18 months of the European Union Emissions Trading Scheme (EU ETS), the allowance price per ton of CO_2 was far above pre-market expectations. The price fell dramatically in April 2006 when the first round of emissions verifications showed the market to be over-allocated with permits and eventually reached zero by mid 2007, but it is not clear what drove the price so high in the first place. A series of studies (Mansanet-Bataller, Pardo and Valor, 2007; Rickels et al., 2007; Bunn and Fezzi, 2008; Alberola, Chevallier and Cheze, 2008; Hintermann, 2009a; b) have attempted to empirically explain the price path by market fundamentals such as fuel prices and weather variables, but only with limited success as fundamentals appear to only account for a small fraction of the allowance price variation, especially so for the period before the April price crash. As such, the high pre-crash price still lacks a satisfactory explanation to date. An inflated permit price in the sense that it is above marginal abatement costs of the market as a whole destroys the most powerful argument in favor of instituting pollution permit markets, which is to achieve a given emissions target at least cost.

In this paper I examine whether price manipulation within the EU power & heat sector could have driven the permit price above the efficient level. I set up a model where a dominant firm has market power in both the output and the permit market and explicitly account for a link between these markets. By solving the model I derive the permit allocation threshold above which the dominant firm will exercise its market power to increase the permit price in order to maximize overall profits in both markets. This threshold is below the neutral allocation threshold proposed by Hahn (1984) under the assumption of market power in the permit market only. This is the core result of my paper and means that even a dominant firm that is a net buyer in the permit market (which was the case for all large power firms in the EU ETS) could find it profitable to manipulate the permit price upwards, provided it receives a sufficiently large permit allocation. I further derive a second allocation threshold at which the distortion in the output market disappears. Because this second threshold is unambiguously below the first, this implies that efficiency in both markets cannot be achieved by means of permit allocation alone.

The interplay between permit and output market is at the root of what has become known as "windfall profits" in the empirical literature. If firms are able to pass through pollution costs to consumers but receive most (or all) permits allocated for free, they get reimbursed for costs they never had to incur. Windfall profits have been identified as an issue in permit markets in general (Vollebergh, De Vries and Koutstaal, 1997; Bovenberg and Goulder, 2000), and in particular in the EU ETS (Grubb and Neuhoff, 2006; Hepburn et al., 2006; Neuhoff, Keats and Sato, 2006; Sijm, Neuhoff and Chen, 2006; Smale et al., 2006). Such profits constitute a wealth transfer from consumers to firms but they do not impact efficiency directly[1] nor affect the permit price in a competitive market. This no longer holds under the presence of market power in both the output and permit market, because a price-setting firm will take windfall profits into account when making its production and permit purchase decisions. To counteract this effect, the permit allocation to the dominant firm must be below the firm's optimal permit demand under the assumption of perfect competition.

While it may be intuitive that my results differ from those derived by focusing exclusively on the permit market, they have not been presented in this form in the

[1] Handing out permits for free impacts efficiency through existing distortions such as income taxes. In theory, the revenue from a tax or selling permits has to be recycled through lower distortionary taxes to achieve (Bovenberg and Goulder, 1996; Parry, 1995).

economics literature. The literature that is most closely related to my paper is that concerned with what is known as "raising rivals' cost" strategies, whereby a dominant firm influences its position in the output market indirectly via manipulation of input prices (e.g. an emissions permit price). However, no direct market power in the output market is assumed and the focus is on firms expanding their market share at the expense of the fringe rather than consumers (see literature section below for a more detailed review). Furthermore, no new allocation threshold is derived based on raising rivals' costs, and welfare implications are examined at Hahn's threshold of neutral allocation.

I believe that my results are not just of theoretical interest but that they are empirically relevant for two reasons: First, the assumption of direct market power in both markets is appropriate: If a firm has market power in the permit market, it almost certainly also has market power in the output market if the latter is a subset of the former (as in the EU ETS).[2] Second, the most likely candidates for price manipulation in the EU ETS are power generators, and they were underprovided with permits relative to their expected emissions. I show that making them net buyers in the market does not necessarily prevent permit price inflation. Using market data from the EU ETS I show that the power and heat sector received a permit allocation that exceeded the allocation threshold derived here. My results imply that the presence of price-setting power in both markets by a firm (or group of firms) in the power sector would have resulted in an inflation of both permit and output price.

[2] It is of course possible that large firms perceive no market power at all, or market power in the output market only. What I'm arguing against is the assumption of market power in the permit market but not in the output market.

2. Literature of market power in permit markets

One of the best-known results about market power in permit markets is Hahn's (1984) finding that the permit price is an increasing function of the dominant firm's permit allocation. If this firm is a net buyer of permits, it will exert its power to decrease the permit price in order to minimize compliance costs, and vice versa.

Westskog (1996) extends the analysis to a Cournot model involving multiple firms and Van Egteren and Weber (1996) allow for noncompliance, but they arrive essentially at the same conclusions. Liski and Montero (2005) examine banking behavior of a dominant firm and find that the firm exhausts its stock of banked permits slower than it would if it had no market power, and it does so by manipulating the permit price upwards. This is the intertemporal equivalent of Hahn's result.

Maeda (2003) develops a model where one dominant firm is a net seller, and a second dominant firm as well as the aggregate of the fringe are net buyers of permits. Again, market power is assumed to exist only in the permit but not the output market. Using linear marginal abatement costs and assuming that the two dominant firms engage in Nash bargaining, he argues that the permit price will never be below the "efficient" price, i.e. the price that would emerge if all firms were price takers. His results are therefore not fully equivalent to Hahn's, but they are driven by the rather specific model setup. If the only dominant firm is a net buyer, the fringe has an aggregate permit surplus and/or marginal abatement costs are nonlinear, the resulting price could fall below the efficient price.

The issue of market power in both permit and output markets is closely related to the literature pertaining to "raising rivals' costs" (Salop and Scheffman, 1983; Krattenmaker and Salop, 1986b; a; Salop and Scheffman, 1987; Hart and Tirole, 1990; Ordover, Saloner and Salop, 1990), henceforth referred to as RRC. The focus of this literature is the theory that predatory firms may increase their market share and overall profits by artificially increasing industry costs, under the assumptions that these costs are lower for the dominant firm than for the fringe. These increased costs can take many forms, including the institution of mandatory standards, labeling, advertising etc, all of which are expected to be less costly on a per-output basis for the dominant firm than for the price-taking fringe. One particular version of RRC is to over-purchase necessary inputs of production (Salop and Scheffman, 1987), which is a profitable strategy if the output price increase from this manipulation exceeds the firm's average cost increase.

A number studies have applied the theory of RRC to the context of a permit market, which can be understood as a necessary input for production. The first of these is by Misiolek and Elder (1989), who set up a model where a dominant firm has market power in the permit market, which enables it to increase rivals' costs in the output market via the permit price. This additional tool, which they call exclusionary manipulation, leads the firm to buy more permits than what it would buy if it were to focus on compliance cost minimization alone (i.e. Hahn's case). In the monopoly case (net permit seller), the increased permit demand unambiguously leads to an increase in permit price distortion and overall efficiency. However, in the case of a net buyer, this effect may result in a permit demand by the dominant firm that is closer to the efficient level than without the link between the two markets, and thus in an increased overall efficiency. If the exclusionary effect is very strong,[3] it can even lead the net buyer to push the permit price beyond its efficient level, which is qualitatively similar to my findings.

[3] The strength of the exclusionary manipulation effect is a function of the dominant firm's degree of market power in the permit market, the sensitivity of the fringe's product output to changes in the permit price, and the own-price elasticity of consumer demand and fringe supply.

Von der Fehr (1993) extends the analysis to the case of two dominant firms that engage in Cournot behavior and focuses on exclusionary manipulation, whereas Sartzetakis (1997a) addresses positioning (predatory) behavior based on RRC in emissions permit markets. He finds that the more stringent the environmental regulation, the more profitable RRC will be, and that welfare implications are ambiguous and depend on the efficiency of the dominant firm relative to the fringe. In a different paper, the same author examines welfare implications under limited information and concludes that in spite of price manipulation, overall welfare is greater in a permit market than under command and control (Sartzetakis, 1997b).

Although this literature is very closely related to my paper and agrees with my key finding that dominant net permit buyers may find it optimal to inflate the permit price, there are important differences: First, RRC abstains from computing an initial permit allocation threshold where the exclusionary effect exactly cancels out the cost-minimizing effect for a net buyer. In any case, such a threshold would be different to the one derived here and it would result in full efficiency. This is because in the RRC setting, the dominant firm only perceives direct market power in the permit market and is able to influence the price in the output market only indirectly via the permit price. In contrast, the presence of two distortions in my model makes it impossible to obtain full efficiency by means of one policy instrument alone.

Second, the focus of RRC is exclusionary manipulation where the dominant firm increases its profits at the expense of the fringe. In my model, profits from jointly manipulating output and permit prices accrue to all firms in the industry and they come at the expense of consumers and taxpayers. In fact, fringe firms can free-ride on the manipulative actions of the dominant firm because they can pass on the increased compliance costs to consumers and enjoy windfall profits without incurring the costs of price manipulation. And third, whether or not RRC is profitable for a firm depends on its costs relative to that of the fringe. As I show below, in my model even extremely pollution-intensive firms can find it profitable to push up the permit price, provided that it receives a sufficiently generous amount of initial allocation.

As a complement to this theoretical literature, a number of experimental studies assess the empirical importance of different features of permit markets, including market power (Muller and Mestelman, 1998). Godby (2002) tests Hahn's and Misiolek's theory in accordingly designed laboratory experiments and finds that it predicts actual outcomes better than theory that is based on completely competitive markets, and that the effect of market power may be significant. Brown-Kruse et al. (1995) carry out similar experiments and likewise find that market power matters, especially when the dominant firm engages in more than simply cost-minimizing manipulation but takes the output market into account. Although the experimental setups are not directly applicable to my model because they follow the assumption of RRC in that the dominant firm only perceives direct market power in the permit market, they nevertheless indicate that market power can be important, especially when it is not limited to cost-minimizing behavior in the permit market.

3. Model

In the following I set up a simple model for an industry sector containing N firms that is subject to an emissions permit market.[4] I define the cost function for firm $i \in N$ as $C^i(q_i, e_i)$, a continuous function which depends on output q_i and emissions e_i and is twice differentiable in both arguments. Costs are increasing in

[4] This permit market may also include other sectors, but for simplicity I will confine the analysis to one sector. Note that the more sectors are covered by the permit market, the less tenable is the assumption of market power in the permit but not the output market.

output, decreasing in emissions and convex in both arguments, such that $C_q^i > 0$, $C_{qq}^i > 0$, $C_e^i < 0$, $C_{ee}^i > 0$, $C_{qe}^i < 0$ and $C_{qq}^i C_{ee}^i - \left(C_{qe}^i\right)^2 > 0$. I assume that firm 1 has market power in both the output and the permit market.

To study the equilibrium, I start by analyzing the behavior of firms $i = 2,...,N$ that comprise the price-taking fringe, before I move on to the dominant firm. The fringe's profit maximization problem is

(1)
$$\max_{q,e,x} \Pi_i = pq_i - C^i(q_i, e_i) - (x_i - \bar{x}_i)\sigma$$
$$s.t.\ e_i \leq x_i$$

where p is the output price, σ the permit price, x_i refers to permit purchases and $\bar{x}_i$ is firm *i*'s free permit allocation. With a binding cap, I can substitute the constraint into the objective function and arrive at the familiar first-order conditions that marginal production costs equal the output price, and marginal abatement costs equal the permit price. This implicitly defines the fringe's optimal output, emissions and permit purchase decisions:

(2)
$$\begin{matrix} p = C_q^i(\cdot) \\ \sigma = -C_e^i(\cdot) \end{matrix} \quad \Rightarrow \quad \begin{matrix} q_i^* = q_i^*(p, \sigma) \\ e_i^* = x_i^* = x_i^*(p, \sigma) \end{matrix}$$

The dominant firm takes (2) into account when maximizing its own profits. It faces an inverse demand function and a permit market-clearing condition of

(3)
$$p = P(Q) = P\left(q_1 + \sum_{i=2}^{N} q_i^*(p, \sigma)\right)$$
$$S = x_1 + \sum_{i=2}^{N} x_i^*(p, \sigma)$$

where S is the overall emissions cap and q_1 and x_1 are the dominant firm's output and permit purchase decisions, respectively. This system of equations describes a fixed point with a mapping of $F\left[p(q_1,x_1),\sigma(q_1,x_1)\right]\rightarrow\left(p(q_1,x_1),\sigma(q_1,x_1)\right)$. A unique solution exists if the vector (p,σ) belongs to a convex set (which is trivially true for prices), and $F[\cdot]$ is upper-semicontinuous and monotone, which is assured by the continuity and monotonicity of the demand function $P(Q)$ and the cost functions $C^i(q_i,e_i)$.

From equations (1)-(3) it follows that the output price and the permit price are both a function of the dominant firm's output and permit purchase decisions:

$$p=p(q_1,x_1)$$
$$\sigma=\sigma(q_1,x_1)$$

The impact of the dominant firm's output and permit purchase decisions on the output and permit price can be assessed using comparative static calculations and is summarized in the following Lemma:

<u>Lemma 1:</u>

The dominant firm's output and permit purchase decisions will influence output and permit price jointly such that

$$\frac{\partial p}{\partial q_1}<0;\qquad \frac{\partial p}{\partial x_1}>0$$
$$\frac{\partial \sigma}{\partial q_1}<0;\qquad \frac{\partial \sigma}{\partial x_1}>0$$

(proof in appendix)

The dominant firm's profit maximization problem and the resulting first-order conditions are

(4) $$\max_{q_1,x_1,e_1}\Pi_1=p(q_1,x_1)q_1-C^1(q_1,e_1)-(x_1-\bar{x}_1)\sigma(q_1,x_1)+\lambda(x_1-e_1)$$

(4a) $$p(\cdot)+\frac{\partial p}{\partial q_1}q_1-C_q^1(\cdot)-(x_1-\bar{x}_1)\frac{\partial \sigma}{\partial q_1}=0 \qquad (q_1>0)$$

(4b) $$\frac{\partial p}{\partial x_1}q_1-\sigma(\cdot)-(x_1-\bar{x}_1)\frac{\partial \sigma}{\partial x_1}+\lambda=0 \qquad (x_1>0)$$

(4c) $$-C_e^1(\cdot)=\lambda$$

(4d) $$x_1\geq e_1;\quad \lambda\geq 0;\quad \lambda(x_1-e_1)=0$$

The last first-order condition implies that the constraint may not be binding. To analyze the incentive of the firm to manipulate the permit price in either direction I combine (4b) and (4c) to get

(5) $$-C_e^1(\cdot)=\sigma(\cdot)+(x_1-\bar{x}_1)\frac{\partial \sigma}{\partial x_1}-\frac{\partial p}{\partial x_1}q_1$$

If with a permit price increase the additional revenue from cost pass-through (the last term on the RHS) outweighs the higher permit purchase costs (the second term), then the firm's marginal abatement costs are below the permit price. This means that it will under-abate -or, equivalently, over-purchase permits-relative to the situation where it perceives no price-setting power through its permit purchase decision in either market[5] $(\partial\sigma/\partial x_1=\partial p/\partial x_1=0)$ and thus push up the permit price. Moreover, if the revenue effect outweighs the compliance cost effect to the point where $-C_e^1=0$, then it will not abate at all and $e_1=e_1^{BAU}\leq x_1$, where e_1^{BAU} refers to business-as-usual (BAU) emissions in the absence of a permit market. Conversely, if compliance costs outweigh increased revenue the firm will find it optimal to under-purchase permits in order to depress the permit price and over-abate accordingly and over-abate accordingly. This can be summarized as

[5] Note that it still may perceive market power through its output decision. Equation (5) strictly applies to output and permit price manipulation through the permit purchase pathway.

$$(6)\qquad \frac{\partial p}{\partial x_1} q_1 \begin{matrix} > \\ = \\ < \end{matrix} (x_1 - \bar{x}_1) \frac{\partial \sigma}{\partial x_1} \Rightarrow \begin{matrix} -C_e^1 < \sigma \\ -C_e^1 = \sigma \\ -C_e^1 > \sigma \end{matrix}$$

Condition (6) implies that there is a specific amount of free allocation that will cause the dominant firm to set its marginal abatement costs equal to the permit price. Solving (6) for this threshold allocation $\bar{x}_1^0$ yields

$$(7)\qquad \bar{x}_1^0 = x_1 - \frac{\partial p / \partial x_1}{\partial \sigma / \partial x_1} q_1$$

This quantity is unambiguously smaller than the firm's actual permit purchases or emissions (since $e_1 = x_1$ in a region around $\bar{x}_1^0$, provided that the overall cap is binding).

Note that the firm's optimal permit purchases and output are a function of its allocation, such that the threshold in (7) is difficult to compute ex-ante, except for very simple functional forms of the cost function and permit and electricity demand. However, the threshold can be evaluated relatively easily ex-post when making some simplifying assumptions about consumer demand response (see below).[6] Equations (6)-(7) lead to the following result:

<u>*Result 1*</u>

a. If the dominant firm receives a free permit allocation equal to $\bar{x}_1^0$, it acts as a price taker in the permit market in the sense that it sets its marginal abatement costs equal to the permit price.

[6] This caveat applies to some extent also to Hahn's results. Only if the firm's cost function is known can the regulator compute its efficient emissions and thus determine $\bar{x}_1^H$. The difference is that in my setup, the regulator also needs to know the firm's degree of market power and find a closed-form or numerical solution for $x_1^*(\bar{x}_1)$.

b. If the dominant firm's allocation is greater than $\bar{x}_1^0$, its marginal abatement costs below the permit price and it manipulates the permit price upwards by over-purchasing permits relative to the situation where its permit purchase decision does not influence market prices, and vice versa.

c. The threshold allocation $\bar{x}_1^0$ is smaller than the firm's emissions and necessarily makes the firm a net buyer of permits.

Result 1 is the core finding of this paper and states that even if the dominant firm is a net buyer of permits it can find it in its interest to manipulate the permit price upwards, provided that its allocation is sufficiently high.

Note that this is a generalization of Hahn's result, which I will denominate as $\bar{x}_1^H = x_1$: A dominant firm will only abstain from manipulating the price if it receives exactly the number of allowances necessary to cover its emissions and therefore does not trade. To see this, simply set $\partial p / \partial x_1 = 0$ in (6) or (7), thus eliminating the link between output and permit markets. Also note that if the second term on the RHS on (7) is sufficiently large (i.e. if the impact of the firm's permit purchases on output and permit price is sufficiently strong) then $\bar{x}_1^0 < 0$. In this case, even full auctioning would lead the firm to choose a permit price that is greater than its abatement costs.

So far I have focused on the effect of permit allocation on the permit price. However, as is clear from (3) and (4), the dominant firm's allocation also has an impact on the output price. I start by re-writing (4a) as

(8) $$p(\cdot) = C_q^1(\cdot) - \frac{\partial p}{\partial q_1} q_1 + (x_1 - \bar{x}_1) \frac{\partial \sigma}{\partial q_1}$$

With neither market power nor a permit market there would be the standard outcome that price equals marginal production cost, i.e. $p = C_q^1$. Market power in the output market increases the output price by the second term on the RHS, which is also a familiar result. The last term describes the effect of linking a permit market to the output market. Because $\partial\sigma / \partial q_1 < 0$, this term decreases (increases) the output price if the firm is a net buyer (seller) of permits. Substituting Hahn's result of $\overline{x}_1^H = x_1$ would cancel this third term, but it would not remove the output price distortion introduced by the second term. To see how my generalized threshold $\overline{x}_1^0$ performs in this case, I solve (5) for $x_1 - \overline{x}_1$ and substitute into (8) to get

(9) $$p(\cdot) = C_q^1(\cdot) - \frac{\partial p}{\partial q_1} q_1 + \frac{\partial p / \partial x_1}{\partial\sigma / \partial x_1} \frac{\partial\sigma}{\partial q_1} q_1 + \frac{\partial\sigma / \partial q_1}{\partial\sigma / \partial x_1}(-C_e^1 - \sigma)$$

By construction, allocating $\overline{x}_1^0$ to the dominant firm eliminates the last term, as in this case the marginal abatement costs are equal to the permit price. The third term on the RHS is negative and thus decreases output price distortion. However, the price distortion is not fully removed because it can be shown that

(10) $$\frac{\partial p / \partial x_1}{\partial\sigma / \partial x_1} \frac{\partial\sigma}{\partial q_1} > \frac{\partial p}{\partial q_1}$$ (proof in appendix)

It follows immediately that the output price can be brought to is efficient level only by allocating less than $\overline{x}_1^0$ to the dominant firm, because in this case the last term will be negative. The threshold allocation to the dominant firm that yields $p = C_q^1$ can be computed using (8) and is

(11) $$\overline{x}_1^{00} = x_1 - \frac{\partial p / \partial q_1}{\partial\sigma / \partial q_1} q_1$$

The fact that $\overline{x}_1^{00} < \overline{x}_1^{0}$ can easily be verified by using the inequality in (10). This leads to the following result:

Result 2:

a. If the dominant firm receives an allocation of $\overline{x}_1^{00}$, the output price is equal to its marginal production costs. If the firm receives more than $\overline{x}_1^{00}$, the output price is greater than its marginal production costs, and vice versa.

b. The first-best solution in the sense that both the output and the permit price are at their competitive levels cannot be achieved by means of permit allocation alone, because $\overline{x}_1^{00} < \overline{x}_1^{0}$.

c. If the firm receives more than $\overline{x}_1^{0}$ (less than $\overline{x}_1^{00}$), both output and permit price will are distorted upwards (downwards) relative to the marginal costs, along with total regulatory costs. If the firm's allocation is $\overline{x}_1^{00} < \overline{x}_1 < \overline{x}_1^{0}$, the output price will be increased whereas the permit price will be decreased relative to competitive levels, and the overall effect on regulatory costs is ambiguous.

Results 1 and 2 imply that under the assumption of market power in both markets, the amount of free allocation is crucial for price distortion, and that a "neutral" allocation will result in an inflation of both output and permit prices.

4. Application

In this section I apply my findings to market data from the EU ETS, specifically to the German, UK and Nordpool power markets.

4.1 The European Union Emissions Trading Scheme (EU ETS)

In the following I describe the main features of the EU ETS. For a more detailed introduction to the market I refer the interested reader to Kruger & Pizer (2004) and the European Environment Agency's technical report (2006).

The EU ETS covers CO_2 emissions from 6 broadly defined industry groups in all countries of the EU. These sectors are power & heat, metals and coke ovens, oil refineries, glass & ceramics, cement & lime, and paper & pulp. In the first phase, about 11,000 individual installations received a total of 2.1 billion EU allowances (EUAs) annually, mostly at no cost. One EUA gives the bearer a one-time right to emit one ton of CO_2.

The market is organized into distinct trading phases. The first phase spanned the years 2005-2007 and was considered a pilot run for the second phase, which coincides with the Kyoto compliance period of 2008-2012. Pilot phase allowances could not be banked into the second phase and lost their value if unused for compliance. Future phases are planned to last five years each, with no banking restrictions from one phase to the next. On the other hand, borrowing is not allowed between any two phases. But because firms receive annual allowances in March of every year but don't have to surrender allowances until the end of April, they can effectively bank and borrow across time within a trading phase.

Firms can trade allowances freely within the EU. By April 31 of each year, firms have to surrender permits corresponding to their emissions in the previous calendar year. For every ton of CO_2 emissions for which firms cannot surrender an allowance, they were fined a penalty of €40 in the first phase, whereas the penalty for the current (i.e. second) phase is €100. In addition, firms have to surrender the missing allowances in the following year.

Jurisdiction in the EU ETS is divided between the EC and the member states. The latter are required to submit detailed national allocation plans (NAPs) to the EC for every phase anew (in other words, the cap changes in every phase). This is a two-step procedure: First, member states have to decide how much of their overall emissions reduction burden (as defined by their individual Kyoto commitments) they want to assign to the EU ETS sectors within their countries, with the remainder of the burden falling on other sectors such as transportation and households. In a second step, the allowances have to be distributed among the individual installations. All NAPs have to be approved by the EC in order to minimize competitive distortions among similar companies in different member states.[7]

The scheme is based on Directive 2003/87/EC, which became law on October 25, 2003. This left little time for firms and EU member countries to prepare for the market. In setting up the first-phase NAPs, countries were faced with the problem that they had very little information about firms' historic emissions. Unlike US power plants that were subject to emissions regulations since at least the mid 1990's, most firms in the EU had never had to disclose emissions of other than local pollutants. The member countries addressed this lack of data by using industry projections generated by the firms themselves, introducing clear incentive problems.

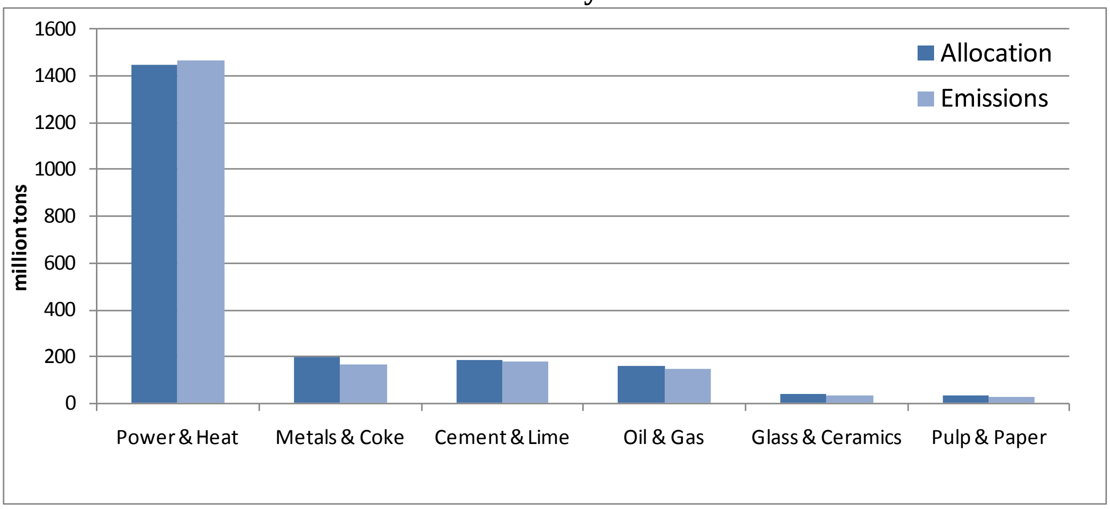
Permit allocations, trades and actual emissions are recorded in national registries run by each Member State, where all installations that are subject to the EU ETS have their individual accounts. The Central Administrator of the EU runs a central registry, called the Community Independent Transaction Log (CITL), which connects the 27 national registries and checks the recorded transactions for

[7] Although the Trading Directive defines both least-cost achievement of the Kyoto targets and harmonization between member states as explicit goals, Boehringer and Lange (2005) show that both cannot be achieved simultaneously, given the constraint of free permit allocation. Thus, there is a tradeoff between efficiency and fairness in terms of a "level playing field" between similar firms located in different member states.

irregularities. It is the duty of member states to establish and/or verify firms' actual emissions by multiplying energy inputs with appropriate conversion factors.

Allocation and emissions by sector are shown in Figure 1. The power & heat sector received nearly 70% of the total allocation. At the same time, this was the only sector with a net shortage of allowances, with all other sectors acting as net allowance suppliers. [8] In terms of installation size, about 90 % of the covered firms are relatively small (<1 million ton (Mt) CO_2/y) and received about 19% of the total allocation. On the other extreme of the spectrum are the very large emitters (>10 Mt/y), which make up less than one percent of all installations in number but received more than a third of all allowances. Most of these large emitters are power plants.

Figure 1: Allowance allocation and emissions by sector for 2006



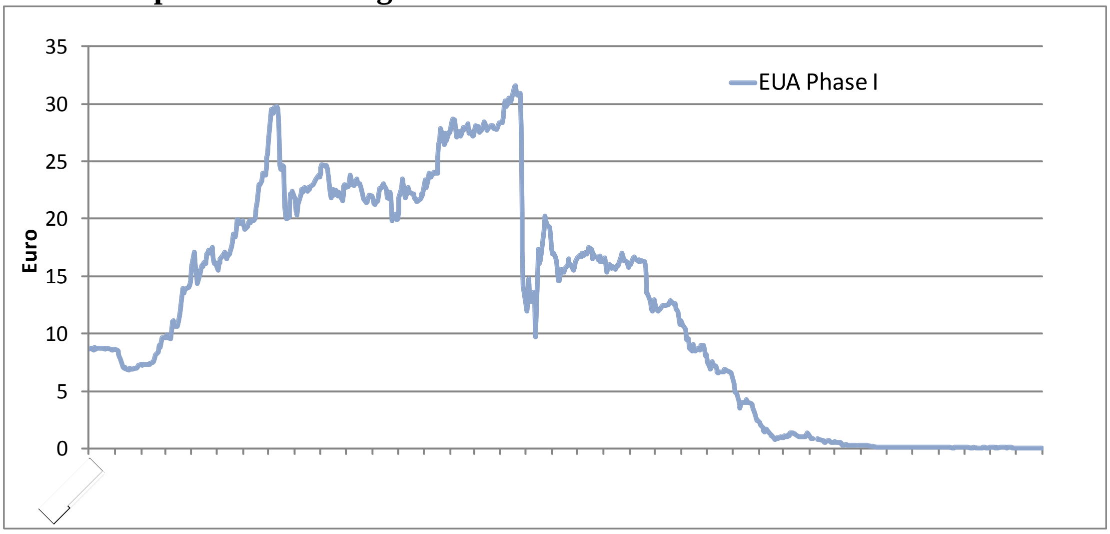
Pre-market expectations of the allowance price were generally low,[9] and the steep price increase took many observers by surprise. Figure 2 shows the EUA price during Phase I. For over a year, the allowance price was above €20, and at its peak it reached over €31 in April 2006. The April price crash was triggered by the first

[8] Note that these are aggregate numbers; individually, there were power stations with an allowance surplus in 2005 and 2006, and many industrial firms with a shortfall.

[9] In a simulation-based analysis of the EU ETS, Reilly and Paltsev (2005) calculated market-clearing marginal abatement costs to be € 0.6-0.9 for their base scenario, with prices in even the most extreme scenarios below €7. Medium price estimates by brokers were somewhat higher, around of €5.00 for the first phase (PEW Center on Global Climate Change, 2005).

round of emissions verifications, which revealed that 2005 emissions were 94 Mt below the cap.[10] The second round of emissions verifications in May 2007 again found an allowance surplus, but this no longer had a significant impact since prices had decreased to a few cents. Liquidity was overall high, and a significant amount of the total allocation was traded even in the first year.

Figure 2: EUA price and trading volumes



The fact that aggregate emissions in all three years were below the total allocation for those years is either due to over-abatement or over-allocation. Without the possibility of banking, abating more than necessary in the first period and using the freed-up allowances for compliance in later periods with a tighter cap is not an option. A preliminary analysis (Ellerman and Buchner, 2008) implies that at least a part of the gap between emissions and allocation was due to abatement. The over-allocation was most likely not intentional but brought on by the fact that the EU did not have reliable information about firms' actual emissions before the market started

[10] Emissions verification numbers were planned to be announced in May, but in late April reports were leaked that Belgium, France, the Czech Republic, the Netherlands and Estonia all had allowance surpluses, and the allowance shortage in Spain was much smaller than anticipated. By early May, the market was found to be 63.6 Mt long, with 21 countries reporting. Interestingly, the announcement of the Polish surplus of another 26 Mt in September 2006 did not affect prices very much.

and largely defined allocations based on industry projections, with obvious incentive problems.

4.2 Empirical approach to evaluating (7)

There is evidence that the power & heat sector was subject to significant windfall profits (Grubb and Neuhoff, 2006; Hepburn et al., 2006; Neuhoff, Keats and Sato, 2006; Sijm, Neuhoff and Chen, 2006), which sets the stage for price manipulation as analyzed in the previous section. According to market observers (e.g. Point Carbon), it was the sustained allowance purchases from power & heat, combined with a relatively short allowance supply from the other sectors, that drove the price to the –in hindsight-very high level. There are a number of very large power producers for which the assumption of some market power seems plausible.

The main difficulty to empirically assess (7) is that the effect of a dominant firm's permit purchase decisions on the output and the permit price is generally unknown. I will work around this problem by making the simplifying assumption that the dominant firm's output does not change in the short run, i.e. during the first 18 months of the market. I will justify this assumption below. Totally differentiating the output and the permit price and dividing the former by the latter gives

(12) $$\frac{dp}{d\sigma} = \frac{\partial p / \partial x_1 * dx_1 + \partial p / \partial q_1 * dq_1}{\partial \sigma / \partial x_1 * dx_1 + \partial \sigma / \partial q_1 * dq_1}$$

It follows directly that for fixed q_1 ,

(13) $$\frac{dp}{d\sigma} = \left. \frac{\partial p / \partial x_1}{\partial \sigma / \partial x_1} \right|_{dq_1 = 0}$$

At $\bar{x}_1 = \bar{x}_1^0$ the emissions constraint will be binding such that $x_1 = e_1$. Substituting (13) into (7), dividing both sides by e_1 and rearranging yields the following condition:

(14) $$\frac{dp/d\sigma}{1-\bar{x}_1/e_1} \begin{smallmatrix} > \\ = \\ < \end{smallmatrix} \rho_1 \equiv \frac{e_1}{q_1} \quad \Rightarrow \quad \bar{x}_1 \begin{smallmatrix} > \\ = \\ < \end{smallmatrix} \bar{x}_1^0 \quad \text{for} \quad \bar{x}_1/e_1 < 1$$

$$\bar{x}_1 > \bar{x}_1^0 \quad \text{for} \quad \bar{x}_1/e_1 \geq 1$$

where ρ_1 is the dominant firm's emission intensity. Condition (14) can be evaluated using market data. If the left-hand side (LHS) is greater than the right-hand side (RHS), it follows that the threshold $\bar{x}_1^0$ was exceeded, and vice versa. The second line in condition (14) is due to the fact that the allocation threshold is necessarily exceeded for a net seller of permits.

Except for very simple functional forms, it is not possible to evaluate (14) ex ante, because the firm's optimal emissions e_1 cannot be computed. However, once actual output and emissions can be observed, it is possible to assess whether $\bar{x}_1^0$ was exceeded.

The assumption of no output change on behalf of the dominant firm is rather stringent and needs some justification. First, I argue that in the short run, consumer demand for electricity is very inelastic. Indeed, the introduction of the EU ETS did not seem to impact electricity consumption in the three markets in question. Table 1 shows the results from a least-squares regression of monthly electricity consumption through June 2006 on a set of monthly dummies, a quadratic time trend, average monthly temperature and a dummy that is equal to zero before, and equal to one after the introduction of the EU ETS (January 2005). The latter is not significant at $p<0.05$

for any market. For the Nordic market, the coefficient is significant at $p<0.06$ but positive rather than negative, as could be expected with a demand response due to an increased electricity price. Possible reasons for a very low short-term demand response include the fact that the most efficient means to reduce electricity use is to make changes in industrial production equipment or the portfolio of household appliances towards increased energy efficiency, both of which takes time. If a zero aggregate demand response is due to an unchanged production schedule by all generators, including the dominant firm, then my assumption is obviously met.

Table1: Impact of EU ETS on aggregate demand for Germany, UK and Norpool

Dependent variable:	Germany		UK		Nordpool	
Electr. cons. (GWh)	coefficient	t-stat	coefficient	t-stat	coefficient	t-stat
EU ETS	0.333	0.60	0.153	0.78	0.664	1.95
period	-0.056	-2.29	0.193	6.06	0.099	6.60
periodsq	0.0003	2.44	-0.0006	-5.85	-0.0003	-4.66
Jan	2.076	3.92	1.166	4.93	1.237	3.75
Feb	-1.911	-3.61	-2.600	-11.05	-2.352	-7.02
Mar	0.748	1.27	-0.386	-1.58	-0.646	-1.99
Apr	-3.130	-4.15	-3.563	-12.34	-4.422	-11.27
May	-3.326	-3.33	-3.527	-9.46	-5.028	-9.58
Jun	-4.065	-3.45	-4.231	-8.51	-6.585	-9.94
Jul	-2.729	-2.22	-3.047	-5.44	-6.519	-8.64
Aug	-3.514	-2.88	-3.289	-5.96	-4.875	-6.61
Sep	-3.451	-3.50	-3.557	-7.63	-5.300	-9.07
Oct	-0.750	-0.97	-1.543	-4.42	-2.658	-6.16
Nov	-0.154	-0.27	-0.895	-3.64	-1.607	-4.69
Temp[a]	-0.122	-3.58	-0.148	-6.58	-0.197	-9.30
cons	55.343	33.59	22.317	8.23	36.401	35.54
Data range[b]	1/1996-12/2007		4/2001-12/2007		1/1996-12/2007	
N	144		81		144	
R2	0.89		0.98		0.98	

a: Average temperature in Fahrenheit for Munich (Germany), London (UK) and the average of Stockholm, Copenhagen and Helsinki(Nordpool)

b: Based on availabiliy of consistently defined historic consumption

However, it is also possible that the zero aggregate demand response masks an increase of the dominant firm's market share at the expense of the fringe (the main pathway of increased profits in the raising rivals' cost literature), or that an output decrease by the dominant firm was (at least partially) offset by an increase in fringe output. From (7) we know that the dominant firm either finds it in its interest to increase the permit price if its allocation is greater than $\overline{x}_1^0$ by over-buying permits (in the sense that its marginal abatement costs are below the permit price), and vice versa. But this means that it is less costly to produce on the margin for the dominant firm than for fringe firms, which equate their marginal abatement costs to the permit price. It follows directly that under permit price inflation ($d\sigma > 0$) we have that $dq_1 > 0$, and vice versa, such that $d\sigma / dq_1 > 0$ in any case. It is straightforward to show that

(15) $$\frac{dp}{d\sigma} < \frac{\partial p / \partial x_1}{\partial \sigma / \partial x_1} \quad \text{for} \quad d\sigma / dq_1 > 0,\ dq_1 \neq 0$$ (proof in appendix)

Therefore, using the approximation $dp / d\sigma$ instead of $(\partial p / \partial x_1) / (\partial \sigma / \partial x_1)$ decreases the LHS of (14) and therefore the likelihood that we find the threshold $\overline{x}_1^0$ to be exceeded. Since the purpose of the empirical section is to find out whether it is possible that dominant firms in the power sector inflated the permit price, this is equivalent to making the test more conservative.

4.3 Application to German, UK and Nordpool electricity markets

The effect of the allowance price on the electricity price ($dp/d\sigma$) depends on the emission intensity of the marginal generator and the cost pass-through rate. For a more detailed description how these concepts are defined and the underlying theory, see Sijm et al. (2008).

The emission intensity is largely determined by the fuel used for generation and ranges are zero for hydro, wind and nuclear, about 0.4 tCO_2/MWh electricity for combined-cycle gas turbines (CCGT), 0.95 tCO_2/MWh electricity for pulverized hard coal and 1.18 tCO_2/MWh for lignite.[11] During the day, many different generators can be at the margin for some time. Because of different generation portfolios across countries, the marginal generators across countries as well as across time.

The cost pass-through rate depends on the market structure and the price elasticity of consumer demand for electricity. With full cost pass-through (as can be expected with a zero demand elasticity), the carbon cost of the marginal generator is fully passed on to consumers. The effect of the permit price on the electricity price is the product of the cost pass-through rate and the emission intensity of the average marginal generator.

Table 2 presents estimates for $dp/d\sigma$ for Germany and the UK computed from values given in Sijm et al. (2008), and for the Nordpool market, taken from Fell (2008). The former two are based on Ordinary Least Squares (OLS) estimates for cost pass-through rates multiplied by the emission intensities the authors used in their analysis[12] and then averaged across years and load regimes, whereas the estimate by Fell is the long-term Impulse-response function (IRF) based on a cointegration analysis. The numbers mean that if the permit price increases by €1, the electricity price increases on average by €0.52-€0.62 per MWh.

Table 3 lists allocation and emissions of the largest power companies in Germany, the UK and Nordpool. In Germany, the four largest power companies combine for 74% of the country's generation capacity. Together received a total of

[11] Note that these are average values. For each technology, emission factors vary to some extent, depending on plant age and technology.

[12] They used 0.973 tCO_2/MWh for coal (peak and off-peak in Germany, off-peak in UK) and 0.367 tCO_2/MWh for CCGT (peak in UK); see Sijm et al. (2008) Table 4.2.

725 million allowances allocated for free and emitted 744 Mt CO_2 during the first phase of the market (2005-2007), which means that on average these firms were allocated 97.4 % of their emissions for free. The firm with the relatively smallest allocation (EnBW) received an allocation that covered 90.6 % of its emissions.

Table 2: Estimates for dp/dσ

	peak[a]	off-peak[a]	weighted average[b]
Germany[c]	0.57	0.51	0.55
UK[c]	0.29	1.00	0.53
Nordpool[d]			0.62

a: Peak and off-peak last 12 hours each per day

b: Average computed as (2*peak+off-peak)/3 for UK and DE

Table 3: Allocation and emissions of select power firms (UK, DE and Nordpool)

Country/Firm	allocation (mio EUA)	emissions (Mt CO_2)	ratio (%)	$\frac{dp/d\sigma}{1-\bar{x}_1/e_1}$
Germany				
RWE	352.72	368.82	95.6	12.60
Vattenfall	233.04	224.21	103.9	alloc>emiss[b]
E.ON	110.81	119.68	92.6	7.42
EnBW	27.93	30.84	90.6	5.83
Total	724.50	743.55	97.4	21.46
UK				
E.ON (Powergen)	66.14	83.43	79.3	2.56
RWE (Npower)	47.52	66.41	71.6	1.86
Scottish Power	37.97	46.52	81.6	2.89
EdF	36.75	61.04	60.2	1.33
Scottish and Southern	24.87	25.73	96.6	15.77
Total	213.25	283.12	75.3	2.15
Nordpool[a]				
Dong	43.46	44.48	97.7	27.03
Fortum	19.36	20.23	95.7	14.38
Pojohla Voima	15.87	13.96	113.7	alloc>emiss[b]
Vattenfall	15.02	17.02	88.2	5.27
Helsingin	8.33	7.57	110.0	alloc>emiss[b]
ENS	7.11	6.49	109.6	alloc>emiss[b]
E.ON	1.05	1.06	99.6	387.98
Total	110.20	110.80	99.5	114.21

a: Denmark, Sweden and Finland (Norway excluded)

b: If allocation>emissions, the firm is a net seller and (7) is exceeded trivially

In the UK, the market is less concentrated but still dominated by large players. The largest six power firms received a total of 213 million allowances, compared to 283 Mt CO_2 of emissions, which translates to an allocation ratio of 75.3 %. Of these, EDF was the firm with the lowest relative allocation with 60.2% of its emissions. In the Nordpool market, the largest companies within Sweden, Denmark and Finland[13] received a total of 110 million allowances in 2005, compared to emissions of 111 Mt with a ratio of 99.5 %.

The rightmost column in Table 3 shows the LHS of condition (14). For all firms, this is larger than any reasonable emission intensity, implying that the allocation threshold $\bar{x}_1^0$ was exceeded everywhere. The smallest value for the net buyers is 1.33 (for EDF), which is greater than the emission intensity of a lignite power plant. These results strongly imply that all large firms considered here, as well as their aggregate, received a permit allocation that exceeded the threshold defined in (7) and made operational in (14). Assuming that any of these firms had market power they would have found it profitable to manipulate the permit price upwards because their increased profits in the output market more than compensate them for increased compliance costs.

5. Conclusions

There is a large literature about market power in permit markets, but to my knowledge, no paper has directly addressed the effect of free allocation on price manipulation in the presence of explicit market power in both permit market as well as the linked output market. Besides being of general economic interest, this particular question is motivated by a very high (in hindsight too high) allowance price

[13] Norway is not in the EU and was therefore not covered by the EU ETS during the first phase. For the second phase, Norway linked its domestic permit market to that of the EU.

during the first phase of the EU ETS, which reportedly led to large windfall profits especially for firms in the power & heat sector. These firms received most of their allowances for free but were able to pass through a large part of the opportunity costs to consumers. The presence of windfall profits and the history of imperfect competition in the power & heat sector raises the question whether dominant power producers could have used their market weight in order to increase the permit price.

According to Hahn's (1984) results, the answer to this question is negative, because power & heat is the only sector that was under-allocated with permits and thus was a net allowance buyer. In Hahn's framework, any dominant permit buyer would depress rather than inflate the permit price, and would act competitively only when given the exact amount of free allocation that covers its emissions.

In contrast, papers that apply the raising rivals' costs framework to permit markets (Misiolek and Elder, 1989; von der Fehr, 1993; Sartzetakis, 1997a; Sartzetakis, 1997b) imply that it could well be in dominant buyer's interest to manipulate the permit price upwards if increased profits in the output market exceed increased permit purchase costs. However, this literature assumes only indirect market power in the output market, and no efficient allocation threshold is computed.

In this paper, I derive a threshold of free allocation under the assumption of explicit market power in both markets, above which a dominant firm finds it profitable to under-abate and over-purchase allowances in order to push up the permit price. This threshold is a function of cost pass-through and the dominant firm's average emission intensity and is always less than the firm's emissions were it to set its marginal abatement costs equal to the permit price (Hahn's threshold). If a dominant firm receives an allocation exceeding this threshold, both the output and the permit price will be inflated.

These findings are not subject to stringent assumptions about relative efficiency in production and/or abatement among firms, as is typically the case in the raising rivals' costs literature that discusses market manipulation in input and output markets. While the dominant firms may profit at the expense of the fringe by increasing its market share, the main source of profit is cost pass-through to consumers via the increased output price. In fact, the industry fringe profits from market manipulation on behalf of the dominant firm, as their windfall profits increase as well.

I apply my theoretical results to the German, UK and Nordpool power markets. I show that the largest energy firms in these countries received an allocation in excess of $\bar{x}_1^0$ and would therefore have been interested in increasing the allowance price, *assuming* they had the ability to do so. This result is due high cost pass-through coupled with a generous free allocation.

An important caveat to my paper is that I present no evidence that power firms in the EU ETS are in fact able to manipulate either the permit or the output price. Given the size of the market, a strict interpretation of market power might conclude that even the largest firms are too small to yield price-setting power (Maeda, 2003). However, considering that initially the main buyers in the EU ETS were power generators, whereas many smaller firms with a permit surplus were not trading until later, it is possible that large power firms were able to manipulate the allowance price upwards, even if under the assumption of perfectly liquid markets they should not be able to do so. I conclude that it is at least possible that the high allowance price during the first 18 months of the EU ETS was due to price manipulation on behalf of large power firms.

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Appendix

A1: Proof of Lemma 1

Differentiating (2) with respect to *p* and rearranging gives

$$\begin{bmatrix} C_{qq}^i & C_{qe}^i \\ C_{qe}^i & C_{ee}^i \end{bmatrix} \begin{bmatrix} \partial q_i / \partial p \\ \partial e_i / \partial p \end{bmatrix} = \begin{bmatrix} 1 \\ 0 \end{bmatrix}$$

Solving for the effect of a price change on output and emissions yields

(A1)
$$\frac{\partial q_i}{\partial p} = \frac{C_{ee}^i}{\Delta^i} > 0$$
$$\frac{\partial e_i}{\partial p} = \frac{-C_{qe}^i}{\Delta^i} > 0 \qquad with \quad \Delta^i \equiv C_{qq}^i C_{ee}^i - \left(C_{qe}^i\right)^2 > 0$$

Similarly, differentiating (2) w.r.t. the permit price gives

(A2)
$$\frac{\partial q_i}{\partial \sigma} = \frac{C_{qe}^i}{\Delta^i} < 0$$
$$\frac{\partial e_i}{\partial \sigma} = \frac{-C_{qq}^i}{\Delta^i} < 0$$

To analyze the effect of the dominant firm's output on output price *p* and permit price σ, differentiate (3) w.r.t. q_1 and rearrange:

(A3)
$$\begin{bmatrix} P' \sum_{i=2}^{N} \frac{\partial q_i}{\partial \sigma} & \left(P' \sum_{i=2}^{N} \frac{\partial q_i}{\partial p} - 1 \right) \\ \sum_{i=2}^{N} \frac{\partial x_i}{\partial \sigma} & \sum_{i=2}^{N} \frac{\partial x_i}{\partial p} \end{bmatrix} \begin{bmatrix} \frac{\partial \sigma}{\partial q_1} \\ \frac{\partial p}{\partial q_1} \end{bmatrix} = \begin{bmatrix} -P' \\ 0 \end{bmatrix}$$

Solving for the effect of q_1 on the permit price:

(A4)
$$\frac{\partial \sigma}{\partial q_1} = \frac{-P' \sum_{i=2}^{N} \frac{\partial x_i}{\partial p}}{\sum_{i=2}^{N} \frac{\partial x_i}{\partial \sigma} + P' * \left[\sum_{i=2}^{N} \frac{\partial q_i}{\partial \sigma} \sum_{i=2}^{N} \frac{\partial x_i}{\partial p} - \sum_{i=2}^{N} \frac{\partial q_i}{\partial p} \sum_{i=2}^{N} \frac{\partial x_i}{\partial \sigma} \right]}$$

Because P'<0 and $e_i = x_i$ for i=(2,…,N), it follows immediately from (A1) that the numerator is positive. The first term of the denominator is negative from (A2). In order to show that (A4) is negative I have to show that the term in the brackets is positive, i.e. that

(A5) $$\Phi \equiv \sum_{i=2}^{N} \frac{\partial q_i}{\partial \sigma} \sum_{i=2}^{N} \frac{\partial x_i}{\partial p} - \sum_{i=2}^{N} \frac{\partial q_i}{\partial p} \sum_{i=2}^{N} \frac{\partial x_i}{\partial \sigma} \overset{?}{>} 0$$

Substituting (A1) and (A2), this is equivalent to showing that

(A6) $$\sum_{i=2}^{N} \frac{C_{qe}^i}{\Delta^i} \sum_{i=2}^{N} \frac{-C_{qe}^i}{\Delta^i} - \sum_{i=2}^{N} \frac{C_{ee}^i}{\Delta^i} \sum_{i=2}^{N} \frac{-C_{qq}^i}{\Delta^i} \overset{?}{>} 0$$

to prove the inequality in (A5). Separating out the a single firm, it is clear that

$$\frac{C_{qq}^i C_{ee}^i}{\left(\Delta^i\right)^2} - \frac{\left(C_{qe}^i\right)^2}{\left(\Delta^i\right)^2} = \frac{1}{\Delta^i} > 0$$

which enables me to express (A6) as

$$\frac{1}{\Delta^i} + \sum_{\substack{i=2 \\ i \neq j}}^{N} \frac{C_{qq}^i C_{ee}^j - C_{qe}^i C_{qe}^j}{\Delta^i} \overset{?}{>} 0$$

Noting the symmetry between i/j and j/i multiplications and dropping the first (positive) term, I can express this as

(A7) $$\sum_{2 \le i < j}^{N} \frac{C_{qq}^i C_{ee}^j + C_{qq}^j C_{ee}^i - 2 C_{qe}^i C_{qe}^j}{\Delta^i} \overset{?}{>} 0$$

Squaring both sides of the numerator in (A7) yields

$$\left(C_{qq}^i C_{ee}^j\right)^2 + 2 C_{qq}^i C_{ee}^j C_{qq}^j C_{ee}^i + \left(C_{qq}^j C_{ee}^i\right)^2 \overset{?}{>} 4 C_{qq}^i C_{ee}^i C_{qq}^j C_{ee}^j > 4\left(C_{qe}^i C_{qe}^j\right)^2$$

where the second inequality comes from the fact that

$$C^i_{qq}C^i_{ee} > \left(C^i_{qe}\right)^2 \; \forall \; i \;\Rightarrow\; C^i_{qq}C^i_{ee}C^j_{qq}C^j_{ee} > \left(C^i_{qe}C^j_{qe}\right)^2$$

Subtracting the RHS of the first inequality completes the proof:

(A8) $$\left(C^i_{qq}C^j_{ee}\right)^2 - 2C^i_{qq}C^j_{ee}C^j_{qq}C^i_{ee} + \left(C^j_{qq}C^i_{ee}\right)^2 = \left(C^i_{qq}C^j_{ee} - C^j_{qq}C^i_{ee}\right)^2 \overset{!}{>} 0 \quad\Rightarrow\quad \Phi \overset{!}{>} 0 \qquad \blacksquare$$

Now I derive the sign of the other three expressions in Lemma 1 by solving (A3) for the effect of firm 1's output on the output price and then using (A2) and (A5):

(A9) $$\frac{\partial p}{\partial q_1} = \frac{P'\sum_{i=2}^{N}\partial x_i / \partial\sigma}{\sum_{i=2}^{N}\frac{\partial x_i}{\partial\sigma} + P'\Phi} < 0$$

because the numerator is positive. Finally, differentiating equation (3) with respect to x_1 gives

$$\begin{bmatrix} P'\sum_{i=2}^{N}\frac{\partial q_i}{\partial\sigma} & P'\sum_{i=2}^{N}\frac{\partial q_i}{\partial p} \\ \sum_{i=2}^{M}\frac{\partial x_i}{\partial\sigma} & \sum_{i=2}^{M}\frac{\partial x_i}{\partial p} \end{bmatrix}\begin{bmatrix}\frac{\partial\sigma}{\partial x_1} \\ \frac{\partial p}{\partial x_1}\end{bmatrix} = \begin{bmatrix}0 \\ -1\end{bmatrix}$$

which can be solved for

(A10) $$\frac{\partial\sigma}{\partial x_1} = \frac{\sum_{i=2}^{N}\partial q_i/\partial p}{\Phi} > 0$$

(A11) $$\frac{\partial p}{\partial x_1} = \frac{-\sum_{i=2}^{N}\partial q_i/\partial\sigma}{\Phi} > 0$$

A2: Proof of equation (9)

Keeping in mind that $\partial\sigma/\partial q_1 < 0$, I re-write (9) as

$$\frac{\partial p/\partial x_1}{\partial\sigma/\partial x_1} \overset{?}{<} \frac{\partial p/\partial q_1}{\partial\sigma/\partial q_1}$$

Substituting (A4) and (A9)-A(10) into this expression and simplifying yields

(A12) $$\frac{-\sum_{i=2}^{N}\partial q_i/\partial\sigma}{\sum_{i=2}^{N}\partial q_i/\partial p} \overset{?}{<} \frac{\sum_{i=2}^{N}\partial x_i/\partial\sigma}{-\sum_{i=2}^{N}\partial x_i/\partial p}$$

Multiplying both sides by the two denominators (again reversing the inequality) and bringing both terms to the left hand side gives

(A13) $$\sum_{i=2}^{N}\frac{\partial q_i}{\partial\sigma}\sum_{i=2}^{N}\frac{\partial x_i}{\partial p} - \sum_{i=2}^{N}\frac{\partial q_i}{\partial p}\sum_{i=2}^{N}\frac{\partial x_i}{\partial\sigma} = \Phi \overset{!}{>} 0$$

which I prove above.

A2: Proof of equation (15)

I need to show that

$$\frac{dp}{d\sigma} = \frac{\partial p/\partial x_1 * dx_1 + \partial p/\partial q_1 * dq_1}{\partial\sigma/\partial x_1 * dx_1 + \partial\sigma/\partial q_1 * dq_1} < \frac{\partial p/\partial x_1}{\partial\sigma/\partial x_1}$$

provided that $d\sigma$ and dq_1 have the same sign. Multiplying both sides by $d\sigma/dq_1 * \partial\sigma/\partial x_1 > 0$ and simplifying gives

(A14) $$\frac{\partial\sigma}{\partial x_1}\frac{\partial p}{\partial q_1} - \frac{\partial\sigma}{\partial q_1}\frac{\partial p}{\partial x_1} \overset{?}{<} 0$$

Substituting the results from Lemma 1 (see above):

(A15)
$$\frac{\sum_{i=2}^{N}\partial q_i/\partial p}{\Phi}*\frac{P'\sum_{i=2}^{N}\partial x_i/\partial\sigma}{\sum_{i=2}^{N}\frac{\partial x_i}{\partial\sigma}+P'\Phi}-\frac{P'\sum_{i=2}^{N}\frac{\partial x_i}{\partial p}}{\sum_{i=2}^{N}\frac{\partial x_i}{\partial\sigma}+P'\Phi}*\frac{\sum_{i=2}^{N}\partial q_i/\partial\sigma}{\Phi}\overset{?}{<}0$$

Multiplying both sides by $\Phi/P'*\left(\sum_{i=2}^{N}\partial x_i/\partial\sigma+P'\Phi\right)>0$ completes the proof:

$$\sum_{i=2}^{N}\frac{\partial x_i}{\partial\sigma}\sum_{i=2}^{N}\frac{\partial q_i}{\partial p}-\sum_{i=2}^{N}\frac{\partial x_i}{\partial p}\sum_{i=2}^{N}\frac{\partial q_i}{\partial\sigma}=-\Phi\overset{!}{<}0$$