# Emissions trading with profit-neutral permit allocations

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**Abstract:** Cap-and-trade schemes - like the U.S. Acid Rain Program and the EU Emissions Trading Scheme - play a central role in environmental policy. In order to minimize their impact on firm profits, these schemes often have the feature that all or part of the emissions permits or allowances are freely allocated to firms. This paper examines the proportion of permits that have to be freely allocated to ensure profit-neutrality, at both the level of the firm and the industry; we relate this to the cost efficiency of the scheme. We develop simple formulae for the calculation of profit-neutral permit allocations in a Cournot model. We show that under a large set of parameter values, profit-neutrality requires that only a fraction of all traded permits be freely allocated. The rest may be auctioned or sold in some other manner.

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# 1 Introduction

On January 1st, 2005, the 25 countries of the European Union launched a major scheme for trading carbon dioxide emissions, the so-called EU 'Emissions Trading Scheme' (EU ETS).[1] The EU ETS was introduced as a mechanism for achieving compliance with the EU commitment under the Kyoto Protocol to the UN Framework Convention on Climate Change. According to the Protocol, the EU-15 nations must reduce combined emissions in the 'first commitment period' (January 2008 to December 2012) by 8%, relative to the base year (in most cases 1990). Though not the first cap-and-trade scheme in the world, the EU ETS was certainly the largest, covering almost 11,500 installations including combustion plants, oil refineries, coke ovens, iron and steel plants, and factories making cement, glass, lime, brick, ceramics, and pulp and paper (European Commission, 2005). It is likely that schemes similar to the EU ETS will continue to play a central role in future climate policy at the national and even global level.

The intellectual origin of cap-and-trade schemes is often traced to the work of J. H. Dales, who published a book in 1968 advocating a system of tradeable property rights for the management of environmental quality. Trading allows a single market clearing price for emissions to emerge, thus ensuring that different firms equalize their marginal abatement costs; in this way, a given emissions target can be achieved at minimum cost to society (see Baumol and Oates (1988)). For this and other reasons, an ETS is generally thought to be economically superior to a command-and-control approach that imposes source-specific emissions limits or requires particular abatement technologies. In the U.S., the Acid Rain Program enacted in 1990 was the first large-scale environmental program to rely on an emissions trading scheme (ETS).

However, an ETS has a significant disadvantage: for a given emissions target, the

[1] The scheme is based on Directive 2003/87/EC, which entered into force on 25 October 2003.

command-and-control approach may well impose higher abatement costs on industry than an ETS, but the latter imposes an additional burden in the form of payments for emissions permits. Even though this does not affect the attractiveness of ETS from society's viewpoint - these payments are transfers - they do raise the burden imposed on industry.[2] Alleviating this burden is important because the extent to which it can be reduced will affect the magnitude of emissions reductions that are politically feasible. In the case of industries for which there is a choice in the location of plants, it is also important that the costs imposed by the ETS are not so great that firms choose to relocate their activities to a place where emissions are free. Clearly, this will undermine any emissions reduction objective (like that for carbon dioxide) that is not location specific.

The approach taken to alleviate this problem in both the EU ETS and in the U.S. Acid Rain Program is to give all or some of the emissions permits for free. This relieves the financial burden of the scheme without affecting firms' incentives to reduce emissions at the margin. This practice is sometimes referred to as *grandfathering* since the number of free permits given is typically related to historical emissions.

While it may be important that firms be compensated for the introduction of the scheme, it is also important that they do not receive more free permit allocations than is necessary for profit-neutrality. Ideally, freely allocated permits should form only a *fraction* of all traded permits. In this way, not only is the scheme profit-neutral for firms, government will also receive revenue for supplying the excess demand for permits from industry. Such a feature may be important from a political economy perspective, because it gives government a fiscal incentive to continue the scheme.[3] This revenue is also important from a normative perspective since it allows for the reduction of distortionary taxes imposed on other parts of the economy. This "revenue recycling effect" is known to be important, even crucial, when evaluating the benefits

[2]For more on this issue, see Baumol and Oates (1988) and Seskin, Anderson, and Reid (1983).

[3]Vollebergh et al. (1997) makes a closely related point.

of an ETS (see Parry and Oates (2000) and Bovenberg, Goulder, and Gurney (2005)).

This article is a theoretical analysis of the factors that influence the number of permits to be freely allocated to a firm that leaves its profit before and after the introduction of the ETS at the same level; we refer to this as the level of profit-neutral (permit) allocations (PNA). A large part of our analysis is carried out using a first order approach. This approach is valid provided the price of permits is low relative to the total marginal costs of a firm; this is appropriate in many settings and, in particular, appears to be true of many industries affected by the EU ETS. The advantage of making this simplification is that we can be very general in other aspects of the problem. For example, we allow firms to have different marginal costs and different emissions intensities; we also make no assumptions on the industry demand curve: it can be linear, convex, or concave.

The following are the major conclusions of this paper:

(1) For a monopoly, the PNA level will always be greater than the monopolist's demand for permits. So a profit-neutral allocation of permits will leave the monopolist a net *supplier* of permits.

(2) Suppose that firms in an oligopoly receive permits at the PNA level. This will be lower than the industry's total demand for permits if and only if, in some specific sense, the ETS encourages firms to move closer to the fully collusive outcome.

(3) The situation in (2) arises if market demand is inelastic, and the introduction of the ETS leads to (i) lower equilibrium output and (ii) firms with lower marginal costs gaining market share.

(4) In the Cournot model, lower cost firms will gain market share so long as the inverse demand function is log-concave. This in turn guarantees that, to first order, the ETS leads to greater cost efficiency; specifically, the average cost of inputs *excluding emissions*, to produce one unit of output falls. This is surprising because the ETS will cause firms to substitute away from emissions and use more of other inputs; however, this effect is of second order and thus dominated by the favorable impact of

the change in market share on average cost. So the ETS leads to a double dividend: lower emissions and greater cost efficiency.

(5) We develop formulae that give first order approximations to the PNA level for a firm or an industry in a Cournot oligopoly. These formulae are expressed in terms of the number of firms, the Herfindahl index, emissions intensity, and the curvature of demand.

(6) In the Cournot model, the level of PNA will typically vary across firms in an industry. A firm's PNA is *below* its demand for emissions permits if and only if the firm faces a more favorable residual demand curve for its output after the introduction of the ETS.

(7) Finally, using our formulae, we perform some illustrative calculations on the level of profit-neutral grandfathering for three industries affected by the EU ETS - cement, newsprint, and steel - using the available information on firm numbers, demand elasticity, etc. These calculations largely bear out the impression of our theoretical work: only a fraction of emissions permits need to be freely allocated to ensure profit-neutrality.

# 2 Profit-neutral permit allocations: general principles

In this section, we consider an oligopoly whose production activity produces a particular type of emission (for example, carbon dioxide) that is harmful to the environment. An emissions trading scheme (ETS) is introduced that imposes a cost on all emissions of this type. We assume that this industry is one of many that is subject to this scheme; in this way, though the firms in this oligopoly have market power in their product market, they are price takers in the market for emissions.

The objective of this section is to spell out the major issues that are relevant when considering the impact of the ETS on firm profits. We measure this by the number of permits that have to be freely allocated to a firm to guarantee profit-neutrality, i.e., the firm's profit before and after the introduction of the ETS remains the same. Throughout this section, we make no substantive assumptions regarding the *manner* of strategic interaction in this oligopoly; in the section following this, we shall be more specific and assume that firms play a Cournot game.

## 2.1 The monopoly case

We begin by considering the case where the industry consists of a monopolist. This case is not typical, but it has the merit of having a complete solution and its solution provides a natural setting in which to introduce several of the major themes.

We assume that the monopolist chooses a production plan that maximizes its profit, given the demand for its output (which may consist of one or several distinct products), its production set, input prices, and an emissions permit price of $t$. We denote the (maximum) profit made by the monopolist by $\Pi^*(t)$ and the associated emission level by $\zeta^*(t)$. The profit before accounting for the cost of permits is denoted by $\underline{\Pi}^*(t)$, i.e., $\underline{\Pi}^*(t) = \Pi(t) + t\zeta^*(t)$. (Note that $\Pi^*(0) = \underline{\Pi}^*(0)$.) The situation before the introduction of an emissions trading scheme (ETS) corresponds to the case where $t = 0$; after the scheme is introduced, we assume that emissions are traded at price $t > 0$. $\Pi^*(0)$ and $\zeta^*(0)$ correspond to the firm's initial profit and emissions level. To keep our notation simple, we shall often suppress the argument when $t = 0$ and write $\zeta^*(0)$ as $\zeta^*$, $\Pi^*(0)$ as $\Pi^*$, and so forth. This is potentially confusing since, for example, $\zeta^*$ also refers to the *function* $\zeta^*$, but it is usually clear from the context what we are referring to.

Profit maximization by the monopolist guarantees that, at any $t > 0$,

$$\underline{\Pi}^*(t) \leq \Pi^* \text{ and} \tag{1}$$

$$\Pi^*(t) = \underline{\Pi}^*(t) - t\zeta^*(t) \geq \Pi^* - t\zeta^*. \tag{2}$$

These inequalities can be simultaneously true only if $\zeta^*(t) \leq \zeta^*$. So our first conclusion is that the introduction of the scheme will indeed reduce emissions. Furthermore, (1) implies that $\Pi^*(t) = \underline{\Pi}^*(t) - t\zeta^*(t) \leq \Pi^*$, so the scheme also reduces the monopolist's profit.

If the monopolist receives a lump sum that exactly compensates him for his reduced profit, what should it be? (2) says that $\Pi^*(t)+t\zeta^* \geq \Pi^*$, so there is $0 \leq \gamma(t) \leq 1$ such that

$$\Pi^*(t) + t\left[\gamma(t)\zeta^*\right] = \Pi^*. \tag{3}$$

In other words, $\gamma(t)\zeta^*$ is the number of permits that the monopolist must receive for free - the *profit-neutral allocation* (PNA) - that will leave his profit unchanged. Since $\gamma(t) \leq 1$, the free permits cover only *a fraction of the firm's initial emissions* (of $\zeta^*$), i.e., the profit-neutral allocation is *partial.*

Suppose that the monopolist does indeed receive $\gamma(t)\zeta^*$ permits for free. Rewriting (3), we obtain $\underline{\Pi}^*(t) + t\left[\gamma(t)\zeta^* - \zeta^*(t)\right] = \underline{\Pi}^*$; this equation, together with (1) tells us that $\gamma(t)\zeta^* - \zeta^*(t) \geq 0$. Thus the monopolist's endowed permits, $\gamma(t)\zeta^*$, will *exceed* his requirement $\zeta^*(t)$.

To recap, we have shown the following: *with the introduction of emissions permits, the monopolist will choose lower emissions and have a lower operating profit; PNA is partial but is high enough to leave the monopolist a net supplier of permits.*

## 2.2 Characterizing partial PNA

When considering an oligopoly, we can no longer rely on the revealed preference arguments that gave us such mileage in the case of a monopoly. Nonetheless, there is much that we can still say. In this section, we assume that there are $N$ firms (with $N \geq 2$) in an industry that interact with each other strategically. For now we leave the precise manner of their strategic interaction unspecified. Retaining our earlier notation, we denote the equilibrium industry profits when the permit price is $t$ by

$\Pi^*(t)$, the equilibrium (total) emissions by $\zeta^*(t)$, etc. The corresponding outcomes for firm $i$ will be denoted by $\Pi_i^*(t)$, $\zeta_i^*(t)$, etc. We assume that these are all smooth functions of $t$ in some interval $[0, T]$, where $T > 0$. We call this model a *smooth oligopoly.*

By definition, the proportion of free permit allocation for firm $i$ needed to preserve firm $i$'s profit, $\gamma_i(t)$, satisfies

$$\Pi_i^*(t) + t\,\gamma_i(t)\zeta_i^* = \Pi_i^*; \tag{4}$$

similarly, the proportion of free allocations needed for profit-neutrality at the industry level, $\gamma(t)$, is given by

$$\Pi^*(t) + t\,\gamma(t)\zeta^* = \Pi^*. \tag{5}$$

The next result gives a sufficient (and as we shall see a bit later, locally necessary) condition for the profit-neutral allocation to be partial.

PROPOSITION 1 *Suppose* $\zeta^*(t) < \zeta^*$ *and* $\underline{\Pi}^*(t) \geq \Pi^*$. *Then* $\gamma(t) < 1$*; with this level of free allocation, the industry has a net demand for permits.*

Proof: Given the assumptions, it is clear that there is $\gamma(t) < 1$ such that

$$\underline{\Pi}^*(t) - \Pi^* + t(\gamma(t)\zeta^* - \zeta^*(t)) = 0.$$

Re-arranging this expression and using the fact that $\underline{\Pi}^*(t) - t\zeta^*(t) = \Pi^*(t)$, we obtain (5). Since $\underline{\Pi}^*(t) \geq \Pi^*$, we must have $\gamma(t)\zeta^* - \zeta^*(t) \leq 0$; in other words, the industry has a net demand for permits. QED

This result is quite intuitive. It says that PNA is partial if $\underline{\Pi}^*(t) \geq \Pi^*$, where $\underline{\Pi}^*(t)$ is industry profit before accounting for permit costs. In other words, *average PNA is partial if permits encourage a more 'collusive' equilibrium outcome*: had the firms in this industry chosen the actions they did upon the introduction of the permit scheme *before* permits were introduced, their total profits would have exceeded $\Pi^*$.

To carry our analysis further we shall now concentrate on the behavior of $\gamma_i(t)$ (and $\gamma(t)$) for low values of $t$. We do this by looking at the behavior of $\tilde{\gamma}_i \equiv \lim_{t\to 0} \gamma_i(t)$

and $\tilde{\gamma} \equiv \lim_{t\to 0} \gamma(t)$. This limit determines the approximate proportion of free permit allocation that satisfies (4) (or (5)) by ignoring higher-order terms in $t$. This simplification allows us to deliver sharp and interpretable results; furthermore, the added marginal cost that arises from the introduction of a permit scheme is typically small compared to a firm's total marginal costs, so an analysis based on this approach delivers insight without being misleading. Furthermore, the main qualitative results valid for small $t$ can be generalized to the case of large $t$, as we show in Section 3.5.

Before we examine the factors that influence the value of $\tilde{\gamma}$, let us first consider one of its implications. Clearly, if $\tilde{\gamma} < 1$ then for small $t$, $\gamma(t) < 1$, i.e., on average, the industry requires only partial PNA. The industry's excess demand for permits, assuming it is given this level of free allocation, is $\zeta^*(t) - \gamma(t)\zeta^*$. Since $\lim_{t\to 0} \zeta^*(t) = \zeta^*$, for low values of $t$, $\zeta^*(t) - \gamma(t)\zeta^* > 0$, i.e., *the industry's demand for permits will exceed its free allocation.* (Conversely, if $\tilde{\gamma} > 1$, then the industry will be a net supplier of permits.) Suppose that $\tilde{\gamma} < 1$ in the industries where permits are required; then a given permit price of $t$ can be supported only if there is an external party - the government - who meets the net demand of permits from industry. Loosely speaking, an ETS with profit-neutral permit allocations raises net revenue for government if and only if $\tilde{\gamma} < 1$.

Recall that if the industry is run by a monopoly then, for all values of $t$, PNA is partial, i.e., $\gamma(t) \leq 1$, but the monopoly is also a net supplier of permits. Comparing this with our observations in the previous paragraph, we conclude that, *for a monopoly,* $\tilde{\gamma} = 1$; in other words, even though PNA is always partial it approaches a full allocation of permits for low permit prices.

It is not possible in general to determine the exact value of $\tilde{\gamma}$ for an oligopolistic industry. As we shall see in the next section, even in the Cournot model, different parameter values will lead to $\tilde{\gamma}$ being above or below 1. (This is not to say that they are all equally plausible, but more on that later.) Before we examine this issue in greater detail, it is useful to write down a simple formula for $\tilde{\gamma}$.

Taking the Taylor expansion of $\Pi^*(t)$ around $t = 0$, (5) tells us that

$$\tilde{\gamma} \equiv \lim_{t \to 0} \gamma(t) = -\frac{1}{\zeta^*} \frac{d\Pi^*}{dt}(0). \tag{6}$$

So the proportion of permit allocation required to ensure profit-neutrality is equal to the loss in operating profit per unit of emission. Since $\Pi^*(t) = \underline{\Pi}^*(t) - \zeta^*(t)t$, we can also write

$$\tilde{\gamma} = -\frac{1}{\zeta^*} \frac{d\underline{\Pi}^*}{dt}(0) + 1. \tag{7}$$

The next proposition follows immediately from (7).

Proposition 2 *In a smooth oligopoly,*

$$\tilde{\gamma} < 1 \Longleftrightarrow \frac{d\underline{\Pi}^*}{dt}(0) > 0. \tag{8}$$

This result is the local analog of Proposition 1. Indeed it goes a bit further than Proposition 1 since it says that for small $t$, the condition that $\underline{\Pi}^*(t)$ be increasing with $t$ is both sufficient - and necessary - for a partial PNA. So when will $d\underline{\Pi}^*/dt > 0$? To answer this question, we first take a closer look at the impact of emissions permits on costs.

## 2.3 The cost impact of the ETS

From this point on, we assume that the industry produces a *single* product using $l$ (costly) inputs, represented by a vector $\bar{x}_i = (\bar{x}_i^1, \bar{x}_i^2, ..., \bar{x}_i^l)$ in $R^l_{++}$. In addition, production leads to emissions, which we denote by $\bar{z}_i$. Following Baumol and Oates (1988), amongst others, we shall think of emissions as an input in the production process, albeit one that is initially free. So firm $i$'s production function $F_i$ maps the input vector $(\bar{x}_i, \bar{z}_i)$ to the output $q_i$. We assume that $F_i$ has constant returns to scale. All inputs - including emissions - are chosen optimally to minimize costs.

With the introduction of an ETS, the firm adjusts its inputs optimally to the new input prices. It will tend to reduce emissions and use more of other inputs (whose prices we assume are unchanged); in other words, there will typically be emissions abatement. We denote the firm's unit cost at the permit price $t$ by $c_i(t)$; the optimal *emissions intensity*, i.e., emissions per unit of output, by $z_i(t)$; and the unit cost before accounting for the cost of permits by $\underline{c}_i(t) = c_i(t) - tz_i(t)$. Standard production theory tells us that, at any $t > 0$, $z_i(t) \leq z_i(0)$ and $a(t) \equiv \underline{c}_i(t) - c_i(0) \geq 0$. We can think of $a(t)$ as the *abatement cost* incurred by the firm as it reduces emissions intensity from $z_i(0)$ to $z_i(t)$. If the production technology is such that abatement is either non-optimal or simply impossible, then $\underline{c}_i(t) \equiv c_i(0)$.

By the envelope theorem,

$$\frac{dc_i}{dt}(t) = z_i(t), \tag{9}$$

which leads to the following important observation:

$$\frac{da_i}{dt}(0) = \frac{d\underline{c}_i}{dt}(0) = 0. \tag{10}$$

Suppose $q_i^*(t)$ is the firm's equilibrium output. Then its total cost excluding the cost of permits is $\underline{C}_i^*(t) = \underline{c}_i(t)q_i^*(t)$. Differentiating by $t$ and appealing to (10), we obtain

$$\frac{d\underline{C}_i^*}{dt}(0) = c_i(0)\frac{dq_i^*}{dt}(0). \tag{11}$$

Equation (11) can be interpreted in the following way. The introduction of the ETS has a twofold impact on $\underline{C}_i^*$. Firstly, it causes the firm to switch away from emissions towards other inputs, thus raising expenditure ($\underline{c}_i$) on those inputs; secondly, through its strategic interaction with other firms, it has an impact on firm $i$'s output. However, the change in $\underline{c}_i(t)$ is of second order, so that for low values of $t$, the change in $\underline{C}_i^*(t)$ is simply driven by the change in firm $i$'s output.

An immediate consequence of this is that the local impact of ETS on the industry's average cost is *solely* driven by its impact on relative output shares. We denote the industry's total costs, excluding permits, by $\underline{C}^*(t) = \sum_{i=1}^{N} \underline{C}_i^*(t)$ and the average cost by $\underline{c}^*(t)$. So $\underline{c}^*(t) = \underline{C}^*(t)/Q^*(t)$; alternatively,

$$\underline{c}^*(t) = \sum_{i=1}^{N} \sigma_i(t)\underline{c}_i(t), \tag{12}$$

where $\sigma_i(t)$ refers to $i$'s market share when permits are priced at $t$. Differentiating this by $t$ and using (10), we obtain

$$\frac{d\underline{c}^*}{dt}(0) = \sum_{i=1}^{N} c_i(0)\frac{d\sigma_i}{dt}(0). \tag{13}$$

(Note that $\underline{c}_i(0) = c_i(0)$.) It is clear from this equation that, the introduction of the ETS notwithstanding, the industry's average cost (excluding permits) will *fall* if firms with lower unit costs increase their market share.

## 2.4 Sufficient conditions for partial PNA

We denote the inverse demand of the industry at output $Q$ by $P(Q)$ and the total equilibrium output of the industry by $Q^*(t)$. When there is no risk of confusion, we shall write the initial output $Q^*(0)$ as $Q^*$. Our observations on the cost impact of permits are relevant in determining the level of profit-neutral allocations since at $t = 0$,

$$\frac{d\underline{\Pi}^*}{dt} = \frac{d\left[P(Q)Q\right]}{dQ}\frac{dQ^*}{dt} - \frac{d\underline{C}^*}{dt}. \tag{14}$$

The first term on the right of (14) measures the impact of the permit scheme on revenue; the second its impact on cost. Suppose that the introduction of the scheme leads to lower output/higher price and that demand is inelastic. Then revenue will increase; in other words, the first term on the right of (14) is strictly positive. Therefore, $d\underline{\Pi}^*/dt > 0$ if $d\underline{C}^*/dt < 0$. The next result then follows from Proposition 2.

Proposition 3 *In a smooth oligopoly, $\tilde{\gamma} < 1$ if (i) demand is strictly inelastic at the initial price $P(Q^*)$; (ii) $dQ^*/dt < 0$ at $t = 0$; and (iii) $d\underline{C}^*(t)/dt < 0$ at $t = 0$.*

It follows from (11) that

$$\frac{d\underline{C}^*}{dt}(0) = \sum_{i=1}^{N} c_i(0)\frac{dq_i^*}{dt}(0). \tag{15}$$

So if firms are symmetric and have identical initial marginal costs, condition (iii) in Proposition 3 follows from (ii) and we obtain the following result.

COROLLARY 1 *In a smooth oligopoly where firms have identical production functions, $\tilde{\gamma} < 1$ if (i) demand is strictly inelastic at the initial price $P(Q^*)$ and (ii) $dQ^*/dt < 0$ at $t = 0$.*

It seems to us that the assumptions of Proposition 3 are all reasonable. One expects the ETS to lead to lower output. The elasticity of demand may vary from one industry to the next, but the assumption of inelastic demand is likely to apply to the type of industries included in an ETS. It is clear from (15) that total costs will fall if the output of every firm falls. From a slightly different perspective, note that $\underline{C}^*(t) = \underline{c}^*(t)Q^*(t)$, so total cost will fall provided the effect of a lower output is not totally negated by an increase in the average marginal cost $\underline{c}^*(t)$.

We conclude that there is prima facie evidence that for many industries, *average PNA is partial*. We now turn to an examination of this issue and others in the specific context of the Cournot model.

# 3 Analytics of the ETS in a Cournot model

We now assume that the $N$ firms interact in a Cournot oligopoly. Without loss of generality, assume that $c_1(0) \leq c_2(0) \leq ... \leq c_N(0)$; in other words, the lower indexed firms have lower initial marginal costs. As we have already pointed out in the last section, the envelope theorem tells us that $dc_i/dt = z_i$; in other words, the impact of emissions trading on marginal cost depends locally on emissions intensity. Without loss of generality, we shall assume that (at $t = 0$) $\sum_{i=1}^{N} z_i/N = 1$. In other words, the average emissions intensity before the introduction of the scheme equals 1. In principle, $z_i$ may vary with $i$ in any possible way, but we shall focus on the two most plausible cases. We say that emissions intensity is *uniform* (across firms) if $z_i = 1$ for all firms. We say that emissions intensity is *monotone* if $z_i$ is weakly increasing with $i$. The first is of course a special case of the second. Monotonicity says that firms with lower marginal costs also tend to pollute less.

We denote by $q$ the vector $(q_i)_{1\leq i\leq N}$ which gives the output of each firm. The aggregate output associated with $q$ is denoted by $Q$ and the output of all firms except firm $i$ by $Q_{-i}$.

The marginal revenue of firm $i$ at $q$ satisfies $MR_i(q) = P(Q) + q_iP'(Q)$, where $P(Q)$ is the downward-sloping inverse demand curve. Firm $i$ maximizes its profit when $MR_i(q) = c_i(t)$. We assume that before the introduction of the ETS firms are at the Cournot equilibrium $q^* = (q_i^*)_{1\leq i\leq N}$ so that total output $Q^* = \sum_{i=1}^{N} q_i^*$. At this equilibrium $q^*$, we have

$$MR_i(q^*) = P(Q^*) + q_i^*P'(Q^*) = c_i(0) \tag{16}$$

for each firm $i$. Assuming demand is downward-sloping, so $P'(Q) < 0$, we obtain that $q_1^* \geq q_2^* \geq ... \geq q_N^*$. In other words, output varies inversely with marginal cost at equilibrium.

Let $E(Q^*) = -\left[d\log P'(Q)/d\log Q\right]_{Q=Q^*}$ denote the elasticity of the *slope* of inverse demand, evaluated at the initial equilibrium industry output. This can be interpreted as an index of demand curvature.[4] Clearly, $E(Q^*) > 0$ ($E(Q^*) < 0$) if $P''(Q^*) > 0$ ($P''(Q^*) < 0$) and inverse demand is locally convex (concave) at $Q^*$. If demand is linear (with $P''(Q) = 0$), then $E = 0$ for all $Q$.

The second-order condition for profit-maximization is satisfied for firm $i$ if its marginal revenue is downward-sloping in its own output, $\partial MR_i(q^*)/\partial q_i < 0$, at equilibrium. Using the above, this can be written as $2P'(Q^*) + q_i^*P''(Q^*) < 0$, or equivalently as

$$2 - \sigma_i^*E(Q^*) > 0, \tag{17}$$

where $\sigma_i^* = q_i^*/Q^*$ is firm $i$'s initial market share (before permits are introduced).

We also assume from here on that inverse demand is not too convex in the sense that

$$N + 1 - E(Q^*) > 0. \tag{18}$$

[4]See, e.g., Seade (1980) for an early application that notes the importance of this parameter.

In our setting, the main implication of this assumption is that industry output falls when emissions trading is introduced. This condition is also necessary the local stability of the equilibrium (see Seade (1980)).

### 3.1 The impact of ETS on output

The Cournot equilibrium changes when the ETS is introduced. We assume that the equilibrium varies smoothly with $t$, i.e., the Cournot oligopoly is a smooth oligopoly in the sense defined in Section 2. The following result shows the impact of emissions trading on firm- and industry-level output and is crucial to understanding its impact on firm profits.

PROPOSITION 4 *In the Cournot model, at $t = 0$,*

$$\frac{dQ^*}{dt} = \frac{N}{P'(Q^*)(N+1-E(Q^*))} < 0; \tag{19}$$

$$\frac{dQ^*_{-i}}{dt} = \frac{dQ^*}{dt}\frac{[2N - \sigma_i E(Q^*)N - z_i(N+1-E(Q^*))]}{N} \quad \textit{and} \tag{20}$$

$$\frac{dq^*_i}{dt} = \frac{dQ^*}{dt}\frac{[-N + \sigma_i E(Q^*)N + z_i(N+1-E(Q^*))]}{N}. \tag{21}$$

The proof of Proposition 4 and other results in this section are found in Appendix A.

Proposition 4 says that the introduction of the ETS causes industry output to fall. However, as a rule, this fall is not shared equally across firms. To isolate the effect of the demand structure on the pattern of the output response, let us first assume that emissions intensity is uniform across firms. In that case, (21) simplifies to

$$\frac{dq^*_i}{dt} = \frac{dQ^*}{dt}\frac{[1 - E(Q^*) + \sigma_i E(Q^*)N]}{N}.$$

If the inverse demand function is convex (so $E(Q^*) \geq 0$), $dq^*_i/dt$ will increase in $i$. In other words, larger firms experience larger falls in output. Since total output falls, this implies that the largest firm (firm 1, with marginal cost $c_1$) *must* experience a fall in output. When the inverse demand function in concave, the distribution of the fall in output is reversed: smaller firms bear the brunt of the reduction, and the smallest firm (firm $N$) must experience a fall in output. This pattern is not surprising: it is easy to check that with convex (concave) demand, larger (smaller) firms have a flatter marginal revenue curve, and thus will cut output by more for any given increase in marginal cost arising from the ETS.

Now consider the case where emissions intensity is monotone and demand is linear, so $E(Q^*) = 0$; (21) simplifies to

$$\frac{dq_i^*}{dt} = \frac{dQ^*}{dt}\frac{[-N + z_i(N+1)]}{N}.$$

Clearly, $dq_i^*/dt$ is decreasing with $i$. The cost impact of emissions trading is greatest on the small (and highest polluting) firms, so they experience the largest fall in output. We shall refer to this as the *emissions intensity effect*, in contrast to the *demand curvature effect* described in the previous paragraph.

When demand is concave ($E(Q^*) \leq 0$) and emissions intensity is monotone, then the two effects reinforce each other, so that $dq_i^*/dt$ decreases with $i$, i.e., the smaller the firm the greater is the fall in output. When demand is convex, the two effects work against each other and (without more assumptions) it is no longer possible to say whether it is the big or small firms that experience larger falls in output.

## 3.2 The impact of ETS on emissions and cost

In deciding whether or not to extend an emissions trading scheme to the emissions from a particular industry, a policy maker would be interested to know how the features of that industry interacts with the impact of the ETS on emissions and cost. It is to these issues that we now turn.

Suppose that $t$ is the permit price and $r$ is the input price vector of all other inputs. At these prices, firm $i$'s optimal input vector (for producing a single unit of output) is $(x_i(t), z_i(t))$. The unit cost excluding the cost of permits is $\underline{c}_i(t) = r \cdot x_i(t)$

and the emissions intensity is $z_i(t)$. At the Cournot equilibrium, firm $i$'s output is $q_i^*(t)$. A basic justification for the use of an ETS is that it represents *the cheapest way of achieving an emissions target subject to a given set of output constraints* (see Baumol and Oates (1988)). In our context, the optimization problem can be stated thus:

$$\min r \cdot \left[\sum_{i=1}^{N} \hat{x}_i\right] \text{ subject to}$$

(i) $F_i(\hat{x}_i, \hat{z}_i) = q_i^*(t)$ for all $i$ and (ii) $\sum_{i=1}^{N} \hat{z}_i = \sum_{i=1}^{N} z_i(t) q_i^*(t)$.

Note that $F_i$ is the production function of firm $i$, so $F_i(\hat{x}_i, \hat{z}_i)$ is the firm's output at the input vector $(\hat{x}_i, \hat{z}_i)$. The problem asks for the cheapest way of achieving an emissions target of $\sum_{i=1}^{N} z_i(t) q_i^*(t)$ (constraint (ii)) subject to firm $i$ producing $q_i^*(t)$ (constraint (i)). The solution is $\hat{x}_i = x_i(t) q_i^*(t)$ and $\hat{z}_i = z_i(t) q_i^*(t)$, i.e., the solution coincides with that achieved by an ETS with permits priced at $t$.

In a Cournot setting, this result is hard to interpret: with each firm's output being perfect substitutes for each other, there is no normative reason for imposing condition (i). But if we replace condition (i) with a condition that *total* output equals $\sum_{i=1}^{N} q_i^*(t)$, then it is clear that neither the initial Cournot equilibrium nor the equilibrium after the introduction of the ETS is cost efficient. Cost minimization will require in both instances that the output be produced solely by the firm with the lowest marginal cost, which does not occur.

A more useful criterion is to check whether the ETS makes the industry more or less efficient in its use of resources (other than emissions). Formally, we wish to study the scheme's impact on the industry's average cost, $\underline{c}^*(t)$. It follows from (13) that the local impact of ETS on average cost is solely driven by its impact on relative output shares. If those firms with lower unit costs (in our setting, those with lower indices) increase their share of output, then cost efficiency will improve. The next result identifies conditions under which $d\sigma_i/dt$ is decreasing in $i$. This implies that the output responses $\{d\sigma_i/dt\}_{1 \leq i \leq N}$ obey the *single crossing property*, i.e., there is $K$

such that for all $i \leq K$, $d\sigma_i/dt \geq 0$ and for all $i > K$, $d\sigma_i/dt < 0$. In other words, firms 1 to $K$ increase their market share while the rest lose market share.

PROPOSITION 5 *Suppose that in the Cournot model, emissions intensity is monotone and $E(Q^*) \leq 1$. Then $d\sigma_i/dt$ is decreasing in $i$ and*

$$\frac{d\underline{c}^*}{dt}(0) \leq 0.$$

Proposition 5 shows that the introduction of an ETS (with a small $t$) can actually *reduce* average cost. The condition $E(Q^*) < 1$ is equivalent to saying that the demand curve is locally log-concave at $Q^*$. It is worth pointing out that the global log-concavity of demand is a common assumption in Cournot analysis. Indeed it is often made as a standing assumption, since amongst other things, it ensures that the best response function of every firm is downward sloping (see, for example, Farrell and Shapiro (1990), and Shapiro's (1989) survey). Even when this condition is violated, it is quite clear that a sufficiently pronounced monotonicity in emissions intensity, working through the emissions intensity effect, can guarantee the single crossing property.[5]

So on balance, we think that an improvement in cost efficiency is the more likely scenario when the permit price is low, and serves as a justification for the ETS. That said, it is not hard to check that there *are* parameter values that lead to low cost firms losing market share, causing cost efficiency to worsen. For example, it is easy to adapt the proof of Proposition 5 to show that $d\underline{c}^*/dt \geq 0$ if $E(Q^*) \geq 1$ and emissions intensity is uniform. (Note also that this last observation means that, when emissions are uniform, $E(Q^*) \leq 1$ is both sufficient and *necessary* for an ETS to improve cost efficiency.)

An issue even more fundamental than the impact of the ETS on costs is its impact on emissions. We know that the ETS lowers total output, so total emissions will fall

[5]To be precise, see (35) in the proof of Proposition 5 in Appendix A.

if average emissions intensity fall. Writing average emissions intensity by $z^*(t)$, and noting that $z^*(t) = \sum_{i=1}^N \sigma(t) z_i(t)$, we see that

$$\frac{dz^*}{dt}(0) = \sum_{i=1}^N z_i(0)\frac{d\sigma_i}{dt}(0) + \sum_{i=1}^N \frac{dz_i}{dt}(0)\sigma_i(0). \tag{22}$$

Standard production theory tells us that $dz_i/dt < 0$, so the second term on the right of this equation is always negative. However, the sign of the first term on the right is uncertain; in other words, while the ETS causes each firm to lower its emissions intensity, it is possible for this effect to be negated in part or in whole by the strategic effects of the ETS. If the ETS causes firms with initially low emissions to gain market share then it has a doubly beneficial impact on emissions reduction; on the other hand, if the scheme causes low emissions firms to loose market share, this will diminish its beneficial impact on emissions. The latter is excluded if the output response obeys the single crossing property, which in turn follows from the log-concavity of demand.

PROPOSITION 6 *Suppose that in the Cournot model, emissions intensity is monotone and $E(Q^*) \leq 1$. Then average emissions intensity $z^*$ and total emissions $\zeta^*$ satisfy*

$$\frac{dz^*}{dt}(0) \leq 0 \;\; \textit{and} \;\; \frac{d\zeta^*}{dt}(0) \leq 0.$$

## 3.3 PNA for firm $i$

Taking the Taylor expansion of $\Pi^*(t)$ at $t = 0$, and using the fact that $\zeta_i^* = z_i q_i^*$, equation (5) tell us that

$$\tilde{\gamma}_i \equiv \lim_{t \to 0} \gamma(t) = -\frac{1}{z_i q_i^*}\frac{d\Pi_i^*}{dt}(0), \tag{23}$$

i.e., the free allocation required to ensure profit-neutrality (to first order) at firm $i$ is equal to the operating profit lost per unit of emission. One can naturally think of the operating profit of firm $i$ as a function of its own output, $q_i$, all other firms' output, $Q_{-i}$, and the market price of emissions permits, $t$. More formally, $\Pi_i(q_i, Q_{-i}, t) =$

$q_iP(q_i + Q_{-i}) - c_i(t)q_i$. The equilibrium profit $\Pi_i^*(t) \equiv \Pi_i(t, q_i^*(t), Q_{-i}^*(t))$ then varies with $t$ according to

$$\begin{aligned} \frac{d\Pi_i^*}{dt} &= \frac{\partial \Pi_i}{\partial t} + \frac{\partial \Pi_i}{\partial q_i}\frac{dq_i^*}{dt} + \frac{\partial \Pi_i}{\partial Q_{-i}}\frac{dQ_{-i}^*}{dt} \\ &= -z_i q_i^* + q_i^* P'(Q^*)\frac{dQ_{-i}^*}{dt}, \end{aligned} \tag{24}$$

where the second equality relies on the first-order condition for profit-maximization that $\partial\Pi_i/\partial q_i = 0$. Using this last result in (23) we obtain a simple expression for the required level of PNA:

$$\tilde{\gamma}_i = 1 - \frac{P'}{z_i}\frac{dQ_{-i}^*}{dt}. \tag{25}$$

The next result follows immediately.

Proposition 7 *In the Cournot model,*

$$\tilde{\gamma}_i < 1 \Longleftrightarrow \frac{dQ_{-i}^*}{dt} < 0.$$

This result says that, for small $t$, PNA for firm $i$ is partial if the total output of all other firms ($Q_{-i}^*(t)$) falls at equilibrium. This should not be surprising. Recall that for a monopolist, $\tilde{\gamma} = 1$. Firm $i$ in a Cournot oligopoly encounters a different situation from a monopolist because, in addition to the change in cost arising from the ETS (which a monopolist will also encounter), the Cournot oligopolist faces a change in its (residual) demand curve, i.e., the curve given by $p = P(q_i + Q_{-i}^*(t))$. Thus $\tilde{\gamma}_i$ is less (more) than 1 if the residual demand curve becomes more (less) favorable for firm $i$, i.e, $Q_{-i}^*(t)) <\ (>)\, Q_{-i}^*$.

Equations (20) and (19) in Proposition 4, together with (25), gives us the following PNA formula.

Proposition 8 *In the Cournot model,*

$$\tilde{\gamma}_i = \frac{2[z_i(N+1) - N] - (2z_i - N\sigma_i)E(Q^*)}{N + 1 - E(Q^*)}. \tag{26}$$

It is clear from (26) that PNA (measured as a proportion of initial emissions) will not typically be the same across firms. One special case where this proportion *is* constant across firms is when demand is linear and firms have the same emissions intensity. In that case, (26) simplifies to $\tilde{\gamma}_i = 2/(N+1)$ for all $i$, so PNA is partial. What if demand is linear but emissions intensity is *not* constant across firms? Then

$$\tilde{\gamma}_i = 2\left[z_i - \frac{N}{N+1}\right]$$

and it is clear that if $z_i$ is sufficiently high, $\tilde{\gamma}_i > 1$. In this case, firm $i$'s PNA is larger than its initial emissions. On the other hand, if $z_i$ is sufficiently low, $\tilde{\gamma}_i < 0$. In other words, while firm $i$ may suffer a small increase in costs from the ETS, the scheme has a far worse impact on its high polluting rivals. Firm $i$'s strategic position improves to the extent that it actually makes a *higher* profit than before the introduction of the scheme, so PNA is negative.

## 3.4 Average PNA in the industry

In this section we shall examine the level of grandfathering required for profit-neutrality for the industry as a whole. Recall the formula (5) for $\tilde{\gamma}$; since $\Pi^*(t) = \sum_{i=1}^N \Pi_i^*(t)$, we have

$$\begin{aligned}\tilde{\gamma} &= -\frac{1}{\left(\sum_{i=1}^N z_i q_i^*\right)}\left[\sum_{i=1}^N \frac{d\Pi_i^*}{dt}(0)\right] \\ &= \frac{\sum_{i=1}^N z_i \sigma_i \tilde{\gamma}_i}{\sum_{i=1}^N z_i \sigma_i}.\end{aligned}$$

This equation, together with (26) gives us a formula for $\tilde{\gamma}$. Note that in the formula below, $H = \sum_{i=1}^N (\sigma_i^*)^2$ denotes the industry's Herfindahl index and $Z = \sum_{i=1}^N z_i \sigma_i$ is the industry's average emissions intensity (weighted by each firm's market share). Bear in mind that the unweighted emissions intensity, $\sum_{i=1}^N z_i/N$, has been normalized at 1. Assuming emissions intensity is monotone, $Z \leq 1$ since $\sigma_i$ and $z_i$ are respectively decreasing and increasing with $i$.

Proposition 9 *In the Cournot model,*

$$\tilde{\gamma} = \frac{2(N+1)Z - 2N - 2ZE(Q^*) + NHE(Q^*)}{Z(N+1-E(Q^*))}. \tag{27}$$

We can use this result to identify some sufficient conditions for profit-neutral grandfathering to be partial.

Corollary 2 *In the Cournot model, $\tilde{\gamma} < 1$ if and only if*

$$Z(N+1) - 2N + E(Q^*)(NH - Z) < 0. \tag{28}$$

*Provided emissions intensity is monotone, $\tilde{\gamma} < 1$ if (i) $E(Q^*) < 1$ or (ii) $H \leq 2/(N+1)$.*

While it is possible in the Cournot model for $\tilde{\gamma} > 1$, we see from Corollary 2 that partial PNA holds under some quite general conditions. Condition (ii) is a bound on the degree of asymmetry in the industry; if firms have identical initial marginal costs (and hence identical market shares) then there is partial PNA since $H = 1/N$. It is interesting to contrast this result with a known result (see Shapiro (1989) or Kimmel (1992)) that, in a symmetric Cournot model, a common increase in marginal cost raises total profit (in our context, $\Pi^*(t) > \Pi^*$ if and only if $E(Q^*) > 2$. (To recover this result, set $H = 1/N$, $Z = 1$, and $\tilde{\gamma} < 0$ in (27).) Recall (see Proposition 2) that partial PNA is equivalent to an increase in $\underline{\Pi}^*(t)$. This condition is less stringent than an increase in $\Pi^*(t)$ and, as it turns out, *always* holds in a symmmetric Cournot model, irrespective of the value of $E(Q^*)$.

Condition (i) we have already encountered in Propositions 5 and 6, and as we had pointed out in Section 3.2, this is a standard assumption in Cournot analysis. Gathering together these results, we conclude that *when the demand function is locally log-concave, the introduction of the ETS will lower emissions, improve cost efficiency, and require only partial PNA.*

### 3.5 PNA when $t$ is large

We shall focus our discussion on the average industry-level PNA; in particular, we wish to show that the qualitative results on partial PNA stated in Corollary 2 are preserved when the permit price is not small. We assume that the permit price is $T > 0$, and for all $t$ in $[0, T]$, the Cournot equilibrium exists and varies smoothly with $t$. It follows from (5) that the industry PNA may be written as

$$\begin{aligned} \gamma(T) &= \frac{1}{T\zeta^*(0)} \left[ \Pi^*(0) - \Pi^*(T) \right] = -\frac{1}{T\zeta^*(0)} \int_0^T \frac{d\Pi^*}{dt}(t)\, dt \\ &= \frac{1}{T\zeta^*(0)} \int_0^T f(t)\zeta^*(t) dt, \text{ where} \end{aligned}$$

$$f(t) = -\frac{1}{\zeta^*(t)} \frac{d\Pi^*}{dt}(t).$$

Using essentially the same arguments that led us to the formula for $\tilde{\gamma}$, we can check that

$$f(t) = \frac{2(N+1)Z(t) - 2N - 2Z(t)E(Q^*(t)) + NH(t)E(Q^*(t))}{Z(t)\ [N + 1 - E(Q^*(t))]}, \qquad (29)$$

where $Z(t)$ is the ratio of the weighted and unweighted emissions intensity, i.e., $Z(t) = z^*(t)/[\sum_{i=1}^N z_i(t)/N]$.[6] It follows from the formula for $\gamma(T)$ that it will be less than 1 provided (i) $f(t) < 1$ and (ii) $\zeta^*(t)$ is decreasing in $t$ for $t$ in $[0, T]$.

Conditions (i) and (ii) both hold in the following cases.

*Case A.* We assume that the demand function obeys $N + 1 - E(Q) > 0$ for any $Q > 0$. All firms have exactly the same technology, and the Cournot equilibrium is symmetric, with each firm producing at the same output level using an identical input (including emissions) mix.

*Case B.* We assume that $E(Q) < 1$ for $Q > 0$. For any $t$ in $[0, T]$, we require $c_i(t)$ to increase with $i$. In other words, at any $t$, Firm 1 is the most efficient firm in the relevant range, Firm 2 the second most efficient, etc. Lastly, emissions intensity is

[6]Note that we have normalized $\sum_{i=1}^N z_i(0)/N = 1$, so $f(0) = \tilde{\gamma}$ (see (27)), as we would expect given (6).

monotone in the sense that, at any $t$, $z_i(t)$ increases with $i$.
Note that the condition $N + 1 - E(Q) > 0$ is in fact required in both cases since it is implied by $E(Q) < 1$ in case B. It is easy to check, using the same arguments that gave us (19), that this condition guarantees that equilibrium output $Q^*(t)$ falls with $t$.

PROPOSITION 10 *Under either Case A or Case B assumptions, the introduction of the ETS lowers industry output, emissions intensity and total emissions, and requires partial PNA. Formally,* $Q^*(T) < Q^*(0)$, $z^*(T) \leq z^*(0)$, $\zeta^*(T) < \zeta^*(0)$, *and* $\gamma(T) < 1$.

The proof for Case A is straightforward; that for B slightly more involved. Standard revealed preference arguments guarantee that optimal emissions intensity at each firm, $z_i(t)$, decreases with $t$. But to guarantee that *average* emissions intensity falls with $t$, we need to show that firms with lower emissions gain market share with increasing $t$. This in turn follows from the fact that, with monotonicity, firms with lower emissions also have lower marginal costs, and these firms gain market share when $t$ increases and demand is log-concave. The next result gives the formal senses in which firms with lower emissions 'gain market share'.

PROPOSITION 11 *Under Case B assumptions, the following holds for* $t$ *and* $t'$ *in* $[0, T]$ *with* $t < t'$:
*(i)* $\sigma_i(t') - \sigma_i(t)$ *is decreasing in* $i$*;*
*(ii) for any* $k$*, we have* $\sum_{i=1}^{k} \sigma_i(t') \geq \sum_{i=1}^{k} \sigma_i(t)$*; and*
*(iii)* $H(t') \geq H(t)$.

Conclusion (i) is just the global and discrete version of the earlier result that, at $t = 0$, $d\sigma_i/dt$ is decreasing in $i$ (see Proposition 5). Conclusion (ii) follows from (i) and says that the market share distribution at $t$ first order stochastically dominates the distribution at $t'$. At any given $t$, firms with lower marginal costs have larger market shares. If they also gain market share as $t$ increases, the industry must become more concentrated, which is reflected in a higher Herfindhal index (conclusion (iii)).

### 3.6 From theory to empirics

It is possible to use the formulae we have developed to perform some illustrative calculations on the level of PNA. We do this for three industries affected by the EU ETS: cement, newsprint, and steel. Naturally, the move from theory to empirics will require some major assumptions. Recall that the formulae for $\tilde{\gamma}$ and $\tilde{\gamma}_i$ are defined in terms of the number of firms, market shares, the curvature of demand $E(Q^*)$, and emissions intensity. Data on the number of firms and market shares are readily available, though drawing the boundaries of an industry must necessarily be a matter of judgment. So for our purposes, firms producing cement in the U.K. are thought to constitute a single industry; in the case of newsprint and steel, the industry is deemed to be EU-wide. For these three industries, there is little firm-level information on emissions intensity, so we shall simply assume that it is uniform across firms.

Another major issue concerns $E(Q^*)$, the value of which is not directly observable. One way of getting around this difficulty is to note that

$$E(Q^*) = \left[1 + \frac{1}{\eta(Q)} + \frac{d \log \eta(Q)}{d \log Q}\right]_{Q=Q^*}, \tag{30}$$

where $\eta(Q) = |P(Q)/QP'(Q)|$ is the industry price elasticity of demand. It is commonplace to contend that demand elasticity is nondecreasing in price, which implies that $\partial\eta(Q)/\partial Q \leq 0$. We assume that this term is negligible, so that demand (approximately) has constant elasticity and $E(Q^*) \approx 1 + 1/\eta$. This gives us a way of calculating $E(Q^*)$, since estimates of price elasticity for the three industries are readily available from previous empirical work.[7] We call this way of estimating PNA the *elasticity approach.*

[7]Note also that an econometric analysis that regresses log quantity on log price (or vice versa) implicitly assumes that demand has constant elasticity.

We also double-check our results using another method of estimation, which we call the *cost pass-through approach*. This approach relies on (19), which implies that

$$\frac{dP^*}{dt} = P'(Q^*)\frac{dQ^*}{dt} = \frac{N}{N+1-E(Q^*)}. \tag{31}$$

This formula shows that it is possible, in principle, to back out the value of $E(Q^*)$ from information on cost pass-through. Unfortunately, empirical estimates of pass-through for the three industries are not available. We therefore report estimates of profit-neutral grandfathering consistent with rates of cost pass-through ranging from 1% to 200%. It seems unlikely that the pass-through arising from the ETS in the three industries will go beyond this range.[8]

This approach has an important advantage over the elasticity approach. In the elasticity approach, $E(Q^*) = 1 + 1/\eta > 1$. This is unfortunate, since it excludes a whole class of demand functions that this paper (see Propositions 5 and Corollary 2) and more generally, the theoretical IO literature, have identified as significant. Furthermore, we know from (31) that when $E(Q^*) > 1$ we have $dP^*/dt > 1$, i.e., cost pass-through exceeds 100%. On the other hand, the cost pass-through approach specifically allows for less than 100% cost pass-through; equivalently, it allows for $E(Q^*) < 1$.

Our calculations suggest that average PNA in all three industries is partial. For the cement industry, estimates of $\tilde{\gamma}$ vary between 30-65%; the corresponding figures for newsprint and steel lie between 15-35%. However, firm-level PNA do vary significantly amongst firms within an industry; for some parameter values, $\tilde{\gamma}_1 > 1$, i.e., to guarantee profit neutrality, the largest firm, Firm 1, will require a free allocation of emissions permits that is larger than his initial emissions.[9] More details on the data

[8] The literature on tax incidence, for example, finds empirical evidence for cost pass-through both above 100% ('overshifting') and below 100% ('undershifting') in markets such as cigarettes, gasoline and groceries. However, there is little evidence of rates of pass-through outside our range of 1% to 200%. See Fullerton and Metcalf (2002) for an overview of this literature.

[9] Note that this claim is of course sensitive to our assumption in the empirical analysis, that

and calculations are found in the Appendix B.

# Appendix A

Proof of Proposition 4: Let $\hat{q}_i(Q_{-i}, t)$ be the best response of firm $i$ when the other firms are producing $Q_{-i}$ and its marginal cost is $c_i(t)$. Abusing notation, let $MR_i(q_i, Q_{-i})$ denote firm $i$'s marginal revenue when its output is $q_i$ and the other firms are producing $Q_{-i}$. The first-order condition guarantees that $MR_i(\hat{q}_i, Q_{-i}) = c_i(t)$. Differentiating this equation by $t$ and evaluating it at $t = 0$, we obtain

$$\frac{\partial \hat{q}_i}{\partial t} = \frac{z_i}{\partial MR_i/\partial q_i} = \frac{z_i}{2P' + q_i P''} \tag{32}$$

Differentiating the same equation by $Q_{-i}$, we obtain

$$\frac{\partial \hat{q}_i}{\partial Q_{-i}} = -\frac{\partial MR_i/\partial Q_{-i}}{\partial MR_i/\partial q_i} = -1 + \frac{P'}{2P' + q_i P''}. \tag{33}$$

At equilibrium, $\hat{q}_i(Q^*_{-i}, t) + Q^*_{-i} \equiv Q^*$. Differentiating this with respect to $t$ and using (32) and (33), we obtain

$$\frac{dQ^*_{-i}}{dt} = \frac{dQ^*}{dt}\left[2 - \sigma_i E(Q^*)\right] - \frac{z_i}{P'}. \tag{34}$$

Summing this equation across firms and using the normalization that $\sum_{i=1}^{N} z_i = N$ gives us

$$(N-1)\frac{dQ^*}{dt} = \frac{dQ^*}{dt}[2N - E(Q^*)] - \frac{N}{P'}.$$

Re-arranging this gives us (19). Using (19) to substitute for $P'$ in (34), we obtain (20). Finally,

$$\frac{dq^*_i}{dt} = \frac{dQ^*}{dt} - \frac{dQ^*_{-i}}{dt}$$

so (21) may be derived from (19) and (20). QED

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emissions intensity is uniform across firms. Monotonicity is emissions will tend to favor big firms and thus lower their levels of profit-neutral grandfathering.

Proof of Proposition 5: Appealing to (19) and (21), we can write

$$\frac{d\sigma_i}{dt}(0) = \frac{1}{Q^*(0)}\frac{dQ^*}{dt}\frac{[-N + \sigma_i(E(Q^*) - 1)N + z_i(N + 1 - E(Q^*))]}{N}. \tag{35}$$

Since $\sigma_i$ decreases with $i$, it is clear that $d\sigma_i/dt$ decreases with $i$ if $E(Q^*) < 1$ and $z_i$ increases with $i$. This implies that $\{d\sigma_i/dt\}_{1\leq i\leq N}$ has the single crossing property.

The second claim relies on the following lemma.

LEMMA: *Suppose that* $\{b_i\}_{1\leq i\leq N}$ *obeys the single crossing property and let* $\{a_i\}_{1\leq i\leq N}$ *be a collection of real numbers that are increasing in* $i$. *Then*

$$\sum_{i=1}^{N} a_i b_i \leq a_K \left[\sum_{i=1}^{N} b_i\right] \tag{36}$$

Proof of the Lemma: By definition, $\{b_i\}_{1\leq i\leq N}$ obeys the single crossing property if there is $K$ such that for all $i \leq K$, $b_i \geq 0$ and for all $i > K$, $b_i < 0$; (36) follows immediately. QED

Returning to the proof of Proposition 5, we can now apply this Lemma since the $\{d\sigma_i/dt\}_{1\leq i\leq N}$ obeys the single crossing property and $c_i(0)$ increases with $i$. Then

$$\frac{d\underline{c}^*}{dt}(0) \leq \underline{c}_K(0)\left[\sum_{i=1}^{N}\frac{d\sigma_i}{dt}\right] = 0,$$

where the second equality follows from the fact that $\sum_{i=1}^{N}\sigma_i(t) \equiv 1$. QED

Proof of Proposition 6: Obviously the second claim follows from the first since $dQ^*/dt < 0$ (see (19)). From Proposition 5 we know that the output response obeys the single crossing property. So

$$\begin{aligned}\frac{dz^*}{dt}(0) &\leq \sum_{i=1}^{N} z_i(0)\frac{d\sigma_i}{dt}(0)\\ &\leq z_K(0)\left[\sum_{i=1}^{N}\frac{d\sigma_i}{dt}\right] = 0,\end{aligned}$$

where the first inequality follows from (22) and the second from the Lemma (with $a_i = z_i(0)$). QED

Proof of Corollary 2: The inequality (28) is easily obtained by requiring the formula in (27) to be less than 1. Note that $H \geq 1/N$ and since $Z \geq 1$, we know that $NH - Z \geq 0$. If $NH - Z = 0$, then it is clear that (28) is satisfied. So assume that $NH - Z > 0$. If $E(Q^*) < 1$, then the left of (28) is strictly less than

$$\begin{aligned} Z(N+1) - 2N + (NH - Z) &\leq Z(N+1) - 2N + N - Z \\ &= N(Z-1) \leq 0. \end{aligned}$$

To prove (ii), note that $E(Q^*) < N + 1$ (see (18)), so that the left of (28) is strictly less than

$$Z(N+1) - 2N + (N+1)(NH - Z) = -2N + (N+1)NH$$

Setting this less than 0 gives (ii). QED

Proof of Proposition 10: For both cases, it suffices to show that $f(t) < 1$ and $\zeta^*(t)$ decreases with $t$.

*Case A.* Standard revealed preference arguments guarantee that $z_i(t)$ (which is identical for all firms and thus equal to $z^*(t)$) decreases with $t$. Since $Q^*(t)$ decreases with $t$, so does total emissions $\zeta^*(t) = z^*(t)Q^*(t)$. Furthermore, with a symmetric equilibrium, $Z(t) \equiv 1$ and $H(t) \equiv 1/N$, so $f(t) = [2-E(Q^*(t))]/[N+1-E(Q^*(t)] < 1$.

*Case B.* Since lower index firms have lower marginal costs, market share $\sigma_i(t)$ decreases with $i$, which guarantees that $Z(t) \leq 1$. Using this fact and the assumption that $E(Q) < 1$, the argument used in the proof of Corollary 2 will guarantee that $f(t) < 1$. Given that equilibrium output decreases with $t$, total emissions $\zeta^*(t)$ will decrease with $t$ if emissions intensity $z^*(t)$ decreases with $t$. Proposition 11(i) tells us that at any $t$, $d\sigma_i/dt$ is decreasing in $i$, which implies that it obeys the single crossing property. It is straightforward to adapt the argument used in Proposition 6 to obtain $d\zeta^*/dt \leq 0$ at $t$ in $[0, T]$. QED

Proof of Proposition 11: (i) is equivalent to having $d\sigma_i/dt$ decreasing in $i$ (at every $t$). To see that the latter is true, we need only adapt the argument used to prove

Proposition 5. To prove (ii), we apply the Lemma, with $a_i = -1$ for $i \leq k$ and $a_i = 0$ for $i > k$. This gives us

$$-\frac{d}{dt}\left[\sum_{i=1}^{k} \sigma_i(t)\right] \leq 0,$$

from which we obtain (ii). To prove (iii), note that

$$-\frac{dH}{dt}(t) = -\sum_{i=1}^{N} 2\sigma_i(t)\,\frac{d\sigma_i}{dt}(t).$$

Set $a_i = -2\sigma_i(t)$ and apply the Lemma to obtain $dH/dt \geq 0$. QED

# Appendix B

While information on the market shares of leading firms in each of the three industries appears to be reliable, it is difficult to obtain any data at all for very small firms (in particular, those with market shares below 5%). For the same reason, the number of firms in an industry is not always easy to determine. However, this is likely to have only a very small impact on the respective industry Herfindahl indices.

Since our data may underestimate the number of firms in an industry, one might ask how this affects PNA calculations. Suppose the true number of firms is $M > N$ and that firm $i$'s market share $\sigma_i^*$ is measured relative to the true industry output $Q^*$ (rather than the output of the $N$ firms). Then the formula (26) for $\tilde{\gamma}_i$ remains *exactly* correct if the $N$ firms act as Cournot players, while the remaining $M - N$ stay do not vary their output. Similarly, the formula (27) for average PNA over $N$ firms is *exactly* correct if $H = \sum_{i=1}^{N}(\sigma_i^*)^2$ and $Q^*$ is the output of all $M$ firms. Note that this $H$ is not the same as the true Herfindahl index (which is $\sum_{i=1}^{M}(\sigma_i^*)^2$) though the difference will be insignificant if the remaining $M - N$ firms are small. If the tail firms are not inert and collectively produce less with emissions trading, then our results overestimate PNA. If they produce more (which is perhaps reasonable if they are non-EU firms that do not require permits for $CO_2$ emissions), then our results are an underestimate.

**Cement.** There are five certified types of cement—Portland cement, Portland blast furnace cement, sulphate-resisting cement, masonry cement, and Portland pulverized fuel ash cement—which we group together because they are manufactured with essentially the same process (Environment Agency, 2005). The cement market definition is complex, mainly because land-based transport is expensive, while sea-based transport is relatively cheap.[10] Nevertheless, it is a fair assumption that large portions of the European cement industry do not face strong international competition. Indeed, since over 90% of the cement consumed in the UK is also manufactured there, we again define the relevant market as the UK.

The UK cement market is dominated by the four members of the British Cement Association: Lafarge Cement UK (previously Blue Circle), Castle Cement (owned by Heidelberg Cement), Cemex (previously Rugby Cement) and Buxton Lime Industries. These four firms collectively produce around 90% of the cement sold in the UK, with approximate market shares of 40%, 25%, 20% and 5% (Environment Agency, 2005). Imports from six different firms (one related to Cemex Cement and another related to Castle Cement) supply the remainder. This implies a Herfindahl index of around 0.28, which is substantially higher than in cement industries in many other countries. Finally, for modelling purposes, we assume there are eight players in the Cournot game—four local firms and four independent importers.

Estimates of the price elasticity of demand for cement in the UK do not seem to be readily available. La Cour and Mollgaard (2002) provide an estimate of 0.27 for demand in Denmark. However, there is only one Danish cement producer, Aalborg Portland, with 85% market share, so this estimate appears to be somewhat low. In the United States, there are several dozen firms and Jans and Rosenbaum (1997) find an average elasticity of demand of 0.80. More recently, Ryan (2005) finds an elasticity

[10]See Lafarge/Blue Circle (Comp/M.1874, 07.04.2000) and Szabo et al. (2006).

of 2.95 from US market-level data on prices and quantities. While noting this is a rather high estimate, he argues that it is consistent with data on profit margins and plant costs. Finally, Roller and Steen (2005) find a short-run elasticity of 0.46 and a corresponding long-run elasticity of 1.47 for the Norwegian market. In the absence of UK data, we employ price elasticities of 0.40 (low), 0.80 (best guess) and 3.00 (high) in our modelling, based on the estimates for other countries.

**Newsprint.** Newsprint producers face more international competition than the previous two sectors, with some 15% of consumption being supplied from outside the EU. According to an EU competition case, there are 19 European firms in the industry with at least six other international firms, but the five leading firms have a combined share of around 70–80% of the market.[11] UPM-Kymmene, Norske Skog and Stora Enso each have around 15–20% of the market. We assume the largest market share is 20% in our modeling. Because market shares otherwise appear to be distributed fairly evenly between firms, we estimate the Herfindahl index to be 0.12.

Using panel data from 1969 to 1992 for the European Union as a whole, Chas-Amil and Buongiorno (2000) estimate the short-run newsprint price elasticity of demand to be 0.30, with a long-run elasticity of 0.48. This is broadly consistent with elasticity estimates for newsprint from European Commission case law of 0.15–0.30, based on approaches outlined in Christensen and Caves (1997) and Pesendorfer (2000). As such, we use elasticity estimates of 0.20 (low), 0.30 (best guess) and 0.50 (high).

**Coated sheet steel.** Rapid structural changes have occurred in the steel industry over the past few years, with a clear trend towards increasing concentration.[12] Steel

[11]See UPM-Kymmene/Norske Skog C(2001)3703. At the time of writing, the Association of European Publication Paper Producers, CEPIPRINT, lists 13 independent newsprint producers (see www.cepiprint.ch/who_are_members/mill_grades/index.htm). The other producers are very small, again according to UPM-Kymmene/Norske Skog C(2001)3703.

[12]For instance, see Defra (2004), Competition Commission (2005), and Deutsche Bank Research (2006).

product markets are defined as European markets, and some of these markets have a relatively high import penetration, reducing the applicability of our theoretical model. For this reason, we examine European data on 'coated sheet steel', where imports comprise only 7% of the market. Coated sheet steel is used in a variety of products, including cars, trucks, buildings, and storage containers. As the name suggests, it is coated with a metal alloy or organic material designed to increase resistance to corrosion.

Data provided by the European Federation of Iron and Steel Industries (2006) for the year 2004 indicates that there were 12 firms supplying the European market for coated sheet steel.[13] The largest firm has a market share of 37% and the Herfindahl index is 0.19. The only available reference on price elasticities in the steel industry is Lord and Farr (2003), who report an estimate of 0.62. We thus employ a range of 0.40 (low), 0.60 (best guess), 1.00 (high) in our modelling.

The industry data are summarized in Table 1.

**Table 1: Industry data**

| | Cement | Newsprint | Steel |
|---|---|---|---|
| Market definition | UK | Europe | Europe |
| Number of firms | 8 | 19 | 12 |
| Highest market share | 40% | 20% | 37% |
| Herfindahl Index | 0.28 | 0.12 | 0.19 |
| Price elasticity (low) | 0.40 | 0.20 | 0.40 |
| Price elasticity (best) | 0.80 | 0.30 | 0.60 |
| Price elasticity (high) | 3.00 | 0.50 | 1.00 |

## 3.7 PNA Estimates

This section provides empirical estimates of PNA using two approaches.

[13]Specifically, the data pertain to steel classified as lines 451, 454 and 457 (European Commission, 1994).

**Price elasticity approach**

Our first empirical approach assumes that demand has constant elasticity and employs estimates of the price elasticity of demand obtained from previous empirical work. Since now $E(Q^*) = 1 + 1/\eta$, the expressions for PNA become

$$\tilde{\gamma}_i = \frac{2 - (2 - N\sigma_i^*)(1 + 1/\eta)}{N - 1/\eta} \tag{37}$$

at the firm-level (see (26)) and

$$\tilde{\gamma} = \frac{2 - (2 - NH)(1 + 1/\eta)}{N - 1/\eta} \tag{38}$$

at the industry-level (see (27)). Note that $N > 1/\eta$ is required for price to increase (and output and pollution to decrease) with the introduction of emissions trading, which we assumed in the theoretical model (see (19)). This condition is satisfied throughout by the data in all three industries.

Since inverse demand is everywhere convex and emissions intensity is assumed to be uniform, we know that largest firm in each industry requires proportionately the highest level of PNA. We report this value ($\tilde{\gamma}_i$) as well as the industry-level $\tilde{\gamma}$. The results for cement, newsprint and steel respectively are summarized in Table 2.

The UK cement industry is more heavily concentrated than the other two. The results in Table 2 indicate that the largest firm has a PNA exceeding 100%. Estimates of PNA at the industry-level vary between 30% and 50%.

The estimates we obtain for the European newsprint industry share a similar pattern with those for cement but are uniformly somewhat lower. The results suggest that the market leader may require close to 100% PNA if price elasticities are near the lower end. At the industry-level, we obtain PNA estimates between 15% and 25%.

Our estimates of PNA for the European coated sheet steel industry are comparable to those for cement and newsprint. PNA for the largest firm is found to be as high as 110% and no lower than 60%. For the industry as a whole, our estimates are rather stable across the range of price elasticities considered, with PNA between 25% and 35%.[14]

**Table 2: PNA and price elasticity**

| Industry | Elasticity | Highest firm-level $\tilde{\gamma}_i$ | Industry-level $\tilde{\gamma}$ |
|---|---|---|---|
| Cement | 0.40 (low) | 1.127 | 0.516 |
| | 0.80 (best) | 0.696 | 0.376 |
| | 3.00 (high) | 0.470 | 0.303 |
| Newsprint | 0.20 (low) | 0.914 | 0.263 |
| | 0.30 (best) | 0.626 | 0.205 |
| | 0.50 (high) | 0.435 | 0.167 |
| Steel | 0.40 (low) | 1.109 | 0.314 |
| | 0.60 (best) | 0.823 | 0.266 |
| | 1.00 (high) | 0.625 | 0.233 |

**Cost pass-through approach**

Our second empirical approach considers the level of PNA as a function of the rate of pass-through from marginal cost onto prices. Given the absence of empirical data on pass-through in the industries considered, we report estimates of PNA consistent with rates of cost pass-through ranging from 1% to 200%. With this approach, we do not restrict attention to constant elasticity demand, and hence pass-through does not have to exceed 100%. This approach is best seen as a robustness check.[15]

As before, we are interested in the highest firm-level PNA as well as the industry-level PNA. Using (26), (27) and (31), these can be written in terms of cost pass-

[14]For the newsprint and steel industries, the presence of significant international competition may mean that our PNA estimates are biased downwards.

[15]The *implied* rates of cost pass-through using the 'best guess' estimates of elasticity (see Table 2) are approximately 119% for electricity and cement, 121% for newsprint and 116% for steel respectively. All of the implied cost pass-through rates in the elasticity approach are within the range 104–146%.

through as

$$\tilde{\gamma}_i = (2 - N\sigma_i^*) - \frac{dP^*}{dt}\left[2 - (N+1)\sigma_i^*\right] \tag{39}$$

at the firm-level and

$$\tilde{\gamma} = (2 - NH) - \frac{dP^*}{dt}\left[2 - (N+1)H\right] \tag{40}$$

at the industry-level. We know that $\tilde{\gamma}_i$ is highest for the largest (smallest) firm when inverse demand is convex (concave). The highest firm-level PNA, denoted $\max_i\{\tilde{\gamma}_i\}$, therefore is that for the largest firm whenever $dP^*/dt > N/(N+1)$ (equivalently, demand is convex) and for the smallest firm whenever $dP^*/dt < N/(N+1)$ (equivalently, demand is concave). Given that reliable data on market shares is much more difficult to obtain for very small firms, we report the results for the smallest firm assuming a market share of 2.5%.

The results on PNA as a function of cost pass-through for all three industries are reported in Table 3.

**Table 3: PNA and cost pass-through**[a]

| | Cement | | Newsprint | | Steel | |
|---|---|---|---|---|---|---|
| $dP^*/dt$ | $\max_i\{\tilde{\gamma}_i\}$ | $\tilde{\gamma}$ | $\max_i\{\tilde{\gamma}_i\}$ | $\tilde{\gamma}$ | $\max_i\{\tilde{\gamma}_i\}$ | $\tilde{\gamma}$ |
| 1% | 1.782 | –0.235 | 1.510 | –0.276 | 1.683 | –0.275 |
| 20% | 1.445 | –0.136 | 1.225 | –0.200 | 1.365 | –0.186 |
| 40% | 1.090 | –0.032 | 0.925 | –0.120 | 1.030 | –0.092 |
| 60% | 0.735 | 0.072 | 0.625 | –0.040 | 0.695 | 0.002 |
| 80% | 0.380 | 0.176 | 0.325 | 0.040 | 0.360 | 0.096 |
| 100% | 0.400 | 0.280 | 0.200 | 0.120 | 0.370 | 0.190 |
| 120% | 0.720 | 0.384 | 0.600 | 0.200 | 0.932 | 0.284 |
| 140% | 1.040 | 0.488 | 1.000 | 0.280 | 1.494 | 0.378 |
| 160% | 1.360 | 0.592 | 1.400 | 0.360 | N/A | 0.472 |
| 180% | 1.680 | 0.696 | 1.800 | 0.440 | N/A | 0.566 |
| 200% | N/A | 0.800 | N/A | 0.520 | N/A | 0.660 |

[a]N/A indicates that the implied rate of value of $E(Q^*)$ leads to a violation the firm's second-order condition (see (17)) for profit-maximization.

The estimates of industry-level PNA, $\tilde{\gamma}$, are linear and increasing in $dP^*/dt$ since $H > 2/(N+1)$ for the industries being considered. The estimates of the highest firm-level PNA are *piecewise* linear in $dP^*/dt$, with a kink where $dP^*/dt = N/(N+1)$—for the industries we consider, this is between 80% and 100%.

Table 3 gives a wider range of PNA estimates than similar estimates obtained using the elasticity approach. This is not surprising since the cost pass-through approach encompasses a far greater range of demand curves. A useful benchmark case to understand the results occurs when the rate of cost pass-through is exactly 100% (and $E(Q^*) = 1$), implying that each firm's profit margin remains constant. Then $\tilde{\gamma}_i = \sigma_i^*$ and $\tilde{\gamma} = H$, so PNA is *always* partial at the firm level; from Table 3 we see that industry-level PNA varies between 9% and 28%. More generally, PNA is partial for *all* firms if the rate of cost pass-through is (approximately) between 50% and 130%. Small firms in all industries may be worse off if pass-through is lower, while large firms may be worse off when pass-through is higher. For any rate of cost pass-through between 1% and 200%, industry-level PNA is partial.

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