Emissions Trading with Profit-Neutral Permit Allocations

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Abstract: This paper examines the impact of an emissions trading scheme (ETS) on equilibrium emissions, output, price, market concentration, and profits in a generalized Cournot model. We develop formulae for the number of emissions permits that have to be freely allocated to firms to neutralize the profit impact of the ETS. We show that its profit impact is usually limited: in a Cournot oligopoly with constant marginal costs, total industry profits are preserved so long as freely allocated permits cover a fraction of initial emissions that does not exceed the industry's Herfindahl index.

Keywords: Cap-and-trade, permit allocation, profit-neutrality, cost pass-through, abatement, grandfathering

JEL Classification Numbers: D43, H23, Q58

1. Introduction

There is increasingly broad recognition that greenhouse gas emissions are contributing to changes to Earth's climate. Emissions trading schemes for CO_2 and other greenhouse gases are an important part of the policy response to this problem. The justification for the use of economic instruments, such as emissions trading and emissions taxes, arises from the observation that imposing a common price on emissions equalizes marginal abatement costs across polluting firms and minimizes the aggregate cost of pollution control (see Baumol and Oates, 1988). In most cases, this makes economic instruments more efficient than "command-and-control" intervention which specifies input or output standards or technologies. However, there is a significant disadvantage to the use of taxes or trading: inframarginal wealth

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transfers in the form of payments of taxes or for emissions permits impose an additional burden on industry. The extent to which this burden can be alleviated affects the magnitude of emissions reductions that are politically feasible.

Policy makers have sought to alleviate this problem by implementing trading schemes where all or some of the emissions permits are granted for free. This is often referred to as *grandfathering* since the number of permits freely allocated to a firm is typically related to its past emissions. Grandfathering relieves the financial burden of the ETS on industry, without affecting firms' incentives to reduce emissions at the margin.[2]

For most emissions trading schemes in the US, and also in the early phases of the European Union's ETS for CO_2 (EU ETS), almost all permits were freely allocated in this manner. It is clear that not selling permits (at auction, say) entails a significant loss of government revenue which could potentially be more productively employed in other ways (for example, in the reduction of distortionary taxes).[3] Furthermore, a firm's incentive to raise prices in response to the higher marginal cost is also unaffected by the free allocation of permits. This raises the possibility that firms will make "windfall profits" from free permit allocations. For these reasons and others, the question of whether to freely allocate permits, and if so, to what extent, is an important one.

Model setup and ETS impact on emissions. The aim of this paper is to provide a basic theoretical framework in which the profit impact and other central issues relating to an ETS can be analyzed. We assume that the industry affected by the ETS is an oligopoly in its product market. The industry's *conduct parameter* θ governs the strategic interaction within the industry, with $\theta = 1$ corresponding to a Cournot oligopoly, $\theta = 0$ corresponding to perfect competition, and higher values of θ implying more collusive behavior. The production process gives rise to emissions, which have to be paid for with emissions permits; firms are price-takers in the market for permits. This is a reasonable setup, since we have in mind a trading scheme, like the EU ETS, where permits are traded across many industries in

[2] Another method of protecting average profits in an industry is to hold an auction for emissions permits but to then return the revenue back to the firms using some other formula. This was originally proposed by Hahn and Noll (1982); a small fraction of the permits in the Sulfur Allowance Program is allocated through a zero-revenue auction (see Tietenberg (2006, Chapter 6)).

[3] See, e.g., Fullerton and Metcalf (2001), Bovenberg and Goulder (2001), and Bovenberg, Goulder and Gurney (2005).

(potentially) many countries, so that firms are price takers in the market for permits, while individual industries have oligopolistic structures.

Before we examine the issue of permit allocations, several more basic questions need to be answered. Most importantly, does the imposition of a price on emissions have the desired effect of reducing emissions in this industry? This effect, however intuitive, is not guaranteed in an oligopoly model. We show that two added conditions on the model guarantee that the ETS has the effect of reducing industry output, reducing firms' average emissions intensity—and hence also reducing total emissions: (a) firms' marginal costs are non-negatively correlated with their emissions intensities,[4] and (b) the industry faces a log-concave demand function.[5]

The imposition of a price on emissions will always encourage firms to engage in abatement, thus (weakly) lowering each firm's emissions intensity. But the ETS also changes firms' output decisions, so that the industry's *average* emissions intensity can increase if dirtier firms gain market share. We show that this possibility is excluded by conditions (a) and (b), which together have two important effects. First, firms with lower marginal costs gain market share and, since these are the bigger firms in the industry to begin with, market concentration in the industry rises. Second, since (b) guarantees that these firms are *not* more emissions intensive, the industry's average emissions intensity and total emissions both decline.

ETS impact on profits. The gain in market share of lower-cost firms means that the ETS has the effect of moving the industry closer to the joint profit-maximizing (fully collusive) outcome. This is one reason why the adverse profit impact (averaged across the whole industry) of the ETS tends to be limited. We measure the profit impact by looking at the *profit-neutral permit allocation* (PNA): the number of permits that have to be freely allocated to the industry to guarantee that aggregate industry profit is preserved at its level from before introduction of the ETS. Our framework yields bounds on this number without

[4] Emissions intensity is defined as emissions per unit of output. Note that condition (a) is consistent with notions of eco-efficiency (see Section 3 for more discussion). It is also satisfied if firms do not differ significantly in their emissions intensities.

[5] Log-concavity is a commonly-made restriction on the demand function; it is a sufficient (and, in a certain sense, necessary) condition for a Cournot oligopoly to be a game of strategic substitutes (see Section 3 for more discussion).

requiring a fully-specified parametric model. In particular, consider a Cournot oligopoly with constant marginal costs and satisfying conditions (a) and (b). We show that if x is the number of permits required to cover the industry's pre-ETS emissions (had the permits been needed), then the profit-neutral permit allocation is below Hx, where H is the Herfindahl index (see case [4], Section 4.2). This bound becomes more (less) stringent if the industry is more (less) competitive than Cournot (equivalently, if the conduct parameter $\theta \leq (>)\, 1$). Even in relatively concentrated industries, the Herfindahl index is often *much* lower than 0.5. For example, consider a Cournot oligopoly with a Herfindahl index of 0.4, and suppose the ETS targets a 20% reduction in emissions. In this case, the number of emissions permits required for profit-neutrality, as a fraction of the number of issued permits, is 0.4/0.8 or 50%. In other words, about half the number of permits can be auctioned whilst preserving total industry profit. If instead the industry's Herfindahl index is 0.20, the required proportion of free permits falls to 25%.

Our results on profit-neutral permit allocations are obtained by developing formulae that bound the level of profit-neutral permit allocations at the firm- and industry-level. These formulae involve familiar parameters that can often be estimated with a reasonable degree of accuracy, making them amenable to empirical implementation. We illustrate this by applying them to calculate the profit-neutral permit allocation in the UK cement industry (which is included in the EU ETS). This application also shows that profit-neutral permit allocations can remain low even if we depart significantly from assumptions (a) and (b).

Related literature. Bovenberg, Goulder and Gurney (2005) (see also Bovenberg and Goulder (2001)) build a competitive general equilibrium model in which capital is imperfectly mobile, so that investment in sectors affected by an ETS will have a lower rate of return. Capital in these sectors could be compensated with free permits, which in turn has an economy-wide efficiency cost (because, for instance, of the foregone opportunity to reduce distortionary taxes). They consider a scheme to control SO_2 emissions in the U.S. and show that the efficiency cost of compensation policies is limited, mainly because the extent of free permit allocations needed to maintain equity returns is low (no more than 50% of issued permits). Their model assumes that all sectors of the economy (including those affected by the ETS) are perfectly competitive, so the qualitative features of their analysis are related to our analysis of the perfectly competitive case (see case [1], Section 4.2).

This paper does not consider various other interesting issues relating to emissions trading, including some that may have an impact on profit-neutral permit allocations.[6] Among our main assumptions is that firms are price takers in the market for permits. This will be violated in situations where the permits market is not significantly broader than the product market; Hahn (1984) and Liski and Montero (2006) consider market power in the emissions market, motivated by the markets for acid rain and particulates.[7] The allocation process can also lead to rent-seeking behavior among firms; for an account of this process in the case of the Acid Rain Program, see Joskow and Schmalensee (1998). It has also been argued that the incentive for technological innovation in emissions abatement is dependent on grandfathering. Some of these issues are surveyed by Cramton and Kerr (2002) who also discuss alternative methods for auctioning permits.

Organization of the paper. Section 2 analyzes the impact of the ETS in a monopoly. It also discusses some general principles underlying profit-neutral permit allocations, and why its level in an oligopoly may differ markedly from its level in a monopoly. Section 3 examines the impact of an ETS in a generalized Cournot model on industry output, market concentration, and emissions. In Section 4 we present our results on profit-neutral permit allocations at the firm- and industry-level. Section 5 applies our formulae to estimate profit-neutral permit allocations in the UK cement industry. Section 6 concludes.

2. The impact of the ETS on firm profits

This section provides a preliminary analysis of the impact of the emissions trading scheme (ETS) on firm profits and of the level of free permit allocations needed to maintain profits at the pre-ETS level. We consider an industry that produces emissions (e.g., of carbon dioxide) that is harmful to the environment. The ETS imposes a cost on these emissions. We assume that the industry is one of many covered by the scheme, so that, although firms have market power in their product market, they are price-takers in the permit market. In this section,

[6] See also Tietenberg (2006) for a careful summary of these points.

[7] Clearly, the presence of transaction costs also means that initial permit allocations have strategic consequences (Stavins, 1995), although there is some evidence of transaction costs being low in the US sulfur dioxide scheme (see Joskow, Schmalensee, and Bailey, 1998).

we make no substantive assumptions regarding the nature of the strategic interaction in the industry. We begin by considering the case of a monopoly. Although not typical, this case has the merit of having a completely general solution and it provides a natural setting to introduce some of the main concepts in our paper.

2.1. The monopoly case

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 the emissions permit price $t \geq 0$. We denote the monopolist's (maximum) profit by $\Pi^*(t)$, and the associated level of emissions by $\zeta^*(t)$. Assuming that one permit is required for each unit of emissions, the profit *before* accounting for the cost of permits is $\underline{\Pi}^*(t) = \Pi^*(t) + t\zeta^*(t)$. (Note that $\Pi^*(0) = \underline{\Pi}^*(0)$.)

The situation before the introduction of the ETS corresponds to the case where $t = 0$, i.e., emissions are unpriced. Therefore, $\Pi^*(0)$ and $\zeta^*(0)$ are the monopolist's initial levels of profits and emissions respectively. Profit maximization by the monopolist guarantees that, at any $t > 0$,

$$\underline{\Pi}^*(t) \leq \Pi^*(0) = \underline{\Pi}^*(0) \text{ and } \tag{1}$$

$$\Pi^*(t) = \underline{\Pi}^*(t) - t\zeta^*(t) \geq \Pi^*(0) - t\zeta^*(0). \tag{2}$$

Equation (1) follows from the fact that Π^* is the optimal profit at $t = 0$, while the production decision that generates a profit of $\underline{\Pi}^*(t)$ is one that the monopolist *could* have made at $t = 0$, so the latter must be smaller than the former. The right-hand side of (2) is the monopolist's profit if it chooses not to adjust production after the introduction of the ETS—this must be less than $\Pi^*(t)$, which is the *optimal* profit when emissions are priced at t.

Combining (1) and (2) yields two conclusions. First, the introduction of the ETS reduces emissions, since these inequalities only hold simultaneously if $\zeta^*(t) \leq \zeta^*(0)$. Second, the ETS reduces the monopolist's profit, since (1) implies that $\Pi^*(t) = \underline{\Pi}^*(t) - t\zeta^*(t) \leq \Pi^*(0)$.

Consider now the level of free allocation of permits required to compensate the monopolist for the reduction in profits from $\Pi^*(0)$ to $\Pi^*(t)$. From (2), $\Pi^*(t) + t\zeta^*(0) \geq \Pi^*(0)$, and furthermore $\Pi^*(t) \leq \Pi^*(0)$, so there is a $0 \leq \gamma(t) \leq 1$ such that

$$\Pi^*(t) + t\,[\gamma(t)\zeta^*(0)] = \Pi^*(0). \tag{3}$$

In other words, $\gamma(t)\zeta^*(0)$ is the number of freely allocated permits—the *profit-neutral allocation* (PNA)—that will leave the monopolist's total profits at the pre-ETS level. Since $\gamma(t) \leq 1$, PNA is a *fraction* of the firm's initial emissions. In this case we say that the profit-neutral allocation is *partial.*

The intuition for this result is as follows. Suppose that the introduction of the ETS is accompanied by a free allocation of permits at the monopolist's original level of emissions; furthermore, suppose that the monopolist chooses *not* to adjust its production plan in response to the introduction of the ETS. Then the increase in her costs would be *exactly* offset by the value of the free allowances. However, the *option* to adjust (e.g., increase price(s) or switch to cleaner inputs) means that the PNA, in general, is partial. It is worth emphasizing that this conclusion is very robust: no restrictions are imposed on the monopolist, except that it is a price-taker in the market for emissions permits.[8]

Finally, suppose that the monopolist indeed receives the PNA of $\gamma(t)\zeta^*(0)$ permits for free. Re-writing (3), we obtain that $\underline{\Pi}^*(t) + t\,[\gamma(t)\zeta^*(0) - \zeta^*(t)] = \Pi^*(0)$. This, together with (1), implies that the monopolist's endowed permits under the PNA, $\gamma(t)\zeta^*(0)$, will *exceed* its requirement $\zeta^*(t)$, so the monopolist will be selling part of its endowment.

The following proposition summarizes our analysis of the monopoly case.

PROPOSITION 1. *Following the introduction of the ETS, a monopolist has lower emissions and lower profit. PNA is partial, i.e.,* $0 \leq \gamma(t) \leq 1$*; with this allocation of permits the monopolist is a net* supplier *in the market for permits.*

2.2. Partial PNA in an oligopoly

When considering an oligopoly, we can no longer rely solely on the revealed preference arguments that gave us such mileage in the monopoly case. Nevertheless, we can still derive some general results which show that PNA in an oligopoly can be very different from that in a monopoly.

Assume that there are $N \geq 2$ firms in an industry that interact with each other strategically; we leave the precise manner of their strategic interaction unspecified for now. Retaining

[8] Furthermore, it is clear that the result holds even if the monopolist is subject to certain regulatory restrictions, such as being prevented from raising prices after the introduction of the ETS.

our earlier notation, we denote equilibrium industry profits when the permit price is t by $\Pi^*(t)$, the equilibrium (total) emissions by $\zeta^*(t)$, and so on. The corresponding outcomes for firm i are $\Pi_i^*(t)$, $\zeta_i^*(t)$, etc. We assume that these are all smooth functions of the permit price t in some interval $[0, T]$, where $T > 0$. We call this model a *smooth oligopoly.*

As in the monopoly case, the proportion of free permit allocation needed for profit-neutrality at the industry-level, $\gamma(t)$, is given by (3). The next result gives a sufficient condition for *strictly* partial PNA.

PROPOSITION 2. *Suppose* $\zeta^*(t) < \zeta^*(0)$ *and* $\underline{\Pi}^*(t) \geq \Pi^*(0)$. *Then PNA is strictly partial, i.e.,* $\gamma(t) < 1$*; with this level of free allocation, the industry has a net demand for permits.*

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

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

Rearranging this expression and using the fact that $\underline{\Pi}^*(t) - t\zeta^*(t) = \Pi^*(t)$, we obtain (3). Since $\underline{\Pi}^*(t) \geq \Pi^*(0)$, we must have $\gamma(t)\zeta^*(0) - \zeta^*(t) \leq 0$, so the industry has a net demand for permits. **QED**

Proposition 2 says that the industry PNA is strictly partial if the introduction of an ETS increases industry profits *before* accounting for emissions costs—in other words, if the ETS leads to a "more collusive" equilibrium outcome. Specifically, had the firms in the industry chosen the (same) actions they did upon the introduction of the ETS *before* it was introduced, their total profits (at $\underline{\Pi}^*(t)$) would have exceeded $\Pi^*(0)$). Of course this scenario is impossible for a profit-maximizing monopolist (see (1)), but it can certainly occur in an oligopoly.[9]

Proposition 2 has a partial converse. Taking the Taylor expansion of $\Pi^*(t)$ around $t = 0$, (3) tells us that the first-order approximation

$$\tilde{\gamma} \equiv \lim_{t \to 0} \gamma(t) = -\frac{1}{\zeta^*(0)} \frac{d\Pi^*}{dt}(0). \tag{4}$$

Since, by definition, $\Pi^*(t) = \underline{\Pi}^*(t) - \zeta^*(t)t$, we can also write

$$\tilde{\gamma} = 1 - \frac{1}{\zeta^*(0)} \frac{d\underline{\Pi}^*}{dt}(0), \tag{5}$$

[9] For example, in the standard textbook case of symmetric Cournot oligopoly with constant marginal cost, industry profits are lower than for a monopolist. If the ETS leads to lower industry output that is closer to the monopoly level, then PNA is strictly partial.

from which the next proposition follows immediately.

PROPOSITION 3. *In a smooth oligopoly,*

$$\tilde{\gamma} < 1 \Longleftrightarrow \frac{d\underline{\Pi}^*}{dt}(0) > 0. \tag{6}$$

We make two other important observations regarding $\tilde{\gamma}$.

(1) If $\tilde{\gamma} < 1$, then for small t, $\gamma(t) < 1$. The industry's net demand for permits, assuming it is given this level of free allocation, is $\zeta^*(t) - \gamma(t)\zeta^*(0)$. Since $\lim_{t\to 0} \zeta^*(t) = \zeta^*(0)$, for low values of t, $\zeta^*(t) - \gamma(t)\zeta^*(0) > 0$. In other words, *if $\tilde{\gamma} < 1$, then (for small values of t) PNA is strictly partial and the industry's net demand for permits will be positive.* If there are sufficiently many industries covered by the ETS with $\tilde{\gamma} < 1$, then overall net demand for permits will be positive. It follows that the permit price can only be supported if there is an external party—the government—that meets this net demand. In this case, an emissions trading scheme will raise net revenue for government even if industries receive their profit-neutral permit allocations.

(2) Recall that if the industry is a monopoly then, for all $t > 0$, $\gamma(t) \leq 1$, but the monopoly is also a net supplier of permits. Comparing this with our previous observation, we conclude that, *for a monopoly,* $\tilde{\gamma} = 1$; so even though PNA is (weakly) partial for a monopoly it approaches a full allocation of permits for low permit prices.[10]

Our discussion already highlights an important distinction between PNA for a monopoly and for an oligopoly. While PNA for a monopolist is so high that allocation at that level will render it a net supplier of permits, PNA for an oligopoly can be significantly lower. This is because an equilibrium oligopoly outcome does not typically maximize the firms' joint profits. This means that an ETS *could* have the effect of leading to a "more collusive" equilibrium outcome (in the sense of raising $\underline{\Pi}$); if it does, PNA will be partial.

In an industry producing a homogeneous good, the oligopoly's equilibrium outcome will typically depart from joint profit-maximization in two ways: (i) output is higher (and price is lower) than it should be, and (ii) production is not divided in a cost-efficient way across

[10] An alternative way of showing that $\tilde{\gamma} = 1$ for a monopolist is to observe that, by the envelope theorem, $d\Pi^*/dt = -\zeta^*$ and then to apply formula (4) for $t = 0$. Notice also that $d^2\Pi^*/dt^2 = -d\zeta^*/dt \geq 0$ since $\zeta^*(t)$ is decreasing in t. In other words, the profit function $\Pi^*(t)$ is convex in t, so $\gamma(t) = [\Pi(0) - \Pi(t)]/t\zeta^*(0)$ is decreasing in t. (This property does not generally extend to oligopoly; see Section 4.3 for related discussion.)

firms. The next section will, amongst other things, examine the conditions under which these "problems" can be ameliorated by an ETS, with the effect that PNA is not just partial but significantly below 100%.

3. The ETS in a generalized Cournot model

Consider an oligopoly with $N \geq 2$ firms producing a homogeneous product. We shall treat emissions like any other input of the firm, so its level is chosen optimally (see, e.g., Baumol and Oates, 1988). To be specific, given the price of emissions and the prices of all other inputs (which we assume are fixed) the firm chooses the emissions level and the bundle of other inputs that minimizes the cost of producing any given output level. We denote the price of emissions by t and assume that it takes values over some relevant range $[0, T]$. The (minimum) cost incurred by firm i when it produces q_i, given an emissions price t, is denoted by $C_i(q_i, t)$.

Model specification on cost functions and emissions intensities. The assumption that firms' production functions have constant returns to scale, so that C_i is a linear function of q_i, is a natural benchmark for a theoretical analysis of an oligopoly model. We will rely on a more general class of cost functions which includes the constant-returns case but also allows for increasing marginal costs of a particular form. We assume that

$$C_i(q_i, t) = c_i(t)q_i + \frac{1}{2}mq_i^2. \tag{7}$$

Therefore, firm i's marginal cost M_i is an affine function of output

$$M_i(q_i, t) \equiv \frac{\partial C_i}{\partial q_i}(q_i, t) = c_i(t) + mq_i. \tag{8}$$

Note that, by assumption, $m \geq 0$ is the same for all firms in the industry and is independent of t. When $m = 0$, firms' have constant—but possibly asymmetric—marginal costs, while a positive m corresponds to increasing marginal cost.

By Shephard's Lemma, the optimal (i.e., cost-minimizing) emissions level at output q_i and permit price t, $\zeta_i(q_i, t)$, satisfies

$$\zeta_i(q_i, t) = \frac{\partial C_i}{\partial t}(q_i, t) = c_i'(t)q_i. \tag{9}$$

Therefore, the firm's emissions are linear in output and one can speak unambiguously of the firm's *emissions intensity* (i.e., emissions per unit of output, ζ_i/q_i) at price t, which is $z_i(t) = c_i'(t)$. Combining (8) and (9) we obtain

$$\frac{\partial M_i}{\partial t}(q_i, t) = z_i(t), \tag{10}$$

so the increase in firm i's marginal cost from a small increase in the emissions price is equal to its emissions intensity.

Model specification on strategic interaction. We denote by q the vector $(q_i)_{1\leq i\leq N}$ representing the output of each firm. Aggregate output is denoted by Q and the output of all firms except firm i by Q_{-i}. We assume that the outcome in this industry at the emissions price $t \in [0, T]$ corresponds to a conjectural variations equilibrium with each firm having the conduct parameter $\theta \geq 0$. We denote the equilibrium output vector by $q^*(t) = \{q_i^*(t)\}_{1\leq i\leq N}$ and equilibrium aggregate output by $Q^*(t) = \sum_{i=1}^N q_i^*(t)$. By definition,

$$q_i^*(t) \in \operatorname{argmax}_{q_i\geq 0} \{q_i P(\theta(q_i - q_i^*(t)) + Q^*(t)) - C_i(q_i, t)\}, \tag{11}$$

where P is the inverse demand function. In other words, firm i's output choice of $q_i^*(t)$ is profit-maximizing, given its belief that, should it deviate from this output to (say) q_i, the industry's aggregate output will increase by $\theta(q_i - q_i^*(t))$.

The standard Cournot-Nash equilibrium, where each firm takes its rivals' output as given, is nested, with $\theta = 1$. More generally, lower values of θ represent more competitive behavior—with perfect competition corresponding to $\theta = 0$. We will usually be interested in cases where industry conduct is weakly more competitive than the standard Cournot equilibrium, that is $\theta \leq 1$. This is consistent with a significant amount of empirical evidence on firm conduct across industries (see, e.g., Perloff, Karp and Golan (2007) for an overview), including many industries that are natural candidates for an ETS such as airlines, cement, electricity, and steel.[11]

[11] Brander and Zhang (1990) find that US airlines' competitive conduct is close to Cournot behavior (so $\theta \approx 1$); they reject both perfect competition and collusion. Jans and Rosenbaum (1996) estimate conduct parameters for US cement markets that lie between perfect competition and Cournot behavior—but are usually close to perfect competition (so $\theta \gtrapprox 0$). Salvo (2010) finds that a Cournot model, augmented with a price ceiling to capture the latent threat of competition from imports, captures the conduct of the Brazilian cement sector. Puller (2007) finds that Californian electricity generators' pricing is largely close to Cournot behavior (so $\theta \approx 1$). Blonigan, Liebman and Wilson (2007) estimate that prices in the US steel industry during the period 1980–2006 were almost always only slightly above marginal cost (so $\theta \gtrapprox 0$).

Firm i's equilibrium output, $q_i^*(t)$ satisfies the first order-condition, which equates firm i's marginal cost with the generalized marginal revenue function $MR_i(q) = P(Q)+\theta q_i P'(Q)$. Formally, $q_i^*(t)$ obeys

$$P(Q^*(t)) + \theta q_i^*(t) P'^*(t)) = c_i(t) + m q_i^*(t). \tag{12}$$

Re-arranging this equation gives us

$$c_i(t) = P(Q^*(t)) \left\{ 1 - \frac{\sigma_i(t)}{\eta(Q^*(t))} [\theta + \bar{m}(Q^*(t)] \right\} \tag{13}$$

where $\sigma_i = q_i/Q$ is firm i's market share, $\eta(Q) = |P(Q)/QP'(Q)|$ is the industry price elasticity of demand, and

$$\bar{m}(Q) \equiv -\frac{m}{P'(Q)} \tag{14}$$

is the ratio of the slope of marginal cost function to the slope of the demand function.[12] It follows from (13) that $\sigma_i(t) \geq \sigma_j(t)$ if and only if $c_i(t) \leq c_j(t)$, i.e., market shares at t vary inversely with $c_i(t)$.

Assumptions on correlation between emissions and costs. In principle, $z_i(t) > 0$ may vary across firms in any possible way, but for some of our results we shall assume that *emission intensities are non-negatively correlated with marginal costs.* By this we mean that, for all $t \in [0, T]$,

$$\operatorname{cov}(c, z) \equiv \frac{1}{N} \sum_{i=1}^{N} c_i(t) z_i(t) - \frac{1}{N^2} \sum_{i=1}^{N} c_i(t) \sum_{i=1}^{N} z_i(t) \geq 0. \tag{15}$$

We say that emissions intensities are *co-monotonic with marginal costs* if, for all $t \in [0, T]$, $z_i(t)$ is weakly increasing with $c_i(t)$ and that it is *uniform* if $z_i(t)$ is equal for all firms. It is not hard to check that co-monotonicity (and, as a special case, uniformity) is stronger than—in fact, considerably stronger than—condition (15).

Using (13) it is straightforward to check that marginal costs and emissions intensities are non-negatively correlated if and only if market shares and emissions intensities are non-positively correlated. In other words, (15) is equivalent to

$$\operatorname{cov}(\sigma, z) \equiv \frac{1}{N} \sum_{i=1}^{N} \sigma_i(t) z_i(t) - \frac{1}{N^2} \sum_{i=1}^{N} z_i(t) \leq 0, \tag{16}$$

[12] Note that any equilibrium with the same value of $[\theta + \bar{m}(Q^*(t)]$ leads to the same equilibrium level of output for firm i and hence also to the same market price (albeit not to the same level of profits).

for all $t \in [0, T]$ (note that $\sum_{i=1}^{N} \sigma_i(t) = 1$).

It almost goes without saying that emissions intensities and marginal costs are not always non-negatively correlated, but this condition is sufficiently weak to cover a broad range of cases. By definition, a firm with the lower marginal cost is the one that uses fewer inputs on average (with inputs weighted by their prices). It seems plausible that such a firm will typically also use less of the inputs that cause emissions. Indeed, the general notion of eco-efficiency holds that reducing waste also reduces costs (Alexander and Buchholz, 1978; Porter and van der Linde, 1995), suggesting that costs and emissions are non-negatively correlated.[13]

More recently, Bloom, Genakos, Martin and Sadun (2008) find strong empirical evidence that more efficient manufacturing firms also tend to have lower energy and emissions intensities. However, the condition is less likely to hold, for example, in an electricity market where some firms operate coal-fired power plants (with low marginal costs, but high emissions intensities), while, *in addition*, there are other firms that instead use cleaner, but also more expensive inputs (such as gas). Nevertheless, the condition is very useful for deriving a clean set of theoretical results, and the broad thrust of our conclusions—especially our main results on partial PNA—remains valid with modest departures from this assumption (see Section 5).

Assumption on demand curvature. We denote the elasticity of the *slope* of the inverse demand function as

$$E(Q) \equiv -\frac{d \log P'(Q)}{d \log Q}.$$

We may also interpret E as an index of demand curvature. Clearly, $E(Q) > 0$ ($E(Q) < 0$) if $P''(Q) > 0$ ($P''(Q) < 0$) and inverse demand is locally convex (concave) at Q. We maintain throughout the paper the assumption that inverse demand is not too convex, in the sense that

$$N + \theta(1 - E(Q)) + \bar{m}(Q) > 0. \tag{17}$$

[13] See also Heal (2008) for several case studies, such as the internal emissions trading scheme set up by BP, which reduced emissions and also cut costs; Dow Chemical and Du Pont provide similar evidence. King and Lenox (2001), amongst others, find a positive correlation between environmental and financial performance. Although there is considerable debate on the reasons for this relationship (Konar and Cohen, 2001), for our purposes the nature and direction of causality between environmental and financial performance is irrelevant, and it suffices that they are non-negatively correlated.

This is a natural assumption to make because it is necessary and sufficient for industry output to fall when emissions trading is introduced (see Proposition 4).[14]

In the case where firms are engaging in Cournot competition ($\theta = 1$), a necessary and sufficient condition for the best response curve of firm i to be downward-sloping at its equilibrium output q_i^* is that

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

(see, for example, Bulow, Geanakoplos, and Klemperer (1985) and Shapiro (1989)).[15] If this condition holds for each firm i, then the Cournot oligopoly is locally a game of strategic substitutes. A sufficient condition for (18) is that $E(Q^*) \leq 1$, which is equivalent to saying that the demand function, i.e., the function P^{-1}, is locally log-concave at $P(Q^*)$. Indeed this condition is *necessary* if (18) is to hold for any distribution of market shares.

We also know that if the demand function is globally log-concave, then the Cournot game has a globally unique and stable equilibrium (Shapiro (1989)). For these reasons and others, the log-concavity of the industry demand curve is a reasonable and commonly-made assumption (see, for example, Farrell and Shapiro (1990) and Shapiro (1989)).[16] This assumption will also feature prominently in some of our main results.

For the rest of this section, we shall examine the impact of the ETS on output, price, market shares, and emissions. Building on this, we examine the impact of the ETS on profits, and thus PNA, in Section 4.

3.1. The impact of the ETS on output and price

The following proposition gives the impact of the ETS on firm- and industry-level output and is crucial to understanding its impact on costs and firm profits. We have omitted arguments

[14] See Bergstrom and Varian (1985) for another use of this condition (in the case where $\bar{m} = 0$), and Seade (1980) for an early application that notes the importance of demand curvature.

[15] Using equation (62) (with $\theta = 1$), it is straightforward to show that the slope of i's best response curve is $-[1 - \sigma_i E(Q^*)]/[2 - \sigma_i E(Q^*) + \bar{m}]$. The second-order condition at firm i's profit-maximizing output requires the denominator to be positive, so this expression is negative if and only if its numerator is positive, hence condition (18).

[16] For products that are consumed only as a single unit or none at all, market demand at price p is proportional to $\bar{F}(p) = 1 - F(p)$, where F is the distribution of the reservation prices. A sufficient condition for $\bar{F}$ to be log-concave is for F to be generated by a log-concave density function. Many commonly used density functions have this property, see Bagnoli and Bergstrom (2005).

to reduce clutter; note that P', E, and $\bar{m}$ are evaluated at $Q^*(t)$, while z_i and σ_i are evaluated at t.

PROPOSITION 4. *At any $t \in [0, T]$ output responses are given by*

$$\frac{dQ^*}{dt} = \frac{\sum_{i=1}^N z_i}{P' \left[N + \theta(1-E) + \bar{m}\right]} < 0; \tag{19}$$

$$\frac{dQ^*_{-i}}{dt} = \frac{dQ^*}{dt} \left\{ \frac{[(\theta + \bar{m}) + (1 - \theta\sigma_i E)]}{(\theta + \bar{m})} - \frac{[N + \theta(1-E) + \bar{m}]}{(\theta + \bar{m})} \frac{z_i}{\sum_{i=1}^N z_i} \right\} \tag{20}$$

$$\frac{dq_i^*}{dt} = \frac{dQ^*}{dt} \left\{ -\frac{(1 - \theta\sigma_i E)}{(\theta + \bar{m})} + \frac{[N + \theta(1-E) + \bar{m}]}{(\theta + \bar{m})} \frac{z_i}{\sum_{i=1}^N z_i} \right\} \tag{21}$$

It is clear from (19) that the ETS reduces industry output if and only if the maintained assumption (17) is satisfied. Consequently, the equilibrium price of output must increase according to

$$\frac{dP^*}{dt} = P'(Q^*)\frac{dQ^*}{dt} = \frac{\sum_{i=1}^N z_i}{[N + \theta(1-E) + \bar{m}]} > 0. \tag{22}$$

This formula is remarkably simple in that the price increase depends on only the *unweighted* average of the emissions intensities and on no other feature of its distribution. So a change in emissions intensities that leaves its unweighted average unchanged does not modify the local price impact of the ETS.

Consider the hypothetical situation where $z_i = 1$ for all i, so every firm experiences a one-dollar increase in marginal cost (see (10)). Then

$$\frac{dP^*}{dt} = \frac{N}{[N + \theta(1-E) + \bar{m}]} \equiv \kappa. \tag{23}$$

The term κ is known as the *rate of cost pass-through* since it measures the change in the equilibrium price following a common increase in the marginal cost of every firm in the oligopoly. Loosely speaking, if marginal cost increases by a dollar at every firm, then the equilibrium price rises by κ dollars. Note that *the rate of cost pass-through $\kappa \leq 1$ under perfect competition (i.e., $\theta = 0$ and $\bar{m} > 0$). When $\theta > 0$, $\kappa \leq 1$ for all $\bar{m} \geq 0$ if and only if $E(Q^*) \leq 1$, i.e., demand is log-concave.*

Using (10), we may also re-write (22) as

$$\frac{dP^*}{dt} = \kappa \frac{1}{N} \left[\sum_{i=1}^N \frac{\partial M_i}{\partial t}(q_i^*(t), t) \right].$$

This says that the output price increase following an increase in the emissions price is proportional to the rise in the unweighted marginal cost, with the rate of cost pass-through κ as the proportionality constant.

While overall industry output falls with the introduction of the ETS, there is heterogeneity across firms in their individual output responses. In particular, it is not hard to see from Proposition 4 that, for certain parameter values, some firms can *increase* their output with t. However, with uniform emissions intensities, there are two important cases where this will not happen: [I] if competition is perfect ($\theta = 0$), or if [II] demand is linear ($E = 0$), for which (21) reduces to $dq_i^*/dt = (1/N)(dQ^*/dt) < 0$ (for all i).

3.2. The impact of the ETS on market shares

It is clear from Proposition 4 that the impact of the ETS does not fall equally across firms. However, while the scheme affects relative output and hence market shares, its effect is not indeterminate. We now show that under reasonable assumptions, the introduction of the ETS (and, more generally, an increase in t) will raise market concentration. This effect on market concentration may not be large (and will not be large if the ETS raises each firm's overall cost only modestly) but it is important that we establish the *direction* of the effect.

To see why the ETS favors large firms, use (19) and (21) to obtain

$$\frac{d\sigma_i}{dt} = \frac{1}{Q^*}\frac{dQ^*}{dt}\left\{-\frac{(1+\sigma_i[\theta(1-E)+\bar{m}])}{(\theta+\bar{m})} + \frac{[N+\theta(1-E)+\bar{m}]}{(\theta+\bar{m})}\frac{z_i}{\sum_{i=1}^{N} z_i}\right\}. \tag{24}$$

We wish to highlight two factors that have an important influence on the impact of the ETS on market shares: the curvature of demand and the distribution of emissions intensities. We consider each in turn.

First, assume that emissions intensities are uniform across firms, so that all firms experience the same increase in marginal cost. In this case, it is clear from (24) that $d\sigma_i/dt$ increases with σ_i (for all $\theta \geq 0$ and $\bar{m} \geq 0$) if and only if $E(Q^*) \leq 1$. Furthermore, it follows from (24) that

$$\text{sign}\left(\frac{d\sigma_i}{dt}\right) = \text{sign}\left\{\left(\sigma_i - \frac{1}{N}\right)[\theta(1-E)+\bar{m}]\right\}.$$

In other words, firms with larger (lower) than average market share will gain (lose) market share. It is straightforward to check that this will raise market concentration as measured by the Herfindahl index $H = \sum_{i=1}^{N} \sigma_i^2$; formally,

$$\frac{dH}{dt} = 2\sum_{i=1}^{N} \sigma_i \frac{d\sigma_i}{dt} \geq 0. \tag{25}$$

The other factor influencing the impact of the ETS on market shares is the distribution of emissions intensities. Consider firms m and n with the same initial market share but different emissions intensities, with $z_m < z_n$. Then (24) shows that $d\sigma_m/dt > d\sigma_n/dt$, so firm n fares less well under the ETS (in terms of market share) because it experiences a larger increase in marginal cost than firm m.

When $E(Q^*) \leq 1$ and emissions intensities are co-monotonic with marginal costs (and hence weakly decreasing with σ_i), both factors work in favor of larger firms. This is reflected in (24) where it is clear that $d\sigma_i/dt$ increases with σ_i (and since $\sum_{i=1}^{N} d\sigma_i/dt = 0$, the larger firms will gain market share). When co-monotonicity is replaced with the weaker assumption that emissions intensities and marginal costs are non-negatively correlated, it is no longer true that $d\sigma_i/dt$ increases with σ_i. However, one can still show (see Appendix A) that the Herfindahl index increases with t.

Proposition 5. *Suppose that emissions intensities are non-negatively correlated with marginal cost and that either* (a) *the industry is perfectly competitive* ($\theta = 0$) *or* (b) *the demand function is log-concave* ($E \leq 1$). *Then*

$$\frac{dH}{dt} \geq 0.$$

3.3. The impact of the ETS on emissions

As the ETS lowers total industry output, total emissions will fall if the average emissions intensity of firms falls. Letting $z^*(t)$ denote average emissions intensity and noting that $z^*(t) = \sum_{i=1}^{N} \sigma(t) z_i(t)$, we obtain

$$\frac{dz^*}{dt} = \sum_{i=1}^{N} z_i \frac{d\sigma_i}{dt} + \sum_{i=1}^{N} \frac{dz_i}{dt}\sigma_i. \tag{26}$$

Standard production theory tells us that $dz_i/dt \leq 0$ (in other words, firms make abatement decisions), so the second term on the right of this equation is always negative. If emissions intensity is uniform across firms, the first term on the right equals zero since $\sum_{i=1}^{N} d\sigma_i/dt = 0$ and we conclude that average emissions intensity must fall.

If emissions intensity is *not* uniform, the sign of the first term on the right of (26)—and thus the sign of dz^*/dt—cannot be guaranteed without further assumptions. While the ETS induces each individual firm to lower its emissions intensity, it is possible for this effect to be negated in part or in whole by strategic effects. If the ETS causes firms with (initially) low emissions intensities to gain market share, then it has a doubly beneficial effect. On the other hand, if these firms lose market share, this diminishes the scheme's ability to lower emissions in this industry.[17] To guarantee that the former holds, we once again rely on the assumptions that demand is log-concave and that emissions intensities are non-negatively correlated with marginal costs. We know from Proposition 5 that the ETS raises market concentration under these conditions; loosely speaking, large firms gain market share at the expense of small firms. Since large firms have lower cost and (by the correlation assumption again) typically lower emissions, average emissions intensity will fall.

PROPOSITION 6. *Average emissions intensity z^* and total emissions ζ^* satisfy*

$$\frac{dz^*}{dt} \leq 0 \text{ and } \frac{d\zeta^*}{dt} \leq 0$$

if any *of the following conditions are satisfied:* (a) *emissions intensities are uniform;* (b) *emissions intensities are non-negatively correlated with marginal cost and the industry is perfectly competitive* ($\theta = 0$)*; or* (c) *emissions intensities are non-negatively correlated with marginal cost and the demand function is log-concave* ($E \leq 1$).

4. PROFIT-NEUTRAL PERMIT ALLOCATIONS

Having established the impact of the ETS on output, price, market shares, and emissions, we now turn to examine its impact on profits. In particular, we develop formulae that determine the level of free permit allocations required to ensure profit-neutrality at the level of the firm and of the industry. We use these formulae to show that, under conditions that ought to be satisfied in many situations, average PNA in the industry is not just partial, but *low*.

[17] The possibility of such perverse effects has also been noted in Levin's (1985) study of taxation in a Cournot model.

4.1. *PNA for an individual firm*

Suppose the introduction of the ETS leads to an emissions permit price of $T > 0$. By definition, the proportion of free permit allocation, $\gamma_i(T)$, needed to preserve firm i's profit (at the level before the introduction of the ETS) satisfies

$$\Pi_i^*(T) + T\,\gamma_i(T)\zeta_i^*(0) = \Pi_i^*(0). \tag{27}$$

Defining

$$\tilde{\gamma}_i(t) = -\frac{1}{\zeta_i^*(t)}\frac{d\Pi_i^*}{dt} \tag{28}$$

and re-arranging (27) we obtain

$$\gamma_i(T) = -\frac{[\Pi_i^*(T) - \Pi_i^*(0)]}{T\zeta_i^*(0)} = \frac{1}{T\zeta_i^*(0)}\int_0^T \tilde{\gamma}_i(t)\zeta_i^*(t)\,dt. \tag{29}$$

It follows from (28) and (29) that

$$\tilde{\gamma}_i(0) = -\frac{1}{\zeta_i^*(0)}\lim_{T\to 0}\frac{[\Pi_i^*(T) - \Pi_i^*(0)]}{T} = \lim_{T\to 0}\gamma_i(T). \tag{30}$$

In other words, $\tilde{\gamma}_i(0)$ gives the approximate value of $\gamma_i(T)$ when T is small.

Suppose we know that $\zeta_i^*(t)$ is decreasing in t; then $\max_{0\le t\le T}\tilde{\gamma}_i(t)$ is an upper bound of $\gamma_i(T)$ since

$$\gamma_i(T) \le \frac{1}{T\zeta_i^*(0)}\max_{0\le t\le T}\tilde{\gamma}_i(t)\int_0^T \zeta_i^*(t)\,dt \le \max_{0\le t\le T}\tilde{\gamma}_i(t) \tag{31}$$

Therefore, to bound the value of $\gamma_i(T)$, it will be helpful to have a formula for $\tilde{\gamma}_i$. To obtain such a formula, write the equilibrium profit of firm i as

$$\Pi_i^*(t) = q_i^*(t)P(q_i^*(t) + Q_{-i}^*(t)) - c_i(t)q_i^*(t) - \frac{1}{2}m\,[q_i^*(t)]^2\,. \tag{32}$$

Differentiating this with respect to t, we obtain

$$\begin{aligned}\frac{d\Pi_i^*}{dt} &= -c_i'(t)q_i^* + [P(Q^*) + q_i^*P'^*(Q^*) - c_i - mq_i^*]\frac{dq_i^*}{dt} + q_i^*P'(Q^*)\frac{dQ_{-i}^*}{dt}\\ &= -z_iq_i^* + (1-\theta)q_i^*P'(Q^*)\frac{dq_i^*}{dt} + q_i^*P'(Q^*)\frac{dQ_{-i}^*}{dt}.\end{aligned} \tag{33}$$

where the second equation relies on $c_i'(t) = z_i(t)$ (by Shephard's Lemma (see (9)) and the first-order condition (12). Inserting this expression for $d\Pi_i^*/dt$ into (28) we obtain

$$\tilde{\gamma}_i = 1 - \frac{P'(Q^*)}{z_i}\left[(1-\theta)\frac{dq_i^*}{dt} + \frac{dQ_{-i}^*}{dt}\right]. \tag{34}$$

So, with Cournot-Nash behavior ($\theta = 1$), PNA is partial, $\tilde{\gamma}_i < 1$, if and only if firm i's faces a more favorable residual demand curve following the introduction of the ETS, $dQ^*_{-i}/dt < 0$.

Using the expressions for dq^*_i/dt and dQ^*_{-i}/dt from Proposition 4 (see (21) and (20)) in (34) gives us the formula (35) for $\tilde{\gamma}_i$ and hence the following result.

Proposition 7. *Suppose ζ^*_i is decreasing in t. Then $\gamma_i(T) \leq \max_{0 \leq t \leq T} \tilde{\gamma}_i(t)$, where*

$$\tilde{\gamma}_i(t) = \frac{(2\theta + \bar{m})}{(\theta + \bar{m})} - \frac{[(\theta + \bar{m}) + \theta(1 - \theta\sigma_i E)]}{(\theta + \bar{m})\,[N + \theta(1 - E) + \bar{m}]} \frac{\sum_{j=1}^{N} z_j}{z_i}. \tag{35}$$

Observe that $\tilde{\gamma}(t) \equiv 1$ for a monopolist (with $N = 1$ and $\theta = 1$), so $\tilde{\gamma}(0) = 1$ and thus $\gamma(T)$ is approximately equal to 100% for small T (as expected from Section 2.2).[18]

The situation becomes more complicated for an oligopoly. It is clear from the formula (35) that $\tilde{\gamma}_i(0)$ (and hence $\gamma_i(T)$ for small values of T) will typically not be the same across firms. Almost inevitably, a "one-size-fits-all" allocation policy, in which every firm receives the same proportion of freely allocated permits, will lead to overcompensation for some firms and undercompensation for others. Indeed, even firms with identical emissions intensities may have different values of $\tilde{\gamma}_i(0)$ if they have different market shares.

Of course, different emissions intensities will also lead to different PNA values. These differences can be large; for example, if demand is linear ($E = 0$), firms have constant marginal costs ($\bar{m} = 0$), and are playing a Cournot-Nash game ($\theta = 1$), then

$$\tilde{\gamma}_i(0) = 2\left[1 - \frac{1}{(N+1)} \frac{\sum_{j=1}^{N} z_j(0)}{z_i(0)}\right]. \tag{36}$$

Clearly, $\tilde{\gamma}_i(0) < 0$ if $z_i(0)/(\sum_{j=1}^{N} z_j(0))$ is sufficiently close to zero, which means that $\gamma_i(T) < 0$ for small T (by (30). In this case, the adverse cost impact of the ETS is so much greater on firm i's rivals that firm i's strategic position improves to the extent that it makes a *higher* profit after the introduction of the scheme. At the other extreme, if $z_i(0)/(\sum_{j=1}^{N} z_j(0))$ is sufficiently close to 1 then $\tilde{\gamma}_i(0) > 1$, so even an allocation of permits to cover all its emissions at the pre-ETS level is *not* sufficient to bring the firm's profit back to the pre-ETS level.

Apart from complete firm symmetry, there are two interesting cases when $\tilde{\gamma}_i(t)$ is the same across firms: *when emissions intensities are uniform and* [I] *the industry is perfectly*

[18] See point (2) in the discussion following Proposition 3. Note that that result is in fact more general because, unlike in this section, it does not require that output be a single good.

competitive ($\theta = 0$) *or* [II] *market demand is linear* ($E = 0$). Furthermore, in both of these cases, PNA has a uniformly low bound for plausible parameter values. Recall from our discussion of Proposition 4 that, in both of these cases, output responses satisfy $dq_i^*/dt = (1/N)(dQ^*/dt) < 0$ (for all i), so that all firms reduce emissions, $d\zeta_i^*/dt < 0$, and Proposition 7 is applicable.

[I] With perfect competition, the formula (35) gives $\tilde{\gamma}_i(t) = \bar{m}(Q^*(t))/(N + \bar{m}(Q^*(t)))$ for every firm i and all $t \in [0, T]$. In particular, for any two firms i and j, $\tilde{\gamma}_i(0) = \tilde{\gamma}_j(0)$ so that (by (30)) PNA is approximately the same across firms for small T. By Proposition 7, we obtain (even when T is not necessarily small)

$$\gamma_i(T) \leq \frac{\hat{m}}{(N + \hat{m})} \text{ for all } i, \tag{37}$$

where $\hat{m} = \sup_{t\in[0,T]} \bar{m}(Q^*(t))$. This bound is common to all firms and lower than 100%. It will be small if the industry consists of many firms (large N) and if $\hat{m}$ is not too big. Recall that $\bar{m}(Q^*(t)) = m/P'^*(t))$, where $m > 0$ is the slope of the marginal cost function. Under perfect competition, m is also the slope of the industry supply curve,[19] so $\bar{m}$ is the ratio of the slopes of supply and demand curves. To have a sense of what this means for PNA, suppose the supply curve is no more than twice as steep as the demand curve, so that $\bar{m} \leq 2$. In this case, $\gamma_i(T) \leq 2/(N + 2)$ for all i; this implies that PNA will be very low whenever the industry has anything more than a handful of firms.

[II] When demand is linear, $E \equiv 0$ and we have $\tilde{\gamma}_i(t) = (2\theta + \bar{m})/(N + \theta + \bar{m})$ for every firm i and for all $t \in [0, T]$. (Note that $\bar{m} = m/P'$ is now independent of t since demand is linear.) By (30), PNA is approximately the same across firms for small T, and will be partial so long as $\theta < N$ (which is an extremely mild condition[20]). By Proposition 7, we obtain (for not necessarily small T)

$$\gamma_i(T) = \frac{2\theta + \bar{m}}{(N + \theta + \bar{m})} \text{ for all } i. \tag{38}$$

Note that this bound is decreasing in θ, so firm-level PNA is lower in a more competitive industry. For example, consider a Cournot oligopoly ($\theta = 1$) with constant returns so scale

[19] This is because each firm's supply curve corresponds with its marginal cost curve.

[20] This condition corresponds to the equilibrium price from a symmetric oligopoly being lower than the monopoly price.

($\bar{m} = 0$). Then $\gamma_i(T) \leq 2/(N+1)$, which is less than 1/3 whenever $N \geq 5$. If $\bar{m} = 2$, the bound is $\gamma_i(T) \leq 4/(N+3)$, which is less than 1/3 whenever $N \geq 9$.

Apart from cases [I] and [II], firm-level PNA need not be similar and uniformly low. However, as we show in the next section, while there may be significant variation at the level of the firm, *average* PNA (across the whole industry) is low under a broad set of conditions.

4.2. *Average PNA for an industry*

We now examine the level of PNA needed for profit-neutrality for an industry as a whole. This number is more relevant than firm-specific PNA in terms of providing policy guidance on how many permits to freely allocate to firms (and conversely how many to auction), since firms are often included in an ETS on an industry-by-industry basis.

By definition, at the permit price T, the industry-level PNA $\gamma(T)$ satisfies $\Pi^*(T) + T\,\gamma(T)\zeta^*(0) = \Pi^*(0)$. By an argument analogous to used to derive (29), we obtain

$$\gamma(T) = \frac{1}{T\zeta^*(0)} \int_0^T \tilde{\gamma}(t)\zeta^*(t)\,dt, \tag{39}$$

where

$$\tilde{\gamma}(t) = -\frac{1}{\zeta^*(t)} \frac{d\Pi^*}{dt}(t) = -\frac{1}{\zeta^*(t)} \sum_{i=1}^{N} \frac{d\Pi_i^*}{dt}(t). \tag{40}$$

Note also that $\tilde{\gamma}(0) = \lim_{T\to 0} \gamma(T)$ so $\tilde{\gamma}(0)$ gives the approximate value of $\gamma(T)$ when T is small. If we know that ζ^* is decreasing in T, then we have

$$\gamma(T) \leq \frac{1}{T\zeta^*(0)} \max_{0\leq t\leq T} \tilde{\gamma}(t) \int_0^T \zeta^*(t)\,dt \leq \max_{0\leq t\leq T} \tilde{\gamma}(t) \tag{41}$$

Note that $d\Pi_i^*/dt = -z_i^* q_i^* \tilde{\gamma}_i$ (see (28)), so we may re-write (5) as

$$\tilde{\gamma}(t) = \frac{\sum_{i=1}^{N} z_i \sigma_i \tilde{\gamma}_i}{\sum_{i=1}^{N} z_i \sigma_i}. \tag{42}$$

Equations (42) and (35) yield a formula for $\tilde{\gamma}$ (43) and so we obtain the following result.

Proposition 8. *Suppose ζ^* is decreasing in t. Then $\gamma(T) \leq \max_{0\leq t\leq T} \tilde{\gamma}(t)$, where*

$$\tilde{\gamma}(t) = \frac{2\theta + \bar{m}}{\theta + \bar{m}} - \frac{[(\theta + \bar{m}) + \theta(1 - \theta H E)]}{(\theta + \bar{m})\,(N + \theta(1 - E) + \bar{m})} \frac{\sum_{j=1}^{N} z_j}{\sum_{i=1}^{N} \sigma_i z_i}. \tag{43}$$

In principle, $\tilde{\gamma}$ can take on a wide range of values, both positive and negative. For example, it is known (see, for example, Kimmel (1992)) that in a symmetric Cournot oligopoly with constant marginal costs, a common increase in marginal cost *raises* total profit (in our notation, $\Pi^*(t) > \Pi^*(0)$ for small $t > 0$) if and only if $E(Q^*(0)) > 2$. We can recover this result using (43); with $\theta = 1$, $\bar{m} = 0$, $H = 1/N$, and $z_i = z_j$ for any i and j, it is easy to check that $\tilde{\gamma}(0) < 0$ if and only if $E(Q^*(0)) > 2$. Therefore, $\gamma(T) < 0$ for small T values, which means that industry profits increase with the introduction of the ETS, so the industry is (at least weakly) better off even if it has to buy all the permits it needs at the market price. This observation is an extreme manifestation of the general rule that in a symmetric Cournot equilibrium ($\theta = 1$ and $H = 1/N$), PNA is partial for small T since

$$\tilde{\gamma} = \frac{2 - E + \bar{m}}{(N + 1 - E + \bar{m})} < 1.$$

On the other hand, it is also possible for $\tilde{\gamma}$ to exceed 100%. For example, consider a Cournot duopoly with constant marginal costs and uniform emissions intensity that faces a unit-elastic demand curve $P(Q) = K/Q$ (so industry revenue is constant at K and $E = 2$). It is easily checked that $\tilde{\gamma}_1 = 2(\sigma_1 - \sigma_2)$ and hence that $\tilde{\gamma}_1 = -\tilde{\gamma}_2$. With symmetric firms, therefore, PNA is zero for both firms (and for the industry as well), but if $\sigma_1 > \frac{3}{4}$, then $\tilde{\gamma}_1 > 1$ and $\tilde{\gamma}_2 < -1$. The average PNA $\tilde{\gamma} = 2(\sigma_1 - \sigma_2)^2$ exceeds unity if $\sigma_1 > (\sqrt{2}+1)/2\sqrt{2} \approx 85\%$.

Such examples notwithstanding, industry PNA is partial—and indeed low—under a broad set of conditions. We assume that emissions intensities and costs are non-negatively correlated and in all the cases [1] to [5] listed below, either $\theta = 0$ or $E \leq 1$. Therefore, Proposition 6 guarantees that industry emissions is decreasing in t. This in turn means that Proposition 8 is applicable and $\gamma(T) \leq \max_{0 \leq t \leq T} \tilde{\gamma}(t)$. Furthermore, in all these cases, it is trivial to check that $(\theta + \bar{m}) + \theta(1 - \theta H E) \geq 0$. Therefore,

$$\tilde{\gamma} \leq \tilde{\beta} \equiv \frac{2\theta + \bar{m}}{\theta + \bar{m}} - \frac{N\,[\theta + \bar{m} + \theta(1 - \theta H E)]}{(\theta + \bar{m})\,(N + \theta(1 - E) + \bar{m})}. \tag{44}$$

It follows that

$$\gamma(T) \leq \max_{0 \leq t \leq T} \tilde{\beta}(t)\,; \tag{45}$$

this bound has the important advantage of being *independent* of firms' emissions intensities, and leads to the following results.[21]

[21] The proof of all five cases below can be found in Appendix A.

Case [1] *In a perfectly competitive industry,*

$$\gamma(T) \leq \frac{\hat{m}}{(N + \hat{m})} \tag{46}$$

where $\hat{m} = \sup_{t \in [0,T]} \bar{m}(Q^*(t))$.

Case [2] *If the industry demand curve is linear,*

$$\gamma(T) \leq \frac{2\theta + \bar{m}}{(N + \theta + \bar{m})}. \tag{47}$$

Note that the bounds obtained for cases [1] and [2] correspond exactly to the firm-level bounds obtained for cases [I] and [II] in the previous subsection (see (37) and (38)).[22] As we have already argued, these bounds are low for plausible values of N, $\bar{m}$ and θ.

For a perfectly competitive industry, the profit impact of the ETS has an instructive graphical depiction.[23] In Figure 1, the market supply curve has slope $S' = m/N$ since it is the ('horizontal') sum of each firm's marginal cost function. The pre-ETS output is $Q^*(0)$ and the industry's aggregate profit is given by the area of the triangle *abc*. The ETS raises marginal cost and leads to a parallel upward shift of the supply curve. The new equilibrium output is $Q^*(T)$ with price $P^*(T)$; aggregate industry profit falls by the area *abde*. Note that the area *abde* must shrink as the supply curve becomes flatter or the demand curve becomes steeper.[24] In other words, PNA is low when the supply curve is flat or the demand curve is steep, as is consistent with the bound on $\gamma(T)$ in (46). Assuming that demand is linear, and defining $\eta \equiv S'/(-P')$, we have

$$\gamma(T) \leq \frac{\bar{m}}{(N + \bar{m})} = \frac{m}{N(-P') + m} = \frac{S'}{(-P') + S'} = \frac{\eta}{(1 + \eta)}. \tag{48}$$

With linear demand and perfect competition, cost pass-through $\kappa = 1/(1+\eta)$ is independent of t (using (23)), so (48) has the intuitive form $\gamma(T) \leq 1 - \kappa$.

Case [3] *If* $\theta \leq 1$ *and* $E \leq 1$*, then* $\gamma(T) \leq 1$.

This result says that PNA is partial whenever demand is log-concave and competitive behavior as measured by the conduct parameter is (weakly) more competitive than Cournot.

[22] But there is a significant difference in the assumptions. The industry-level bounds were obtained under the assumption that emissions intensities and marginal costs are non-negatively correlated, while the firm-level results rely on the stronger assumption that emissions are uniform across firms.

[23] Bovenberg and Goulder (2001) and Bovenberg et al. (2005) provide a similar graphical analysis. In their context, the supply curve is upward sloping because capital has limited ability to move out of an ETS-affected sector in the short term.

[24] To see that the loss in profit decreases as the supply curve becomes flatter, pivot the supply curves clockwise at the points b and f. Pivoting the demand curve clockwise at b also shrinks *abde*.

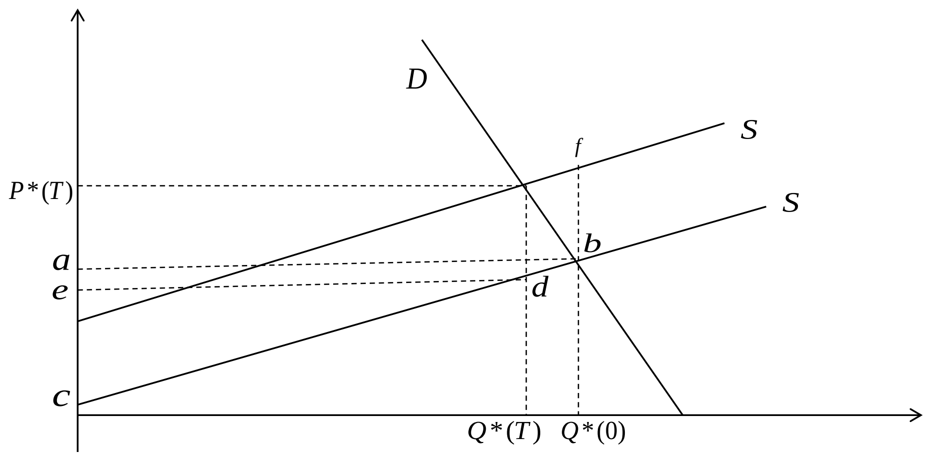

Figure 1: ETS under perfect competition

Case [4] *If* $\theta \leq 1$, $E \leq 1$, *and* $H(Q^*(0)) \geq (2\theta + \bar{m}(Q^*(0))) / (\theta(\theta + N + \bar{m}(Q^*(0))))$, *then*

$$\gamma(T) \leq \theta H(T). \tag{49}$$

Substituting $\theta = 1$ and $\bar{m}(Q^*(0)) = 0$ into this result shows that *in a Cournot oligopoly with* $H(0) \geq 2/(N+1)$ *and constant marginal costs, industry-level PNA is bounded above by the Herfindahl index,* $\gamma(T) \leq H(T)$. The restriction $H(0) \geq 2/(N+1)$ is permissive and likely to be satisfied in many industries (including, for example, in our application to the cement industry in Section 5). If it is, we obtain a tight upper bound on PNA since the Herfindahl index is usually below 50%—and often *considerably* below this level. Although we know from Proposition 5 that $H(T)$ will be higher than $H(0)$, in most likely scenarios the cost of emissions will be a small part of a firm's total marginal costs, so that the ETS will not have a big impact on the Herfindahl index.[25]

Case [5] *If* $\theta \leq 1$ *and* $E \in [0, 1]$, *then*

$$\gamma(T) \leq \max\left\{ \frac{2\theta + \bar{m}(Q^*(0))}{(\theta + N + \bar{m}(Q^*(0)))}, \theta H(T) \right\}. \tag{50}$$

Unlike case [4], this result does not rely on a lower bound on $H(0)$, but it does require that the demand function to be convex (in addition to log-concavity). This assumption is not

[25] Recent studies of the cost impact of CO_2 pricing typically conclude that the likely cost impact is small in most industries; see, e.g., Ho, Morgenstern and Shih (2008) on U.S. cap-and-trade proposals and de Bruyn et al. (2008) on the EU ETS. Earlier studies also found that the cost of environmental regulations is typically small (see, for example, Jaffe et al. (1995)).

particularly restrictive, at least in the sense that most commonly used demand functions are convex functions.[26] The upper bound formula on $\gamma(T)$ is increasing in θ (so PNA is lower for more competitive markets), and is a piecewise linear function of H, with a kink at

$$H^* = \frac{2\theta + \bar{m}(Q^*(0))}{\theta(\theta + N + \bar{m}(Q^*(0)))}. \tag{51}$$

For $H \leq H^*$, the bound is constant and equal to $(2\theta + \bar{m}(Q^*(0)))/(\theta + N + \bar{m}(Q^*(0))) < 1$; for $H > H^*$, it is equal to θH. To have a sense of what it means for PNA, suppose we have Cournot competition ($\theta = 1$) with moderately increasing marginal cost $\bar{m}(Q^*(0)) \leq 2$ and a Herfindahl index $H(T) < 1/2$. Then $\gamma(T) \leq \max\{4/(N+3), H(T)\}$, so PNA will be lower than 50% if $N \geq 5$. If instead industry conduct is more competitive with $\theta = 1/2$, then $\gamma(T) \leq \max\{6/(5+2N), H(T)/2\}$ which is less than 40% if $N \geq 5$.

These results show that PNA— and thus the profit impact of an ETS—will vary according to industry characteristics. Whether, as a matter of public policy, there should be such allocations and whether they ought (in some normative sense) to vary across industries is a larger issue where other considerations may enter. Our results do suggest, however, that PNA is modest in many scenarios so that even if permits are allocated based on the higher end of those estimates, there will still be substantial auctioning.

Besides providing some guidance on permit allocations, our analysis could also be useful in developing a *positive* theory of environmental regulation. We have shown which industry characteristics are relevant in determining the profit impact of an ETS, and in what way. This could help explain differences in the level of political resistance to emissions trading and taxes in different industries and the types of settlement they reach with government.

4.3. Other issues in PNA calculations

Incorporating the overall emissions cap We have defined γ as the level of emissions permits needed for profit-neutrality as a fraction of the industry's *initial* (pre-ETS) demand for permits. The same number of permits would obviously be a larger fraction of the actual

[26] For example, Genesove and Mullin's (1998) influential study of the U.S. sugar industry employs four demand specifications. Three of these specifications, linear ($E = 0$), quadratic ($E = \frac{1}{2}$), and exponential ($E = 1$) demand, satisfy the condition $E \in [0, 1]$. Their fourth specification, constant-elasticity demand, has $E > 1$; we discuss the robustness of our results to log-convex demand in Section 5.

number of permits issued with the introduction of the ETS. In principle it is even possible that profit-neutrality will require that an industry receives more permits than it needs to cover its emissions. This is precisely the case for any industry run by a monopoly, where profit-neutrality requires that it be a net *supplier* of permits to other firms in the scheme (see Proposition 1).

However, for most plausible oligopoly situations, this will not arise. For example, suppose an ETS is introduced across a number of industries, targeting an aggregate 20% fall in emissions, from L to $0.8L$. The market price of permits would adjust so that the aggregate demand for permits equals the supply of $0.8L$; let the clearing price of permits be T. Assume that the industries covered by the ETS are Cournot oligopolies ($\theta = 1$), with firms having constant returns to scale. Assume also that each industry k's Herfindahl index satisfies $2/\left(N^k + 1\right) \leq H^k < 0.4$, where N^k is the number of firms in industry k. Using case [4] (Section 4.2), we then know that $\gamma^k(T) \leq H^k(T) < 0.4$. Therefore, the profit-neutral permit allocation, *as a fraction of the target level of emissions*, for the ETS as a whole will not exceed 0.4/0.8 or 50%.[27] In other words, the total demand for permits will be twice as great as the allocation of free permits.

Now suppose instead that the targeted emissions reduction is larger, say 40%. The clearing price for emissions permits will be different, say $T' > T$ (because total emissions is a decreasing function of emissions price by Proposition 6). Industry k's PNA will now be bounded above by $H^k(T')$. This is higher than $H^k(T)$ by Proposition 5, but let us assume that $H^k(T')$ is still lower than 0.4. The profit-neutral allocation, as a fraction of this (more stringent) target level of emissions is then 0.4/0.6, or about 67%.

Finally, note that 0.4 is an extraordinarily high cap to impose on the Herfindahl index and has the obvious effect of inflating our PNA estimates. All the upper bounds on PNA will be halved if we use a (still concentrated) Herfindahl index of 0.2: with a 20% reduction in emissions, PNA is 25% of the target level of emissions; with a 40% reduction in emissions, it is 34% of the target level of emissions.[28]

[27] If each industry is freely allocated 40% of its initial emissions, the total free allocation is 40% of the aggregate initial emissions across all industries or 50% of post-ETS aggregate emissions.

[28] The Antitrust Division of the U.S. Department of Justice considers Herfindahl indices between 0.10 and 0.18 to be moderately concentrated and indices above 0.18 to be concentrated. Ali et al. (2009) report an average Herfindahl index of 0.064 for four-digit SIC industries using the U.S. Census of Manufactures over the period 1982 to 2002.

Tightening the bounds on PNA It is possible under some plausible assumptions to tighten the upper bounds on PNA significantly. In particular, our estimate of $\gamma(T)$ in equation (41) is permissive, and particularly permissive when the emissions reduction target is large. This is because it uses only the fact that ζ^* is decreasing to bound $\int_0^T \zeta^*(t)\,dt$ by $\zeta^*(0)T$. Suppose we know that ζ^* is a decreasing and *convex* function of t, and assume that the ETS targets a reduction in emissions from $\zeta^*(0)$ to $\alpha\zeta^*(0)$ for some $\alpha < 1$. In that case, we have $\int_0^T \zeta^*(t)\,dt \leq \zeta^*(0)[1+\alpha]T/2$ and we may modify (41) in the following way:

$$\gamma(T) \leq \frac{1}{T\zeta^*(0)} \max_{0\leq t\leq T} \tilde{\gamma}(t) \int_0^T \zeta^*(t)\,dt \leq \frac{(1+\alpha)}{2} \max_{0\leq t\leq T} \tilde{\gamma}(t) \tag{52}$$

Consider, once again, the 40% emissions reduction target discussed in the previous paragraph. Then $\alpha = 0.6$ and the profit-neutral allocation of permits is less than $(0.4)(0.8)\zeta^*(0)$ (using (52) and assuming that the Herfindahl index is bounded by 0.4). As a fraction of the *target* emissions level, the profit-neutral allocation of permits is bounded by $(0.4)(0.8)/(0.6)$, or about 53%. This is significantly below the 67% we calculated above without convexity.

To have a sense of when ζ^* is a convex function of t suppose that emissions are uniform across firms, so that $\zeta^*(t) = Q^*(t)z(t)$.[29] Then

$$\frac{d\zeta^*}{dt} = Q^*(t)\frac{dz}{dt} + z\frac{dQ^*}{dt}. \tag{53}$$

Since Q^* and z are both decreasing in t, and dz/dt and dQ^*/dt are both non-positive, ζ^* *is a convex function of t if z^* and Q^* are convex functions of t*; in other words, if dz/dt and dQ^*/dt are both increasing in t. Whether or not z^* is convex in t simply depends on the emissions technology available; convexity is not, prima facie, an implausible assumption. Re-writing (19) slightly, we have

$$\frac{dQ^*}{dt} = \frac{Nz(t)}{P'(Q^*(t))\;[N+\theta(1-E(Q^*(t))]+m} < 0. \tag{54}$$

With Q^* and z are both decreasing in t, dQ^*/dt is increasing in t if E is positive and non-decreasing in Q (the former to ensure that $P'(Q)$ is increasing with Q). Again, this assumption is satisfied for various familiar demand specifications, including linear ($E = 0$), quadratic ($E = \frac{1}{2}$), and exponential ($E = 1$) demand. We summarize our observations formally as follows.

[29] Unfortunately, we do not have an elegant formulation of when $\zeta^*(t)$ is convex in t when emissions intensities are not uniform.

Proposition 9. *Suppose that $E(Q) \in [0,1]$ and non-decreasing in Q and the emissions intensity $z(t)$ is uniform across firms and convex in t. Then total equilibrium emissions, $\zeta^*(t)$, is a decreasing and convex function of t, and (52) holds for $\alpha\zeta^*(0) = \zeta^*(T) < \zeta^*(0)$.*

For example, with linear demand ($E = 0$), $\tilde{\gamma}(t) \equiv (2\theta + \bar{m})/(N + \theta + \bar{m})$ for all $t \in [0, T]$ if emissions intensity is uniform across firms (use (43)). By (39),

$$\gamma(T) = \frac{\tilde{\gamma}}{T\zeta^*(0)} \int_0^T \zeta^*(t)dt.$$

Since $z(t)$ and $Q^*(t)$ are both decreasing in t, so is $\zeta^*(t) = z(t)Q^*(t)$. Therefore, $\int_0^T \zeta^*(t)dt \in [T\zeta^*(T), T\zeta^*(0)]$ and we obtain

$$\alpha \frac{2\theta + \bar{m}}{(N + \theta + \bar{m})} \leq \gamma(T) \leq \frac{2\theta + \bar{m}}{(N + \theta + \bar{m})}$$

where, by definition, $\alpha = \zeta^*(T)/\zeta^*(0)$. Depending on the slope of demand and the shape of $z(t)$, $\gamma(T)$ could be anywhere between these two limits. By Proposition 9, however, if $z(t)$ is convex in t, then

$$\gamma(T) \leq \frac{(1+\alpha)}{2} \frac{2\theta + \bar{m}}{(N + \theta + \bar{m})}.$$

Estimating PNA for an existing ETS So far we have considered the scenario where an ETS is *introduced* and free permit allocations are used to compensate firms for profit reductions. However, our analysis can be easily modified to determine the permit allocation needed to compensate firms for the reduction in profit arising from a *tightening* of an (existing) emissions trading scheme. In formal terms, the initial emissions price is $T > 0$ and a tightening of the ETS leads to a higher price of T', which in turn causes a change in average industry profit, from $\Pi(T)$ to $\Pi(T')$. Let $\gamma(T, T')$ be the profit-neutral allocation, as a fraction of the industry's initial demand for permits $\zeta^*(T)$ as defined by the equation $\Pi(T') + \gamma(T, T')\zeta^*(T) = \Pi(T)$. This may be rewritten as

$$\gamma(T, T') = -\frac{[\Pi(T') - \Pi(T)]}{\zeta^*(T)T'}.$$

Since $\Pi(T') - \Pi(T) = -\int_T^{T'} \tilde{\gamma}(t)\zeta^*(t)\, dt$ (see (40)),

$$\gamma(T, T') = \frac{(T' - T)}{T'} \frac{\int_T^{T'} \tilde{\gamma}(t)\zeta^*(t)\, dt}{(T' - T)\zeta^*(T)}$$

Assuming that ζ^* is decreasing in t, we have $\int_T^{T'} \zeta^*(t)\,dt \leq \zeta^*(T)(T'-T)$, so

$$\gamma(T,T') \leq \frac{(T'-T)}{T'} \max_{T\leq t\leq T'} \tilde{\gamma}(t) \leq \max_{T\leq t\leq T'} \tilde{\gamma}(t).$$

This result is clearly analogous to Proposition 8. Just as we used the formula for $\tilde{\gamma}$ to bound $\gamma(T)$ in Section 4.2, we could now use it to bound $\gamma(T,T')$.

5. Calculating PNA: an example

In our discussion of PNA so far, we have focussed on the case where demand is log-concave (so $E \leq 1$) and emissions and marginal costs are non-negatively correlated. It is useful to have some appreciation of how sensitive PNA estimates are to departures from these assumptions. To do this, we apply our formulae to make indicative calculations of PNA for the UK cement industry, which is covered by the EU ETS, using different estimates of demand curvature and of the correlation between emissions and marginal costs. The empirical approach we adopt here could potentially be applied to other industries (to be) covered by an ETS.

For the UK cement industry, it is reasonable to set the number of firms at $N = 8$ with a Herfindahl index $H = 0.28$.[30] We assume that the firms are in a Cournot oligopoly (so $\theta = 1$) and firms have constant returns to scale (so $\bar{m} = 0$). Note that the concentration condition $H \geq 2/(N+1)$ is satisfied and case [4] in Section 4.2 tells us that PNA is less than $H = 0.28$ so long as demand is log-concave ($E \leq 1$) and there is non-negative correlation between emissions and marginal costs.

We now consider relaxing the assumption that demand is log-concave while retaining the correlation assumption. Assuming that industry emissions is decreasing in t, we know from (45) that $\gamma(T)$ is bounded above by

$$\tilde{\beta} \equiv 2 - N\frac{(2-HE)}{(N+1-E)}. \tag{55}$$

A less stringent way of bounding demand curvature $E(Q^*)$ derives from what we call the *elasticity approach*. Observe that we can write

$$E(Q^*) = \left[1 + \frac{1}{\eta(Q)} + \frac{d\log\eta(Q)}{d\log Q}\right]_{Q=Q^*}, \tag{56}$$

[30] Appendix B contains a justification of these values and all other data used in this example.

where $\eta(Q)$ is the industry price elasticity of demand. With the commonly-made and reasonable assumption that demand elasticity is non-decreasing in price (so $\partial\eta(Q)/\partial Q \leq 0$), we thus obtain an upper bound on demand curvature $E(Q^*) \leq 1 + 1/\eta(Q^*) \equiv \bar{E}$, where $\bar{E} > 1$. If demand has constant elasticity $E(Q^*) = \bar{E}$, but otherwise $\bar{E}$ may be a significant overestimate of the true demand curvature. Calculating $\bar{E}$ is usually straightforward, as it is relatively easy to find estimates of price elasticity $\eta(Q^*)$ for many emissions-intensive industries from previous empirical work. For the UK cement industry, our 'best guess' is $\eta = 0.8$ but we also use a low estimate of 0.5 and a high estimate of 2.0 to check robustness.

Since $\tilde{\beta}$ is increasing in E (see (55)),

$$\tilde{\beta} \leq \bar{\beta} \equiv 2 - N\frac{\left(2 - H\bar{E}\right)}{\left(N + 1 - \bar{E}\right)}. \tag{57}$$

Table 1 displays values for the upper bound $\bar{E}$ on demand curvature, as well as of the upper bound $\bar{\beta}$ on PNA for our range of elasticity estimates. Notice that PNA (as bounded above by $\bar{\beta}$) is always below 50% for $N = 8$. We also repeat these calculations for a larger number of firms in the industry (to account for any potential ambiguity over any very small firms not captured in our industry data—since $\bar{\beta}$ also increases with N). The upper-bound estimates of PNA remain well below 100% for these cases, even in the limiting case as we let $N \to \infty$ and so $\bar{\beta} \to \bar{E}H$.

Table 1: Upper bounds on PNA in terms of price elasticity (η)

Price elasticity (η)	$\bar{E}$	$\bar{\beta}$ ($N = 8$)	$\bar{\beta}$ ($N = 10$)	$\bar{\beta}$ ($N = 12$)	$\bar{E}H$
0.5 (low estimate)	3.00	0.45	0.55	0.61	0.84
0.8 (best guess)	2.25	0.38	0.43	0.47	0.63
2.0 (high estimate)	1.50	0.31	0.34	0.35	0.42

Now consider what happens if we relax the assumption that emissions intensities and marginal costs are non-negatively correlated. In the formula for $\tilde{\gamma}$ in Proposition 8 (see 5), the emissions-intensity component can be re-written as

$$\frac{\sum_{i=1}^{N} z_i}{\sum_{i=1}^{N} z_i\sigma_i} = \frac{N\bar{z}}{\bar{z} + N\mathrm{cov}(\sigma, z)} \tag{58}$$

where $\bar{z} = \sum_{i=1}^{N} z_i/N$ denotes the average emissions intensity across firms. By definition, the correlation coefficient ρ (of z and σ) is the ratio of $\mathrm{cov}(\sigma, z)$ and the product of the standard deviations of z and σ. We write the standard deviation of z as $\bar{z}\upsilon$, so $\upsilon \geq 0$ is the coefficient of variation of emissions intensities. It is not hard to check that the standard deviation of σ can be written $(\sqrt{HN-1})/N$. In this way, we obtain

$$\operatorname{cov}(\sigma, z) = \rho\,(\bar{z}\upsilon)\frac{\sqrt{HN-1}}{N}.$$

Thus we may re-write the formula for $\tilde{\gamma}$ (in equation (43), substituting $\theta = 1$ and $\bar{m} = 0$) as

$$\tilde{\gamma} = 2 - \frac{[2 - HE(Q^*)]}{[N+1-E(Q^*)]}\frac{N}{\left(1+\rho\upsilon\sqrt{HN-1}\right)} \tag{59}$$

By Proposition 8, PNA is bounded by $\tilde{\gamma}$, provided emissions are decreasing in t.

The formula (59) allows us to consider departures from the correlation condition $\rho \leq 0$ that we have maintained up to this point. While detailed information on emissions intensities across firms may not be available, the average emissions intensity across firms $\bar{z}$ may be known and also that emissions intensities are highly unlikely to lie outside a certain range, say $[\bar{z}(1-s), \bar{z}(1+s)]$. This information puts an upper bound on the coefficient of variation $\upsilon \leq s$, which in turn implies an upper bound on $\tilde{\gamma}$ in (59). For the UK cement industry, the information available suggests $s \leq 0.15$ as an upper bound on the coefficient of variation. Table 2 displays estimates of this upper bound on PNA for a range of (maximal) coefficients of variation $\upsilon \leq 0.15$, as well as for the entire range of possible correlation coefficients $\rho \in [-1, 1]$. We assume that demand is log-linear $E(Q^*) = 1$; the PNA estimates would be lower for any strictly log-concave demand curve.

Note first that $\tilde{\gamma} \leq H = 0.28$ (as it should be) whenever the correlation coefficient is negative, and that PNA itself turns negative for very low correlations. Also as expected, the upper bound of the Herfindahl index is tight whenever the coefficient of variation is zero or if the correlation coefficient is zero, as either of these imply that emissions intensities are uniform across firms. Most significantly, these upper bounds on PNA remain low even if the correlation is strongly positive. This exercise confirms something that is fairly clear from (59): even with positive correlation (i.e., $\rho > 0$), PNA is low if either there is relatively little variation in emissions intensities (low υ) or if firms' market shares are sufficiently close to symmetric (so H is close to $1/N$).[31]

[31] We also examined the "worst case" scenario for PNA in which the parameter values are all chosen to go as far as possible in the "wrong" direction. In particular, let $E = 3$ for a constant-elasticity demand curve

Table 2: Upper bounds on PNA in terms of correlation (ρ) and variation (υ) of emissions intensities

	Correlation ρ				
Variation υ	–1.0	–0.5	0	0.5	1.0
0.00 (uniform intensities)	0.28	0.28	0.28	0.28	0.28
0.05	0.18	0.23	0.28	0.33	0.37
0.10	0.06	0.18	0.28	0.37	0.45
0.15 (maximal variation)	–0.06	0.12	0.28	0.41	0.53

For the UK cement industry, a balanced view of this suite of estimates suggests that PNA (as a fraction of initial emissions levels) is likely to be no greater than 25–45%. These robustness checks give us confidence that our claim that PNA is typically partial and low extends significantly beyond the benchmark assumptions that demand is log-concave and there is non-negative correlation between emissions intensities and marginal costs.

6. Conclusion

In this paper we examined the impact of an emissions trading scheme on output, price, emissions, market shares, and profits in a canonical theoretical framework. It was shown that an ETS leads to more cost-efficient firms gaining market share and a reduction in aggregate industry emissions under the following assumptions: (a) firms' marginal costs are non-negatively correlated with their emissions intensities and (b) the industry faces a log-concave demand function. We also developed simple formulae to calculate firm- and industry-level PNA. These formulae indicate that the profit impact of the ETS will differ from one industry to another, depending on market structure, competitive conduct, firms' emissions intensities, and demand conditions. However, PNA is low for a large set of plausible parameter values. In particular, in a Cournot model with constant marginal costs, PNA (measured as a fraction of pre-ETS emissions level) is lower than the Herfindahl index. In this case, a profit-neutral ETS will typically involve the free allocation of less than 50% of

with the low elasticity estimate $\eta = 0.5$, and also let $\rho = 1$ and $\upsilon = 0.15$, so both the correlation coefficient and the coefficient of variation lead to as high a value of PNA as possible. Even in this very extreme case, we find that $\tilde{\gamma} \approx 0.67$, so PNA remains clearly partial and low. Indeed, it is still lower than the proportion of freely allocated permits in both phases I and II of the EU ETS.

the permit allowances issued, and thus raise a significant amount of government revenue.

This analysis may help to inform public discussion of cap-and-trade schemes as they are implemented in different parts of the world. Our results could also serve as a natural starting point for further theoretical and empirical studies into ETS design.

Appendix A: Proofs

Proof of Proposition 4: Let $\hat{q}_i(Q_{-i}, t)$ be the output of firm i at which it will have no incentive to deviate, given total output of $Q_{-i} + \hat{q}_i(Q_{-i}, t)$ and given its perception of how total output will vary with its deviation. The function $\hat{q}_i$ is defined implicitly through the first-order condition

$$P(\hat{q}_i(Q_{-i}, t) + Q_{-i}) + \theta \hat{q}_i(Q_{-i}, t) P'(\hat{q}_i(Q_{-i}, t) + Q_{-i}) = c_i(t) + m\hat{q}_i(Q_{-i}, t). \tag{60}$$

Differentiating (60) with respect to t, we obtain

$$\frac{\partial \hat{q}_i}{\partial t} = \frac{z_i}{(1+\theta)P' + \theta \hat{q}_i P'' - m} \tag{61}$$

Differentiating (60) by Q_{-i} we obtain

$$\frac{\partial \hat{q}_i}{\partial Q_{-i}} = -\frac{(P' + \theta \hat{q}_i P'')}{(1+\theta)P' + \theta \hat{q}_i P'' - m}, \tag{62}$$

from which we obtain

$$\frac{\partial \hat{q}_i}{\partial Q_{-i}} + 1 = \frac{\theta P' - m}{(1+\theta)P' + \theta \hat{q}_i P'' - m}. \tag{63}$$

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

$$\frac{dQ^*_{-i}}{dt}\left(\frac{\partial \hat{q}_i}{\partial Q_{-i}} + 1\right) = \frac{dQ^*}{dt} - \frac{\partial \hat{q}_i}{\partial t}. \tag{64}$$

Using (61) and (63), we obtain

$$\frac{dQ^*_{-i}}{dt} = \frac{dQ^*}{dt}\frac{[(1+\theta)P' + \theta q^*_i P'' - m]}{(\theta P' - m)} - \frac{z_i}{(\theta P' - m)} \tag{65}$$

Summing this equation across all firms gives us

$$(N-1)\frac{dQ^*}{dt} = \frac{dQ^*}{dt}\frac{[(1+\theta)NP' + \theta Q P'' - Nm]}{(\theta P' - m)} - \frac{\sum_{i=1}^N z_i}{(\theta P' - m)} \tag{66}$$

and hence

$$\frac{dQ^*}{dt} = \frac{\sum_{i=1}^N z_i}{[(\theta+N)P' + \theta Q P'' - m]}. \tag{67}$$

Using the definitions $E(Q^*) = -Q^* P''(Q^*)/P'(Q^*)$ and $\bar{m} = m/(-P'^*))$ gives us (19). It follows from (65) and (67) that

$$\frac{dQ^*_{-i}}{dt} = \frac{dQ^*}{dt}\left\{\frac{[(1+\theta)P' + \theta q_i^* P'' - m]}{(\theta P' - m)} - \frac{[(\theta+N)P' + \theta Q P'' - m]z_i}{(\sum_{i=1}^N z_i)(\theta P' - m)}\right\}$$

This gives us (20). Since $dq_i^*/dt = dQ^*/dt - dQ^*_{-i}/dt$, we may derive (21) from (19) and (20). **QED**

Proof of Proposition 5: Using (24) and (25), we obtain

$$\frac{dH}{dt} = \frac{2}{NQ^*}\frac{dQ^*}{dt}\left\{-\frac{N}{(\theta+\bar{m})} + \frac{NH[\theta(E-1)-\bar{m}]}{(\theta+\bar{m})} + \frac{[N+\theta(1-E)+\bar{m}]}{(\theta+\bar{m})}\frac{\sum_{i=1}^N z_i\sigma_i}{\sum_{i=1}^N z_i/N}\right\}. \tag{68}$$

Since $dQ^*/dt < 0$, $dH/dt \geq 0$ if the term in curly brackets is non-positive. Since market shares and emissions intensities are negatively correlated (16), the term in curly brackets is bounded above by

$$\frac{(NH-1)([\theta(E-1)-\bar{m}]}{\theta+\bar{m}}, \tag{69}$$

which is non-positive since $E \leq 1$ and $H \geq 1/N$. **QED**

Proof of Proposition 6: Since $dQ^*/dt < 0$ (see (19)), $d\zeta^*/dt \leq 0$ if $dz^*/dt \leq 0$. For case (a), we have already established that $dz^*/dt \leq 0$ in the main part of the paper. For case (b), it suffices to show that $\sum_{i=1}^N z_i\,(d\sigma_i/dt) \leq 0$. By (24), we have that

$$\sum_{i=1}^N z_i\frac{d\sigma_i}{dt} = \frac{1}{NQ^*}\frac{dQ^*}{dt}\left\{\begin{array}{c} -\frac{N(\sum_{i=1}^N z_i)}{(\theta+\bar{m})} + \frac{N[\theta(E-1)-\bar{m}](\sum_{i=1}^N \sigma_i z_i)}{(\theta+\bar{m})} \\ +\frac{[N+\theta(1-E)+\bar{m}]}{(\theta+\bar{m})}\frac{\sum_{i=1}^N z_i^2}{\sum_{i=1}^N z_i/N}\end{array}\right\}. \tag{70}$$

We require the term in the curly brackets to be non-negative. Using the fact that $\sum_{i=1}^N z_i^2 \geq (\sum_{i=1}^N z_i)^2/N$, the term in the curly brackets is bounded below by

$$\frac{[\theta(1-E)+\bar{m}]\left[\sum_{i=1}^N z_i - N\sum_{i=1}^N \sigma_i z_i\right]}{(\theta+\bar{m})}, \tag{71}$$

which is non-negative since both terms in the numerator are non-negative (by (16)). **QED**

Proof of cases [1] to [5], Section 4.2: For cases [1] and [2], the bounds are obtained by substituting $\theta = 0$ and $E = 0$ into (44) respectively.

To prove the other cases, we rewrite $\tilde{\beta}$ as

$$\tilde{\beta} = 1 + \frac{\theta(1-HN)}{(\theta+\bar{m})} - \frac{N\theta(\theta+N+\bar{m})\left[(2\theta+\bar{m})/\left(\theta(\theta+N+\bar{m})\right)-H\right]}{(\theta+\bar{m})(N+\theta(1-E)+\bar{m})} \tag{72}$$

For $H > (2\theta+\bar{m})/\left(\theta(\theta+N+\bar{m})\right)$, $\tilde{\beta}$ is an increasing function of E, so we may replace E with 1 to obtain (from (44))

$$\tilde{\gamma} \leq \tilde{\beta} \leq \frac{2\theta+\bar{m}}{(\theta+\bar{m})} - \frac{N\left[\theta+\bar{m}+\theta(1-\theta H)\right]}{(\theta+\bar{m})\left(N+\bar{m}\right)}. \tag{73}$$

Since$(\theta+\bar{m})+\theta(1-\theta H) \geq 0$, the upper bound for $\tilde{\gamma}$ in (73) is an increasing function of N. Letting $N \to \infty$, we obtain

$$\tilde{\beta} \leq \frac{\theta^2 H}{(\theta+\bar{m})} \leq \theta H. \tag{74}$$

Since H is increasing in t by Proposition 5, $\theta H(t) \leq \theta H(T)$, completing the proof of case [4].

Suppose $H = (2\theta+\bar{m})/\left(\theta(\theta+N+\bar{m})\right)$, then $\tilde{\beta} = (2\theta+\bar{m})/(\theta+N+\bar{m})$, which is less than 1 so long as $\theta < N$. Suppose $H \leq (2\theta+\bar{m})/\left(\theta(\theta+N+\bar{m})\right)$, then the last term on the right of (72) is positive, so that

$$\tilde{\beta} \leq 1 + \frac{\theta(1-HN)}{\theta+\bar{m}} \tag{75}$$

This bound cannot be improved on since the last term on the right of (72) goes to zero as $E \to -\infty$. The right hand side of (75) is a decreasing function of H and is greatest when $H = 1/N$, where it equals 1. Therefore, we know that so long as $\theta < N$, $\tilde{\beta} \leq 1$ for H between $1/N$ and $(2\theta+\bar{m})/\left(\theta(\theta+N+\bar{m})\right)$.

Therefore, we have shown that for all values of H (whether smaller or greater than $(2\theta+\bar{m})/\left[\theta(\theta+N+\bar{m})\right]$), $\tilde{\beta} \leq 1$. This completes the proof of case [3].

Finally, to prove case (5), note that when $H \leq (2\theta+\bar{m})/\left(\theta(\theta+N+\bar{m})\right)$, $\tilde{\beta}$ is an decreasing function of E (see (72)). Therefore, we may bound it above by setting $E=0$. This gives the value $(2\theta+\bar{m}(Q^*(t)))(\theta+N+\bar{m}(Q^*(t)))$. We conclude that

$$\tilde{\beta}(t) \leq \max\left\{\frac{2\theta+\bar{m}(Q^*(t))}{(\theta+N+\bar{m}(Q^*(t)))}\,,\, \theta H(t)\right\}. \tag{76}$$

Since Q is decreasing in t and P is convex, $-P'$ is increasing in t, so $\bar{m}$ is decreasing in t. Therefore, $\bar{m}(Q^*(0)) \geq \bar{m}(Q^*(t))$ for all $t \in [0,T]$. On the other hand, $H(T) \geq H(t)$ for all

$t \in [0, T]$. Therefore, for all $t \in [0, T]$,

$$\tilde{\beta}(t) \leq \max\left\{\frac{2\theta + \bar{m}(Q^*(0))}{(\theta + N + \bar{m}(Q^*(0)))}, \theta H(T)\right\}. \tag{77}$$

This completes our proof of case [5]. **QED**

Appendix B: The UK cement industry

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 are considered in aggregate in Section 5 because they are manufactured with a very similar process (Environment Agency, 2005). 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 four other firms (all manufacturing within the EU and subject to the EU ETS) supply the remainder. This gives a Herfindahl index of around $H = 0.28$ with a number of firms $N = 8$.

Estimates of the price elasticity of demand for cement in the UK do not seem to be readily available. Jans and Rosenbaum (1997) find an average elasticity of demand of 0.80 for cement industry in the U.S. More recently, Ryan (2005) finds an elasticity 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, Röller and Steen (2005) find a short-run elasticity of 0.46 and a corresponding long-run elasticity of 1.47 for the Norwegian market. For our calculations, we employ price elasticities of 0.5 (low), 0.8 (best guess) and 2.0 (high).

The common standard of measurement for carbon emissions intensities in cement production is kilograms of CO_2 per ton of Portland cement equivalent (tPCE). Emissions intensities are driven by a combination of factors, including plant size, plant age, processing technology and fuel mix. The British Cement Association stated in its 2006 Performance Report that its four members had an average emissions intensity of 822 $kgCO_2$/tPCE in 2005, but the report does not contain any data for individual firms. We have obtained emissions intensities for the two largest firms from other sources, but have not been able to do the same for the other firms in the industry. Lafarge Cement UK, the market leader, reports an emissions intensity of around 770 $kgCO_2/tPCE$ for 2005, while Castle Cement's emissions intensity was around 820 $kgCO_2/tPCE$ (see Lafarge Cement UK – 2005 Environmental Statement, and Castle Cement – 2007 Sustainability Report respectively).

We found no indication from cement industry sources of large differences in emissions intensities across firms. It seems likely that firms in the sector have emissions intensities within the range 700-940 $kgCO_2/tPCE$, implying that the larger part of the marginal cost impact of the EU ETS is commonly experienced. Amongst other things, this implies that the coefficient of variation of emissions intensities (that is, their standard deviation divided by the average emissions intensity in the industry of around 820 $kgCO_2/tPCE$) is likely to be no greater than around 0.15. Our evidence, though limited, is also consistent with the assumption that emissions intensities and market shares are (weakly) negatively correlated. In any case, it seems unlikely that this correlation coefficient takes on an extreme value on either the positive or negative side in the UK cement industry.

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