Emissions trading and profit-neutral grandfathering

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Abstract

This paper examines the amount of grandfathering needed for an emissions trading scheme (ETS) to have a neutral impact on firm profits. We provide a simple formula to calculate profit-neutral grandfathering in an asymmetric Cournot model with a general demand function. Using this formula, we obtain estimates of profit-neutral grandfathering for the electricity, cement, newsprint and steel industries. Under the current EU ETS, firms obtain close to full grandfathering; we show that while this may still leave *some* firms worse off, others have probably benefitted substantially. We find no evidence that any industry as a whole could be worse off with full grandfathering. We also show that the common presumption that a higher rate of cost pass-through lowers profit-neutral grandfathering is unreliable.

1 Introduction

On 1 January 2005, the 25 countries of the European Union launched a major scheme for trading carbon dioxide emissions, the so-called EU 'Emissions Trading Scheme' (EU ETS).[1] It is arguably the most significant practical application of economic theory to climate change, reportedly covering almost 11,500 installations including combustion plants, oil refineries, coke ovens, iron and steel plants, and factories making cement, glass, lime, brick, ceramics, and pulp and paper (European Commission, 2005). Emissions trading also features prominently in the Stern Review commissioned by the UK government (Stern et al., 2006) and is likely to play a central role in future climate policy.

The EU ETS was introduced as a mechanism for achieving compliance with the EU commitment under the Kyoto Protocol to the United Nations Framework Convention on Climate Change. According to the Protocol, the EU-15 nations must reduce combined emissions in the 'first commitment period' (January 2008 to December 2012) by 8%, relative to the base year (in most cases 1990). Specific targets for each individual nation are specified by the European 'burden sharing' agreement. For instance, while Portugal is entitled to a 27% increase, the United Kingdom and Luxembourg must achieve reductions in greenhouse gas emissions of 12% and 28% respectively. The industries currently participating in the EU ETS account for almost half of the total European CO_2 emissions.[2]

To facilitate the introduction of emissions trading, and to promote learning by doing, an initial phase of the EU ETS ('Phase 1') commenced in January 2005, running until December 2007. Phase 2 of the scheme, corresponding to the 'first commitment period' under Kyoto, will begin in January 2008. Participating firms have to monitor their emissions, and produce an annual report which is audited and verified by a third party. To avoid financial sanctions, firms must hold a sufficient number of 'European allowances', or EUAs, which are surrendered on a yearly basis (the first surrender date was the end of April 2006).[3] Firms in need of EUAs can purchase them on one of several exchanges, while other firms can sell their surplus EUAs.[4]

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

[2] See European Council Decision 2002/358/EC of 25 April 2002 and European Environment Agency (2006) for more detail.

[3] The sanction is set at €40/tCO$_2$ in Phase 1 and €100/tCO$_2$ in Phase 2. Moreover, payment of the sanction does not relieve firms of the obligation to reduce emissions—those in breach still have to make the required reductions in the following phase.

[4] The price of EUAs has been quite volatile. From the inception of the scheme to the time of writing, they have traded both below €10/tCO$_2$ and above €30/tCO$_2$.

The EUAs are distributed to firms according to National Allocation Plans (NAPs). The NAPs are determined by discussion and negotiation between Member States and the participating firms, and are then submitted to the European Commission for approval. Although the NAP development process is not particularly transparent, there are two salient stylized facts. First, nearly all allowances are currently allocated to installations (for free) as a function of historical emissions, a practice known as *grandfathering*.[5] Second, the total number of allowances allocated is not much less than 100% of past emissions (Reilly and Paltsev, 2005; Schleich and Betz, 2005).

The introduction of the EU ETS has had some interesting effects on firm cost structure. The requirement that firms surrender these allowances when they emit greenhouse gases increases marginal costs. However, firms benefit in three ways. First, a proportion of this cost increase can be passed through to consumers, depending upon market structure. Second, they may adopt abatement technologies which reduce marginal emissions and thus ameliorate the marginal cost increase. Third, as noted above, firms are compensated in that they are given almost all the allowances for free. This represents a lump-sum transfer to the firms from the regulator (ultimately, the taxpayer).

While protecting firm profits may be politically necessary to ensure 'buy-in' by firms, substantial 'windfall profits' are also likely to prompt strong public criticism. Thus we face an important policy question: What proportion of allowances should be freely allocated to achieve a *neutral* impact on firm profits? If this is achieved, a firm should be indifferent about the introduction of an ETS. Under perfect competition, the increase in marginal cost due to the introduction of emissions permits[6] causes price to increase by exactly the same amount, thus keeping profits at zero. Hence, no grandfathering is necessary here. Under *symmetric* Cournot competition, simulations in various papers (Vollebergh et al., 1997; Bovenberg and Goulder, 2001; Quirion, 2003; Bovenberg et al., 2005; Smale et al., 2006) have suggested that no more than 50%, and probably a much smaller percentage, should be allocated for free. For instance, Bovenberg and Goulder (2001) examined the coal, oil and gas industries in the United States and concluded that no more than 15% of permits would need to be grandfathered in a (hypothetical) CO_2 cap and trade scheme to ensure profit-neutrality.

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[5]In Phase 1, Denmark auctioned 5%, Hungary auctioned 2.4%, Lithuania auctioned 1.5%, and Ireland auctioned 0.75%. Other countries did not run auctions and instead gave 100% of allowances to firms for free. Member States are currently considering whether to auction up to 10% of the allowances for Phase 2.

[6]We use the terms 'emissions permits' and 'emissions allowances' interchangably throughout the paper.

Despite these results, a survey of European firms by PriceWaterhouseCoopers (2005) found that companies were 'concerned about the possible detrimental long-term impacts on shareholder value and profitability of carbon constraints.' Moreover, the director-general of the Confederation of British Industry, Sir Digby Jones, reportedly claimed that 'the Government is risking the sacrifice of UK jobs on the altar of green credentials' (*Daily Telegraph*, 23 February 2004). The article concludes that 'the introduction of the European carbon emissions trading scheme from next January will hit the profitability and share price of companies across all the major industrial sectors.' Fears from industries facing international competition seem understandable, but some firms in industries without much international competition (such as electricity, newsprint and cement) have also expressed reservations.

This paper investigates the impact of emissions trading on firm profits in an asymmetric Cournot model with a general demand function. We model the EU ETS as a change in cost structure, where the firms in the Cournot oligopoly face increased marginal costs as a result of the scheme and are compensated by the (lump sum) allocation of free permits. We focus on the direct impact of the EU ETS on this Cournot oligopoly, ignoring the possibility that it may also be affected indirectly.[7] We also ignore any perverse dynamic incentives, such as the ratchet effect.[8] Finally, we assume that firms take the allowance price as exogenous, because we are interested in the impact of emissions trading on specific industries, rather than general equilibrium effects.

Amongst other things, this analysis allows us to answer three interesting questions. First, what level of grandfathering is required to ensure profit-neutrality of an emissions trading scheme at the firm-level and at the industry-level? Our approach allows us to present a simple formula that can be used to calculate the level of profit-neutral grandfathering. Since in many industries, there is something close to full (i.e., 100%) grandfathering, we also use our formula to obtain the precise conditions under which full grandfathering is too much or too little for profit-neutrality (either at the firm- or industry-level).[9] Second, how important are firm asymmetries? Previous work on the impact of the EU ETS has typically assumed that firms are symmetric. It

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[7]For example, the firms may use electricity as an input, and its price may increase as a result of the ETS for the electricity industry.

[8]For example, a firm may have an incentive to increase output in the current period to gain a larger free allocation in subsequent periods if it is convinced that these are a function of past output.

[9]There is also a theoretical reason for using full grandfathering as a benchmark, which will become clear later on. Note that we are not claiming, nor does our analysis assume, that there is *exactly* full grandfathering in *all* industries. Obviously, such a scenario may well be incompatible with our assumption (and the fact) that the emissions permits have a strictly positive price.

turns out that this simplification is highly restrictive because the profit impact of the scheme differs significantly for firms of different sizes. Third, how reliable is the common presumption that a higher rate of cost pass-through helps firms (and thus lowers profit-neutral grandfathering)? We provide simple conditions under which this presumption is *not* correct.

The remainder of the paper is structured as follows. In Section 2, we present some preliminary observations on the impact of a fully grandfathered emissions scheme on firm profits. In Section 3, we derive easily interpretable formulae for the level of profit-neutral grandfathering in an asymmetric Cournot model with general demand. In Section 4, we investigate in detail the theoretical conditions under which a firm and indeed an industry as a whole could be worse off under a scheme with full grandfathering. In Section 5, we obtain estimates of profit-neutral grandfathering using data on the electricity, cement, newsprint and steel industries. In Section 6, we discuss conclusions and policy implications.

2   Preliminary observations on full grandfathering

As noted in the introduction, several studies have suggested that grandfathering of 50% or less of a firm's previous output is sufficient to ensure profit-neutrality. This would imply that the current EU ETS policy of an approximately fully grandfathered scheme must make firms substantially better off.

This section shows that this is indeed the case under some standard scenarios. It is useful to build intuition by first examining an industry with a single firm.

2.1   Monopoly

Consider a monopolist whose initial profit $\Pi(Q)$ is a function of her output, Q. Let Q_M^* denote the associated profit-maximizing output level before the ETS is introduced.[10]

Suppose now that an emissions trading scheme with full grandfathering is introduced. The market value of an emissions permit is $t > 0$ which is given exogenously. We assume that one unit of pollution is created for every unit of output. We also

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[10]We assume throughout that there are no exogenous shifts in demand that occur when the ETS is introduced.

assume, without loss of generality, that one permit is required per unit of pollution (equivalently, output), so that the emissions scheme raises the monopolist's marginal cost by t. This decreases her operating profits, but must be set off against the value of the lump-sum transfer received from the regulator. In particular, a policy of full grandfathering based on previous output levels means that this transfer is worth tQ_M^*.

A simple revealed preference argument shows that it is the latter, positive effect that dominates. Let Q_M^{**} denote the profit-maximizing output level after emissions permits are introduced.

Proposition 1. *A monopolist is better off under full grandfathering, that is* $\Pi(Q_M^{**}) - tQ_M^{**} + tQ_M^* \geq \Pi(Q_M^*)$.

Proof. Since the monopolist chooses optimally after the introduction of the emissions permits, the preference $\Pi(Q_M^{**}) - tQ_M^{**} \geq \Pi(Q_M^*) - tQ_M^*$ is revealed. ∎

The proposition can be understood as follows. Suppose that, despite the increase in marginal costs, the monopolist decides not to change her level of output after the emissions scheme is introduced, such that $Q_M^{**} = Q_M^*$. This implies that her *operating* profits must have decreased by the increase in marginal cost times the number of units of output (which is unchanged), namely by tQ_M^*. This is exactly equal to the market value of the lump-sum transfer implied by a policy of full grandfathering. Thus, by simply leaving her output unchanged at Q_M^*, the monopolist can ensure that she is exactly as well off as before. Clearly, the option to adjust by decreasing output (alternatively, increasing price) means that the monopolist must, in general, be better off.

Given the industries we are concerned with, a more realistic scenario is the one where several firms compete in the same industry. We therefore now turn to examining the impact of full grandfathering on a Cournot oligopoly.

2.2 Cournot oligopoly

Consider a general N firm Cournot oligopoly facing a downward-sloping inverse demand curve $P(Q)$, where $Q = \sum_{i=1}^{N} q_i$ is the industry output level. Firm i's initial profit function is given by

$$\Pi_i(q_i, Q_{-i}) = P(q_i + Q_{-i})q_i - C_i(q_i), \tag{1}$$

where $Q_{-i} = \sum_{j \neq i} q_j$ denotes the aggregate output of all firms except firm i. Note that we are neither assuming that marginal costs are constant nor that costs are identical across firms.

Note also that our assumption that a firm requires one emissions permit per unit of output (equivalently, pollution) means that, although firms may differ in their *production* technology, they all have the same *pollution* technology. Put differently, one unit of output creates one unit of pollution, regardless of the marginal cost at which it is produced.

Let q_i^* and q_i^{**} denote respectively the equilibrium output of firm i before and after the introduction of emissions permits. As in the monopoly case, we assume that the scheme causes each firm's marginal cost to increase by the market value of emissions permits, t. Under a policy of full grandfathering each firm also receives a lump-sum transfer that has a market value of tq_i^*.

The following proposition demonstrates that each firm (and, by extension, the industry as a whole) is better off under full grandfathering provided that *every* firm's output is reduced following the introduction of the emissions trading.

Proposition 2. *Suppose that each firm decreases output in response to the introduction of the emissions trading scheme, such that $q_i^{**} \leq q_i^*$ for all i. Then each firm is better off under full grandfathering, that is, for all i,*

$$\Pi_i(q_i^{**}, Q_{-i}^{**}) - tq_i^{**} + tq_i^* \geq \Pi_i(q_i^*, Q_{-i}^*). \tag{2}$$

Proof. Suppose that q_i^0 is in $\operatorname{argmax}_{q_i \in R_+}[\Pi_i(q_i, Q_{-i}^*) - tq_i]$. Then

$$\Pi_i(q_i^0, Q_{-i}^*) - tq_i^0 \geq \Pi_i(q_i^*, Q_{-i}^*) - tq_i^*. \tag{3}$$

Note also that $P(q_i + Q_{-i}^{**}) \geq P(q_i + Q_{-i}^*)$ for all q_i, since demand is downward-sloping and $Q_{-i}^{**} \leq Q_{-i}^*$. In other words, each firm i faces a more favourable residual demand since the other firms are producing less. Therefore, we have that

$$\max_{q_i \in R_+}[\Pi_i(q_i, Q_{-i}^{**}) - tq_i] \geq \max_{q_i \in R_+}[\Pi_i(q_i, Q_{-i}^*) - tq_i]. \tag{4}$$

By definition, firm i is playing its best response after the introduction of the permits, so q_i^{**} is in $\operatorname{argmax}_{q_i \in R_+}[\Pi_i(q_i, Q_{-i}^{**}) - tq_i]$. Thus, the previous expression can also be written as

$$\Pi_i(q_i^{**}, Q_{-i}^{**}) - tq_i^{**} \geq \Pi_i(q_i^0, Q_{-i}^*) - tq_i^0. \tag{5}$$

Combining (3) and (5) yields the result. ∎

Example 1. We illustrate Proposition 2 by considering a symmetric Cournot oligopoly with constant marginal cost $c \geq 0$ and linear demand of the form $P(Q) = \alpha - \beta Q$. (Note that the monopoly case considered in Proposition 1 is also covered by setting $N = 1$.) Straightforward calculations show that the initial firm profit in symmetric Cournot equilibrium can be written as $\Pi_i(q_i^*, Q_{-i}^*) = \beta(q_i^*)^2$ for all i. The corresponding equilibrium *operating* profit after the introduction of emissions permits is $\Pi_i(q_i^{**}, Q_{-i}^{**}) - tq_i^{**} = \beta(q_i^{**})^2$ for all i. We wish to confirm that (2) holds which in this context is equivalent to $\beta(q_i^{**})^2 + tq_i^* \geq \beta(q_i^*)^2$. Straightforward calculations again show that the two output levels satisfy $q_i^{**} = q_i^* - t/\beta(N+1)$. Note that each firm indeed decreases output in this example, so $q_i^{**} < q_i^*$ for all t, as assumed in Proposition 2. Substituting for q_i^{**} one can now easily confirm directly that the condition from (2) holds—with strict inequality—for all $N \geq 1$.

Proposition 2 assumes that the introduction of emissions permits causes *every* firm to reduce its output. Crucially, this implies that $Q_{-i}^{**} \leq Q_{-i}^*$ for all i, so each firm faces a more favourable residual demand curve with the scheme in place. In this case, full grandfathering is more than sufficient for profit-neutrality. In a symmetric model, the assumption that all firms reduce their output is completely reasonable as it is equivalent to assuming that industry output falls in response to an increase in marginal cost.

However, this endogenous assumption is no longer immediately compelling when firms are asymmetric. Indeed, we show in the next two sections that, under natural assumptions on costs and demand, some firms will face a *less* favourable residual demand curve after the introductions of emissions permits. When this occurs, full grandfathering will no longer be sufficient for profit-neutrality.

3 Profit-neutral grandfathering

The results of the previous section suggest that a full understanding of the EU ETS requires taking into account the different impact emissions permits have on firms of different sizes. A useful approach to this problem is to ask directly: How much grandfathering is needed to make a firm indifferent to the introduction of a permit scheme (that is, for profit-neutrality)?

As above, we denote by q_i^* and q_i^{**} respectively the equilibrium output of firm i before and after the introduction of the emissions permits. Correspondingly, Q_{-i}^* and Q_{-i}^{**} are the respective equilibrium aggregate outputs of all other firms. Assuming that

the market price of a permit is $t > 0$, a policy of full grandfathering gives firm i a lump-sum transfer worth tq_i^*. The proportion of this transfer that is actually needed to ensure profit-neutrality, which we denote by γ_i, must satisfy

$$\left[\Pi_i(q_i^{**}, Q_{-i}^{**}) - tq_i^{**}\right] + \gamma_i tq_i^* = \Pi_i(q_i^*, Q_{-i}^*). \tag{6}$$

The first term in square brackets on the left-hand side is the firm's *operating* profit after permits are introduced, taking into account the increase in marginal cost and changes in firms' equilibrium outputs. The second term is the value of the lump-sum transfer. The sum of these two must be equal to the firm's initial profit, which is given on the right-hand side of the equation.

Note that changing t will change q_i^{**} and Q_{-i}^{**} and thus γ_i as well; in formal terms, they are all functions of t. There does not appear to be any instructive and general way of analyzing $\gamma_i(t)$ for different values of t, but fortunately $\tilde{\gamma}_i \equiv \lim_{t \to 0} \gamma_i(t)$ is well-behaved and susceptible to analysis. This limit determines the approximate proportion of grandfathering that satisfies (6) by ignoring higher-order terms in t. Effectively, this amounts to linearizing the *equilibrium* profit function around t. It is a good approximation provided the increase in marginal cost arising from the introduction of emissions trading is a small relative to other components of a firm's marginal cost. We confine our attention from now on to the properties of $\tilde{\gamma}_i$.[11]

By assuming that the increase in marginal cost coincides with the price of the permit, we are assuming that the firm cannot switch to a cleaner technology. It is clear that the possibility of abatement will diminish the adverse impact on marginal cost and thus the amount of grandfathering that a monopolist requires for profit-neutrality. Intuition suggests that this will also be true for a Cournot oligopoly. In the Appendix, we provide a formal way of incorporating emissions abatement into our analysis, which amongst other things, confirms this intuition. In the main body of the paper, we ignore abatement in order to present a model that is directly empirically implementable.

Indeed, the first-order approach delivers easily interpretable, closed-form solutions that do not impose any additional restrictions on firm asymmetry or the shape of demand—both of which turn out to be crucial for the problem at hand. We proceed by re-examining along these lines first the monopoly case and then concentrating, in more detail, on a Cournot oligopoly for which results at both the firm- and industry-level are derived.

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[11]It is worth mentioning that tractable expressions for $\gamma_i(t)$ are available for a few highly restrictive cases. For instance, it is easy to check that in Example 1 (with symmetric firms and linear demand), $\gamma_i(t) = [2 - t/(\alpha - c)]/(N + 1)$ for all i.

3.1 Monopoly

We assume that the monopolist initially has a constant marginal cost of $c > 0$ and produces output of Q_M^* before the introduction of the permit scheme. We denote by $\Pi^*(c)$ the firm's equilibrium operating profit at marginal cost c. This is the profit it derives from its operations alone, without accounting for the value of any lump-sum transfers. The introduction of the emissions trading scheme causes marginal cost to rise to $c + t$. The exact proportion of grandfathering needed for profit-neutrality is $\gamma_M(t)$ and satisfies

$$\Pi^*(c + t) + \gamma_M(t)tQ_M^* = \Pi^*(c). \tag{7}$$

The first-order approach described above yields a striking result.

Proposition 3. *To first order, full grandfathering is required to make a monopolist indifferent, that is, $\tilde{\gamma}_M \equiv \lim_{t \to 0} \gamma_M(t) = 1$.*

Proof. The Taylor expansion of $\Pi^*(c + t)$ around $t = 0$ gives

$$\Pi^*(c + t) = \Pi^*(c) + \frac{d\Pi^*(c)}{dc}t + \text{higher-order terms of } t. \tag{8}$$

The envelope theorem implies that for a profit-maximizing monopolist $d\Pi^*(c)/dc = -Q_M^*$ (since $\partial\Pi/\partial Q = 0$). Substituting this into (8) and the resulting expression into (7) gives us the result. ∎

The envelope theorem guarantees that, to first order, the increase in marginal costs due to the permit price decreases a monopolist's operating profits by tQ_M^*. This is exactly offset by the market value of the lump-sum transfer of permits—thus ensuring profit-neutrality—only if $\tilde{\gamma}_M = 1$. At the margin, therefore, full grandfathering is necessary to ensure indifference. This gives a theoretical motivation for the use of 100% grandfathering as a benchmark for analysis. Of course, the result from Proposition 1 remains valid and it implies here that higher-order terms of t tend to work in the monopolist's favour, such that $\gamma_M \leq 1$ more generally.

We now turn our attention to the Cournot oligopoly.

3.2 Cournot oligopoly

Consider an oligopoly consisting of N firms in which firm i has constant marginal cost of c_i. Without loss of generality, assume that $c_1 \leq c_2 \leq ... \leq c_N$. We denote by

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

The marginal revenue of firm i at q satisfies $MR_i(q) = P(Q) + q_i P'(Q)$, where $P(Q)$ is the downward-sloping inverse demand curve. Firm i maximizes its profit when $MR_i(q) = c_i$. We assume that before the introduction of emissions permits the firms are at the Cournot equilibrium $q^* = (q_i^*)_{1 \leq i \leq N}$ so that total output $Q^* = \sum_{i=1}^{N} q_i^*$. At this equilibrium q^*, we have

$$MR_i(q^*) = P(Q^*) + q_i^* P'(Q^*) = c_i \tag{9}$$

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

Let $E(Q^*) = -[d \log P'(Q)/d \log Q]_{Q=Q^*}$ denote the elasticity of the *slope* of inverse demand, evaluated at the initial equilibrium industry output. This can be interpreted as an index of demand curvature.[12] Clearly, $E(Q^*) > 0$ ($E(Q^*) < 0$) if $P''(Q^*) > 0$ ($P''(Q^*) < 0$) and inverse demand is locally convex (concave) at Q^*. If demand is linear (with $P''(Q) = 0$), then $E = 0$ for all Q.

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

$$2 - \sigma_i^* E(Q^*) > 0, \tag{10}$$

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

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

$$N + 1 - E(Q^*) > 0. \tag{11}$$

In our setting, the main economic implication of this assumption is that it ensures that industry output falls when there is a common increase in marginal cost. Given that output and pollution are equivalent in the model, this is a necessary condition for the emissions scheme to lead to a decrease in pollution. Put differently, *not* making this assumption would remove a basic environmental justification for introducing such a scheme.

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

As before, the Cournot equilibrium changes when emissions permits are introduced. The following lemma shows the impact of emissions trading on firm- and industry-level output and is crucial to understanding its impact on firm profits.[13]

Lemma 1. *(i) The first-order change in equilibrium industry output satisfies*

$$\frac{dQ^*}{dt} = \frac{N}{P'(Q^*)(N + 1 - E(Q^*))} < 0. \tag{12}$$

(ii) If inverse demand is locally convex, $P''(Q^*) > 0$ (concave, $P''(Q^*) < 0$)[14], then

$$\frac{dQ_{-i}^*}{dt} \text{ is decreasing (increasing) with } i,$$

$$\frac{dq_i^*}{dt} \text{ is increasing (decreasing) with } i.$$

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

$$\frac{\partial \hat{q}_i}{\partial t} = \frac{1}{\partial MR_i / \partial q_i} = \frac{1}{2P' + q_i P''} \tag{13}$$

and

$$\frac{\partial \hat{q}_i}{\partial Q_{-i}} = -\frac{\partial MR_i / \partial Q_{-i}}{\partial MR_i / \partial q_i} = -1 + \frac{P'}{2P' + q_i P''}. \tag{14}$$

At equilibrium, $\hat{q}_i(Q_{-i}^*, t) + Q_{-i}^* \equiv Q^*$. Differentiating with respect to t and using (13) and (14), we obtain

$$\frac{dQ_{-i}^*}{dt} = \frac{dQ^*}{dt} \frac{2P'(Q^*) + q_i^* P''(Q^*)}{P'(Q^*)} - \frac{1}{P'(Q^*)}. \tag{15}$$

Note that the sum across i of the left-hand side of this equation equals $(N - 1)dQ^*/dt$. Performing this summation on both sides and noting that $E(Q^*) = -Q^* P''(Q^*)/P'(Q^*)$, we obtain (12) for part (i) of the lemma. Our assumption in (11) implies that $dQ^*/dt < 0$. The first claim in (ii) follows from (15), bearing in

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[13]Up to now we have used Q^* to denote the equilibrium industry output before the introduction of permits. We shall now also use it to denote the *function* that maps the permit price t to equilibrium output. Although common practice, this is strictly speaking an abuse of notation which we employ analogously for Q_{-i}^*, q_i^* etc.

[14]Note that the inverse demand function P is locally convex (concave) at Q^* if and only if the demand function $Q = P^{-1}$ is locally concave (convex) at $P(Q^*)$.
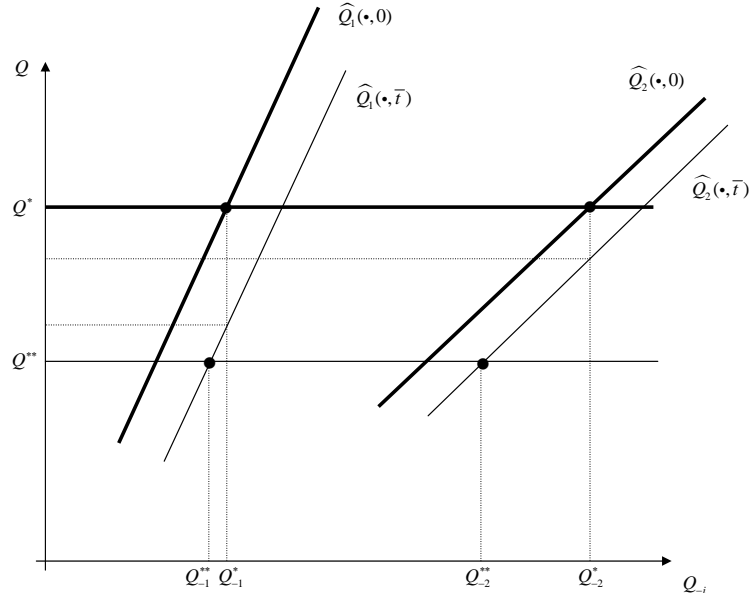
Figure 1: Differential impact of the ETS on firms of different sizes.

mind that $dQ^*/dt < 0$ and that q_i^* is decreasing in i. Using (15) and the equation $dq_i^*/dt = dQ^*/dt - dQ_{-i}^*/dt$, we obtain

$$\frac{dq_i^*}{dt} = \frac{dQ^*}{dt} \frac{1 - (1 - N\sigma_i^*)E(Q^*)}{N}. \tag{16}$$

The second claim in (ii) follows from this equation. ∎

Part (i) of Lemma 1 says that equilibrium total output will fall with the introduction of emissions permits (so the price of output will rise). Part (ii) says that this fall in output is shared differently across firms. When the inverse demand function is convex, the negative impact is greater for the larger firms (those with small i). This implies that the largest firm (firm 1, with marginal cost c_1) *must* experience a fall in output. When the inverse demand function in concave, the distribution of the fall in output is reversed. In this case, the smaller firms bear the brunt of the reduction, and the smallest firm (firm N, with marginal cost c_N) must experience a fall in output.

There is a simple diagrammatic way of explaining how firms of different sizes respond to an increase in t. Let $\hat{Q}_i(Q_{-i}, t) = \hat{q}_i(Q_i, t) + Q_{-i}$ denote the total output that will result if other firms are producing Q_{-i} and firm i responds optimally. We refer to $\hat{Q}_i$ as firm i's *accumulated best response function*. This function is locally increasing in Q_{-i}, since using equation (14),

$$\frac{\partial \hat{Q}_i}{\partial Q_{-i}} = \frac{1}{2 - \sigma_i^* E(Q^*)} > 0, \tag{17}$$

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where the denominator is positive by the second-order condition (see (10)).

In Figure 1, we have drawn the accumulated best response functions of firms 1 and 2 for the case when inverse demand is convex (the other case is just the opposite). The thicker lines depict the situation before the introduction of permits and the thinner lines the situation after permits (with a market price of $t > 0$) are introduced (where Q^{**} is the new equilibrium output). Note that the accumulated best response function of firm 1 intersects the (horizontal) equilibrium output line at (Q^*_{-1}, Q^*) (and similarly, for firm 2).

The diagram has two crucial features. First, it follows from (17) that when $P''(Q^*) > 0$ (equivalently, $E(Q^*) > 0$) the larger firm, firm 1, has a steeper accumulated best response function than firm 2. Second, it follows from (13) that $\partial \hat{q}_1 / \partial t < \partial \hat{q}_2 / \partial t$. In diagrammatic terms, the gap between the old and new accumulated best responses is greater for firm 1 than for firm 2. These two features reinforce each other and guarantee that $Q^*_{-1} - Q^{**}_{-1} < Q^*_{-2} - Q^{**}_{-2}$ (see Figure 1). Adding $Q^{**} - Q^*$ to both sides of this last inequality gives $q^*_1 - q^{**}_1 > q^*_2 - q^{**}_2$. In other words, firm 1 experiences a larger fall in output than firm 2 when inverse demand is convex, $P''(Q^*) > 0$.

3.3   A simple formula

We now turn to the impact of the emissions permit scheme on firm profits and obtain a simple formula to calculate profit-neutral grandfathering.

Denote the equilibrium operating profit of firm i at a permit price of $t > 0$ as $\Pi^*_i(t)$, so the firm's initial profit before introduction of the scheme is $\Pi^*_i(0)$. The exact profit-neutral proportion of grandfathering for firm i, $\gamma_i(t)$, satisfies

$$\Pi^*_i(t) + \gamma_i(t)tq^*_i = \Pi^*_i(0). \tag{18}$$

Taking the Taylor expansion of $\Pi^*_i(t)$ around $t = 0$, we determine the approximate level of grandfathering as

$$\tilde{\gamma}_i \equiv \lim_{t \to 0} \gamma_i(t) = -\frac{1}{q^*_i} \frac{d\Pi^*_i}{dt}(0). \tag{19}$$

In words, the proportion of grandfathering required to ensure profit-neutrality (to first order) at firm i is equal to the operating profit lost per unit of initial output. One can naturally think of the operating profit of firm i as a function of its own output, q_i, all other firms' output, Q_{-i}, and the market price of emissions permits, t. More formally, $\Pi_i(q_i, Q_{-i}, t) = q_i P(q_i + Q_{-i}) - (c_i + t)q_i$. The equilibrium profit

$\Pi_i^*(t) \equiv \Pi_i(t, q_i^*(t), Q_{-i}^*(t))$ then varies with t according to

$$\begin{aligned}
\frac{d\Pi_i^*}{dt} &= \frac{\partial \Pi_i}{\partial t} + \frac{\partial \Pi_i}{\partial q_i}\frac{dq_i^*}{dt} + \frac{\partial \Pi_i}{\partial Q_{-i}}\frac{dQ_{-i}^*}{dt} \\
&= -q_i^* + q_i^* P'(Q^*)\frac{dQ_{-i}^*}{dt},
\end{aligned} \tag{20}$$

where the second equality relies on the first-order condition for profit-maximization that $\partial \Pi_i/\partial q_i = 0$. Using this last result in (19) we obtain a simple expression for the required level of grandfathering:

$$\tilde{\gamma}_i = 1 - P'(Q^*)\frac{dQ_{-i}^*}{dt}. \tag{21}$$

Given that $P'(Q^*) < 0$, this makes clear why the assumption of every firm reducing its output in response to the introduction of emissions permits was crucial for Proposition 2 to go through. Then $dQ_{-i}^*/dt < 0$ holds for all i and full grandfathering makes each firm (and the industry) better off.

The following proposition uses Lemma 1 to express this formula for $\tilde{\gamma}_i$ in terms of more tangible quantities.

Proposition 4. *To first order, the level of grandfathering required to make firm i indifferent is*

$$\tilde{\gamma}_i = \frac{2 - (2 - N\sigma_i^*)E(Q^*)}{N + 1 - E(Q^*)}. \tag{22}$$

Proof. This result can be obtained by using (12) and (15) in the expression for the required level of grandfathering from (21). ∎

Proposition 4 shows that the level of grandfathering required for profit-neutrality at firm i depends on industry characteristics (that is, the number of firms in the industry, N, and demand curvature, $E(Q^*)$) as well as on a firm's market share, σ_i^*. Note also that the denominator is positive by (11).[15]

We use Proposition 4 to examine in detail the conditions under which firms (and industries) can be *worse* off under a policy of full grandfathering in the next section

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[15]The level of profit-neutral grandfathering for firm i can be related (using Proposition 4) to that for firm j as

$$\tilde{\gamma}_i = \frac{2(\sigma_i^* - \sigma_j^*) + [2 - (N+1)\sigma_i^*]\,\tilde{\gamma}_j}{2 - (N+1)\sigma_j^*}.$$

Therefore, profit-neutral grandfathering for any firm can generally be expressed relative to a benchmark level in a way that does not depend on demand curvature. For example, this may be useful if the appropriate level can be determined independently for (at least) one firm. Then the level for all other firms can easily be calculated in a consistent way. We thank Martin Browning for this observation.

of the paper. Before doing so, the remainder of the current section points out two properties of $\tilde{\gamma}_i$ that are also relevant to the ongoing policy debate.

A 'one-size-fits-all' policy? The NAPs are currently determined in a politicized environment involving asymmetric information, lobbying and transactions costs. Delays and disputes about the appropriateness of the NAPs should not be surprising.[16] One might be tempted to, as far as possible, automate the process by insisting on a 'one-size-fits-all' policy that provides all firms with the same level of grandfathering, and makes no distinction between, say, small and large firms in an industry.

Proposition 4 reveals that such a policy is imperfect in at least one respect. A 'one-size-fits-all' policy is unable to achieve profit-neutrality (to first order) at all $N \geq 2$ (asymmetric) firms simultaneously in all but the 'knife-edge' case when demand is exactly linear (at least locally at Q^*), so $E(Q^*) = 0$. In this case, all firms contract output by the same amount, since $dq_i^*/dt = 1/2P'(Q^*)$ for all i (by (16)), and Proposition 4 tells us that $\tilde{\gamma}_i = 2/(N+1)$. From this one also observes that whenever a non-discriminatory policy is required, it must involve only *partial* grandfathering, in particular $\tilde{\gamma}_i \in (0, \frac{2}{3}]$.

The manner in which $\tilde{\gamma}_i$ varies with i (firm size) depends on demand curvature. When the inverse demand function is convex, larger firms require (in proportional terms) relatively more grandfathering for profit-neutrality than smaller ones, as they suffer relatively larger falls in output (recalling Lemma 1). These results are reversed when demand is concave. The following proposition summarizes.

Proposition 5. *If inverse demand is locally convex, i.e., $P''(Q^*) > 0$ (concave, i.e., $P''(Q^*) < 0$), then $\tilde{\gamma}_i$ decreases (increases) with i. If demand is locally linear, $P''(Q^*) = 0$, then $\tilde{\gamma}_i = 2/(N+1)$ for all i.*

Proof. This follows immediately from Proposition 4 since σ_i^* is decreasing with i and $E(Q^*) > 0$ ($E(Q^*) < 0$) when $P''(Q^*) > 0$ ($P''(Q^*) < 0$). ∎

Negative grandfathering? Interestingly, the amount of grandfathering required to achieve profit-neutrality need not be positive. In other words, the impact of emissions trading on firm profits could be such that an industry should be willing to pay the government to introduce an ETS without any grandfathering at all.

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[16]For instance, the NAPs for Phase 2 of the EU ETS were due to be submitted to the European Commission by 30 June 2006. However, most plans were late, and the European Commission subsequently commenced legal action against eight Member States who had failed to submit their NAPs.

This possibility should be borne in mind as further industries (such as aviation) are considered for inclusion in the EU ETS.

The reason for this lies in the well-known observation that an increase in marginal cost may actually *increase* a Cournot oligopolist's operating profits (see e.g., Kimmel (1992) and the references cited therein). In this case, the introduction of the emissions permits actually helps firm(s) increase their profits. The lump-sum transfer of permits from the regulator must therefore have negative value to ensure profit-neutrality, which implies that $\tilde{\gamma}_i < 0$.

4 When are firms (and industries) worse off?

We now turn to the question of when a policy of full grandfathering is not sufficient to ensure profit-neutrality. We first examine the case of an individual firm and then, building on this, look at the impact on an industry as a whole. We also examine the related issue of how the level of profit-neutral grandfathering is affected by the rate of cost pass-through.

4.1 Firm-level analysis

The results from the previous sections indicate that the residual demand curve that a firm faces plays a crucial role in answering the question at hand. Indeed, recall from (21) that

$$\tilde{\gamma}_i > 1 \text{ if and only if } dQ^*_{-i}/dt > 0.$$

In words, full grandfathering is insufficient for profit-neutrality at firm i if and only if the firm faces a more unfavourable residual demand curve after the introduction of the emissions trading scheme. A starting observation is that this cannot be true for every firm in an industry. To see this, note that

$$\sum_{i=1}^{N} \frac{dQ^*_{-i}}{dt} = (N-1)\frac{dQ^*}{dt} \tag{23}$$

where the right-hand side is negative since $dQ^*/dt < 0$ (by Lemma 1).

The following proposition states the condition for an individual firm in terms of more tangible quantities.

Proposition 6. *Full grandfathering is not sufficient to achieve profit-neutrality at firm i, that is $\tilde{\gamma}_i > 1$, if and only if*

$$N + (1 - N\sigma_i^*)E(Q^*) < 1. \tag{24}$$

In particular, $\tilde{\gamma}_i > 1$ only if (i) $E(Q^*) > 1$ and $\sigma_i^* > 2/(N+1)$ or (ii) $E(Q^*) < -1$ and $\sigma_i^* < 1/N$. If $\sigma_i^* \in [1/N, 2/(N+1)]$, then $\tilde{\gamma}_i < 1$ for any $E(Q^*)$.

Proof. The condition (24) follows immediately by setting $\tilde{\gamma}_i > 1$ in Proposition 4 and rearranging terms. Note that if $\tilde{\gamma}_i > 1$, then we know that (24) holds. Thus $0 < N - 1 < N(\sigma_i^* - 1)E(Q^*)$. This implies that $|E(Q^*)| > |N-1|/|N\sigma_i^* - 1|$. Since $-1 < N\sigma_i^* - 1 < N - 1$, it must be the case that $|E(Q^*)| > 1$. If $E(Q^*) > 1$, then (24) is more easily met with higher $E(Q^*)$. Since $E(Q^*) < N + 1$ (by (11)) we find that $\sigma_i^* > 2/(N+1)$ is necessary. If $E(Q^*) < -1$, then clearly (24) holds only if $1 - N\sigma_i < 0$. It follows that if $\sigma_i^* \in [1/N, 2/(N+1)]$, then $\tilde{\gamma}_i < 1$ for any $E(Q^*)$. ∎

The condition identified in Proposition 6 is not excluded in theory, so it is indeed possible for *some* firms to be worse off under a fully grandfathered emissions scheme. Furthermore, the condition does not require any manifestly implausible assumptions on the firm or industry concerned. There are two key requirements for it to hold. First, firm i must be non-average in the sense that $\sigma_i^* \neq 1/N$. Clearly, this rules out symmetric equilibria which are often a convenient model simplification, but do not appear very satisfactory for the industries affected by the EU ETS that we are concerned with. Second, industry demand must be sufficiently non-linear in the sense that the absolute value of (local) demand curvature satisfies $|E(Q^*)| > 1$. This is always the case, for instance, when demand has constant elasticity.

Example 2. We can illustrate many of the results obtained with a simple example of an asymmetric duopoly. Suppose that the two firms face a unit-elastic inverse demand curve of the form $P(Q) = K/Q$ so there is a fixed pie of $K > 0$ in total industry revenues. The low-cost firm has marginal cost of $c_1 = \bar{c} - \Delta$ and the high-cost firm has $c_2 = \bar{c} + \Delta$, where $0 < \Delta < \bar{c}$. Noting that $N = 2$ and $E = 2$, we can apply Proposition 4 to obtain that the (approximate) proportion of grandfathering needed to ensure profit-neutrality at the low-cost firm is $\tilde{\gamma}_1 = 2(\sigma_1^* - \sigma_2^*)$. Straightforward calculations show that, in equilibrium, $\sigma_1^* = (\bar{c} + \Delta)/2\bar{c}$, so this can be written as $\tilde{\gamma}_1 = 2\Delta/\bar{c} > 0$. Since an analogous expression also holds for high-cost firm, we find the striking result that $\tilde{\gamma}_2 = -\tilde{\gamma}_1$ which is quite the opposite of a 'one-size-fits-all' policy (see Proposition 5). Since this implies that $\tilde{\gamma}_2 < 0$, *negative* grandfathering

is required at firm 2. Moreover, the low-cost firm is worse off under a policy of full grandfathering (that is, $\tilde{\gamma}_1 > 1$) whenever the cost asymmetry is sufficiently large, $\Delta > \bar{c}/2$ (see Proposition 6).

A more general theme to emerge from Proposition 6 is that, depending on demand conditions, *either* small *or* large firms can be worse off under a fully grandfathered emissions scheme. Recall from Proposition 5 that larger (smaller) firms require more grandfathering when demand is convex (concave) as they suffer larger reductions in output. Accordingly, if $\tilde{\gamma}_i > 1$ then either firm i is above average, $\sigma_i^* > 1/N$, and demand is sufficiently convex $E(Q^*) > 1$ (as in Example 2) or firm i is below average $\sigma_i^* < 1/N$, and demand is sufficiently concave $E(Q^*) < -1$.

Given that full grandfathering is not always sufficient to ensure profit-neutrality at all firms, one might ask: What is? Our analysis reveals a simple answer to this question.

Proposition 7. *To first order, $\tilde{\gamma}_i < 2$ for all i.*

Proof. Substituting (15) into (21) and after some manipulation we obtain

$$\tilde{\gamma}_i = 2 - P'(Q^*)\frac{dQ^*}{dt}\left[2 - \sigma_i^* E(Q^*)\right]. \tag{25}$$

Since $P'(Q^*) < 0$, $dQ^*/dt < 0$ by (12), and $2 - \sigma_i^* E(Q^*) > 0$ by (10), it follows that $\tilde{\gamma}_i < 2$ for all i. ∎

Proposition 7 tells us that the theoretical upper bound on profit-neutral grandfathering is 200% (to first order). This holds regardless of the number of firms in the industry, the distribution of market shares, and the shape of demand. Of course, grandfathering at that level will leave some firms *much* better off.

4.2 Industry-level analysis

The analysis thus far has helped shed considerable light on the conditions under which an individual firm is worse off under full grandfathering. A natural extension of this line of enquiry—that is also directly related to complaints from the Confederation of British Industry—is to ask whether this is also possible for an industry as a whole. Could industry-level profits actually decline with the introduction of fully grandfathered emissions trading?

We have already shown that it is not possible for *all* firms to be worse off under a policy of full grandfathering. The relevant issue therefore is whether the losses to some firms outweigh the gains experienced by others. Let $\gamma(t)$ be the proportion of grandfathering required for profit-neutrality for the whole industry. Formally,

$$\sum_{i=1}^{N} \Pi_i^*(t) + \gamma(t)tQ^* = \sum_{i=1}^{N} \Pi_i^*(0). \tag{26}$$

Taking the Taylor expansion around $t = 0$, we obtain

$$\tilde{\gamma} \equiv \lim_{t \to 0} \gamma(t) = -\frac{1}{Q^*} \sum_{i=1}^{N} \frac{d\Pi_i^*}{dt}(0), \tag{27}$$

where, similar to the previous section, $\tilde{\gamma}$ is the approximate proportion of grandfathering needed. In words, the proportion of grandfathering required to ensure profit-neutrality (to first-order) at the industry-level is equal to total operating profits lost per unit of (initial) industry output.[17] The following proposition provides a formula for $\tilde{\gamma}$ in terms of more tangible quantities. Let $H = \sum_{i=1}^{N} (\sigma_i^*)^2$ denote the industry's Herfindahl index. A convenient feature of the formula is that H is a sufficient statistic for the distribution of firm's market shares.

Proposition 8. *To first order, the level of grandfathering required to achieve profit-neutrality at the industry-level is*

$$\tilde{\gamma} = \frac{2 - (2 - NH)E(Q^*)}{N + 1 - E(Q^*)}. \tag{28}$$

Proof. Using Proposition 4 and (19), we obtain

$$\frac{d\Pi_i^*}{dt}(0) = \frac{2q_i^* - q_i^*(2 - N\sigma_i^*)E(Q^*)}{N + 1 - E(Q^*)}. \tag{29}$$

Substituting this into (27) and performing the summation gives us the result. ∎

One issue worth considering is how the proportion of grandfathering required for the industry, $\tilde{\gamma}$, varies with the number of firms, N. Should we expect an industry with many firms to require more or less grandfathering than one with only few? With symmetric firms $NH = 1$ for all N, so $\tilde{\gamma} = (2 - E(Q^*))/(N + 1 - E(Q^*))$. Holding $E(Q^*)$ fixed and less than two (such that *industry* marginal revenue is downward-sloping), we see that $\tilde{\gamma}$ is positive and decreasing in N. Comparing two industries

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[17]Profit-neutral grandfathering at the industry-level can also be seen as a weighted average of that at the firm-level since $\tilde{\gamma} = \sum_{i=1}^{N} \sigma_i^* \tilde{\gamma}_i$ (using (19) and (27)).

with symmetric firms and the same demand conditions, the industry with fewer firms will thus require more grandfathering to achieve profit-neutrality.[18,19]

Consider now any sequence of industries for which $E(Q^*)$ is uniformly bounded and the Herfindahl index $H \to 0$ as $N \to \infty$. The latter condition is one on the rate at which firm market shares are shrinking as N becomes large. (In particular, it holds if firms are symmetric, in which case $H = 1/N$.) With these assumptions it is clear that $\tilde{\gamma} \to 0$ as $N \to \infty$. This is the limit one would expect. As the number of firms increases we approach the case of perfect competition. In a perfectly competitive industry, there are no initial profits; furthermore, the increase in marginal cost due to the introduction of emissions permits causes price to increase by exactly the same amount, keeping profits at zero. Thus no grandfathering is necessary.

The next result identifies when an industry as a whole is worse off despite full grandfathering.

Proposition 9. *Full grandfathering is not sufficient to achieve profit-neutrality at the industry-level, that is $\tilde{\gamma} > 1$, if and only if*

$$N + (1 - NH)E(Q^*) < 1. \tag{30}$$

In particular, $\tilde{\gamma} > 1$ only if $E(Q^*) > 1$ and $H > 2/(N+1)$.

Proof. The inequality (30) follows immediately by setting $\tilde{\gamma} > 1$ in (28) and rearranging terms. Note that $H \geq 1/N$, so $1 - NH \leq 0$. If $E(Q^*) < 0$, we have $(1 - NH)E(Q^*) \geq 0$ so clearly (30) cannot hold. Since $H \leq 1$, we have $1 - NH \geq 1 - N$. If $0 \leq E(Q^*) \leq 1$, we have $E(Q^*)(1 - NH) \geq E(Q^*)(1 - N) \geq 1 - N$, in which case (30) also cannot hold. Thus it must be the case that $E(Q^*) > 1$. If $E(Q^*) > 1$, then (30) is more easily met with higher $E(Q^*)$. Since $E(Q^*) < N + 1$ by (11) we find that $H > 2/(N+1)$ is necessary for $\tilde{\gamma} > 1$. ∎

Once again, the condition identified in Proposition 9 is not excluded in theory, so it is indeed possible for an industry to be worse off, provided it is sufficiently non-symmetric, i.e., $H > 2/(N+1)$.[20] This condition is stronger than the analogous

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[18]The same conclusions holds if, instead of symmetry, we assume that NH takes on the same value in both industries.

[19]When $E > 2$, $\tilde{\gamma}$ is negative and increasing in N. This is because industry operating profits increase following the introduction of emissions trading. (See again Kimmel (1992).) When $E = 2$, $\tilde{\gamma} = 0$ for all $N \geq 2$. (See also Example 2 with $\Delta = 0$.)

[20]It is easily checked that the condition for the duopoly 'industry' in Example 2 to be worse off can be written as $\Delta > \bar{c}/\sqrt{2}$.

condition for an individual firm (see Proposition 6) in an important respect: Market demand can no longer be concave. Indeed, it is possible for an industry to be worse off only if inverse demand is sufficiently convex, i.e., $E(Q^*) > 1$. Only then is it possible for the losses (incurred by large firms) to outweigh the gains (experienced by small firms).

4.3   Cost pass-through effects

Another useful way to gain intuition about when a firm (and an industry) is worse off under full grandfathering is to think about the problem in terms of cost pass-through. Indeed, the question of what fraction of the increase in marginal costs due to emissions permits is passed on to prices has received considerable attention in the policy debate.

From Lemma 1, we obtain the (well-known) fact that the rate of cost pass-through in Cournot oligopoly satisfies

$$\frac{dP^*}{dt} = \frac{N}{N + 1 - E(Q^*)} > 0, \tag{31}$$

and conveniently is invariant to the distribution of firm's market shares in the industry.

It is important to see that an industry may be left worse off with full grandfathering, even if cost pass-though is high—contrary to what has recently been implied by reports in the press.[21] From (31), the rate of cost pass-through exceeds 100% if and only if $E(Q^*) > 1$. This condition is certainly compatible with $\tilde{\gamma} > 1$ (see Proposition 9). In this case, we know from Proposition 6 that it is the larger firms that suffer more (and hence would require higher levels of grandfathering) since the concomitant increase in profit margins tends to help firms with small market shares.

Not only is $E(Q^*) > 1$ compatible with $\tilde{\gamma} > 1$, Proposition 9 tells us that it is *necessary* for $\tilde{\gamma} > 1$. Surprisingly, therefore, the industry can be worse off with full grandfathering only when the rate of cost pass-through *exceeds* 100% and profit margins *increase* due to the introduction of an emissions trading scheme.

Indeed, the underlying presumption that a higher rate of cost pass-through helps a

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[21]One of many examples is: 'Analysts say the (power) generators are profiting by up to £800m a year from the first three-year phase by passing on the notional cost of the permits to consumers through higher bills even though they had received the permits for free' (*Financial Times*, 25 May 2006).

firm and thus lowers $\tilde{\gamma}_i$ is not necessarily correct. Consider the following proposition.

Proposition 10. *To first-order, the amount of grandfathering required to achieve profit-neutrality at firm i as a function of cost pass-through is*

$$\tilde{\gamma}_i = (2 - N\sigma_i^*) - \frac{dP^*}{dt} \left[2 - (N+1)\sigma_i^* \right]. \tag{32}$$

A higher rate of cost pass-through decreases $\tilde{\gamma}_i$ if and only if $\sigma_i^* < 2/(N+1)$.

Proof. Since $dP^*/dt = P'(Q^*) \left[dQ^*/dt \right]$, (25) can be rewritten as

$$\tilde{\gamma}_i = 2 - \frac{dP^*}{dt} [2 - \sigma_i^* E(Q^*)]. \tag{33}$$

Rearranging (31) yields

$$E(Q^*) = (N+1) - N/[dP^*/dt]. \tag{34}$$

Substituting this into (33) gives (32). Clearly, $\tilde{\gamma}_i$ decreases with dP^*/dt if and only if $2 - (N+1)\sigma_i^* > 0$. ∎

Note that the condition for higher cost pass-through to decrease profit-neutral grandfathering at firm i is always satisfied when firms are symmetric. However, any firm with a market share greater than $2/(N+1)$ (which is not particularly large) has profit-neutral grandfathering that *increases* with cost pass-through. This is not entirely surprising: While a higher rate of cost pass-through increases profit margins, it also lowers market demand, which has a larger impact on larger firms.

Similarly, the amount of grandfathering needed for profit-neutrality at the industry-level can be cast in terms of cost pass-through. Here too, it is not necessarily true that a higher rate of cost pass-through leads to lower profit-neutral grandfathering.

Proposition 11. *To first order, the level of grandfathering required to achieve profit-neutrality at the industry-level as a function of cost pass-through is*

$$\tilde{\gamma} = (2 - NH) - \frac{dP^*}{dt} \left[2 - (N+1)H \right]. \tag{35}$$

A higher rate of cost pass-through decreases $\tilde{\gamma}$ if and only if $H < 2/(N+1)$.

Proof. The formula is obtained by substituting (34) into (28). Clearly, $\tilde{\gamma}$ decreases in dP^*/dt if and only if $2 - (N+1)H > 0$. ∎

Proposition 11 says that $\tilde{\gamma}$ decreases with dP^*/dt only when firms are sufficiently symmetric, specifically, $H < 2/(N+1)$. Recall (from Proposition 9) that this bound

on H also guarantees that full grandfathering is never required for profit-neutrality. This is also obvious from (35), which then gives $2 - NH \leq 1$ as an upper bound on $\tilde{\gamma}$. These observations are potentially useful for empirical work as 'sufficient symmetry' can be verified without requiring any information on demand. Indeed, the condition is satisfied by one of the industries examined in the next section.

Ultimately, the question of whether firms and industries can be worse off under full grandfathering is an empirical one since the details of the market structure are crucial. The theoretical results we have obtained emphasize the importance of firm asymmetry and the curvature of the demand function. In the next section, we obtain empirical estimates of the level of profit-neutral grandfathering for firms affected by the EU ETS. A particular focus is placed on whether the conditions identified for a firm and an industry to be worse off have any empirical relevance.

5 Estimates of profit-neutral grandfathering

5.1 From theory to empirics

The main advantage of the first-order approach is that it yields easily interpretable, closed-form conditions. The key results on profit-neutral grandfathering at the firm- and industry-level, i.e., the formulae for $\tilde{\gamma}_i$ and $\tilde{\gamma}$, only require information on the number of firms in the industry, the firm's market share (respectively, the Herfindahl index) and demand curvature (see Propositions 4 and 8).

We have obtained data on the number of firms and the distribution of market shares in four key industries affected by the current EU ETS: Electricity, cement, newsprint and steel. Depending on the industry concerned, our focus is either only on UK firms or at a European level. The relevant market definitions and cautionary remarks on data quality are given in the next section.

The more obvious challenge in going from theory to empirics lies in the prominent role played by the index of demand curvature, $E(Q^*)$. To our best knowledge, no empirical data is available to give us any direct guidance on which value $E(Q^*)$ takes in any industry. To get round this difficulty, we first note that the elasticity of the slope of inverse demand can also be expressed as

$$E(Q^*) = \left[1 + \frac{1}{\eta(Q)} + \frac{d \log \eta(Q)}{d \log Q} \right]_{Q = Q^*}, \quad (36)$$

where $\eta(Q) = |P(Q)/QP'(Q)|$ is the industry price elasticity of demand. It is

commonplace to contend that demand elasticity is nondecreasing in price, which implies that $\partial \eta(Q)/\partial Q \leq 0$. We assume that this term is negligible, so that demand (approximately) has constant elasticity and $E(Q^*) \approx 1 + 1/\eta$. This gives us a way of calculating E, since estimates of price elasticity for the four industries are available from previous empirical work.[22] We call this way of estimating profit-neutral grandfathering the *elasticity approach*.

We also double-check our results using another method of estimation, which we call the *cost pass-through approach*. This approach relies on Propositions 10 and 11, which give formulae for $\tilde{\gamma}_i$ and $\tilde{\gamma}$ in terms of cost pass-through. Unfortunately, empirical estimates of pass-through for the four industries are not available. We therefore report estimates of profit-neutral grandfathering consistent with rates of cost pass-through ranging from 1% to 200%.

This approach has an important advantage over the elasticity approach since, unlike the latter, it does not impose $E(Q^*) > 1$, and hence cost pass-through *need not* exceed 100% (see (31)). Furthermore, since inverse demand is not required to be convex, the cost pass-through approach also allows for the possibility that the smallest firm (rather than the largest) requires the most grandfathering for profit-neutrality (see Proposition 5).

5.2   Industry data

In this section, we present and discuss data collected for four industries: Electricity, cement, newsprint and steel. Some cautionary remarks on data quality are in order at this juncture. While information on the market shares of leading firms in each industry appears to be reliable, it is difficult to obtain any data at all for very small firms (in particular, those with market shares below 5%). For the same reason, the number of firms in an industry is not always easy to determine. However, this is likely to have only a very small impact on the respective industry Herfindahl indices.

Since our data may underestimate the number of firms in an industry, one might ask how this affects the calculation of profit-neutral grandfathering. Suppose the true number of firms is $M > N$ and that firm i's market share σ_i^* is measured relative to the true industry output Q^* (rather than the output of the N firms). Then the formula (22) for γ_i remains *exactly* correct if the N firms act as Cournot players, while the remaining $M - N$ stay do not vary their output. Similarly, the

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

formula (28) for average profit-neutral grandfathering over N firms is *exactly* correct if $H = \sum_{i=1}^{N}(\sigma_i^*)^2$ and Q^* is the output of all M firms. Note that this H is not the same as the true Herfindahl index (which is $\sum_{i=1}^{M}(\sigma_i^*)^2$) though the difference will be insignificant if the remaining $M - N$ firms are small. If the tail firms are not inert and collectively produce less with emissions trading, then our results overestimate profit-neutral grandfathering. If they produce more (which is perhaps reasonable if they are non-EU firms that do not require permits for CO_2 emissions), then our results are an underestimate.

Electricity generation. Due to high transmission losses and the limited number of interconnectors, the market for electricity is not subject to fierce international competition. For this reason, we regard the UK as the relevant market.[23]

Although there are 66 electricity generators in the UK, according to data from the National Grid Company (2006), these generators can be grouped into a smaller number of firms. There are only 16 firms with capacity over 1GW (Ofgem, 2006), and Oxera (2004) note that the generation market is dominated by 10 firms, each owning capacity of at least 2.5GW. In this paper, we take the industry to contain 16 firms. In 2006, the largest UK generator was British Energy with a market share of approximately 16% (Ofgem, 2006). The Herfindahl index for the electricity market in England and Wales has fallen from around 0.16 in 1997/8 to around 0.08 in 2002 (Evans and Green, 2003). Ofgem (2006) report the Herfindahl index to be around 0.09, based on data from the National Grid Company (2006).

Several studies suggest that electricity demand is relatively inelastic in the UK, as in the rest of the world. For instance, Jones (1996) finds long-run elasticities of 0.47 for France, 0.42 for Germany, 0.24 for Italy and 0.38 for the United Kingdom. Filippini (1999) finds a price elasticity of 0.30 for the Swiss residential market.

Bernstein and Griffin (2005) use panel data on residential electricity consumption from 1977 to 2004 in 48 US states and find short-run and long-run elasticities of 0.20 and 0.32 respectively. The equivalent values for commercial electricity consumption are 0.21 (short-run) and 0.97 (long-run) and they find a moderate degree of variation between US regions and states. These estimates are broadly consistent with Maddala et al. (1997), who estimate elasticities for 49 US states, and also with results for California by Garcia-Cerutti (2000). Given these estimates, we consider

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[23]This is also broadly consistent with the definition of electricity generation markets adopted in competition law. European Commission cases that discuss this issue include EDF/Seeboard (Comp/M.2890, 25.07.2002), EDF/London Electricity (Comp/M.1346, 27.01.1999), and EDF/TXU Europe/West Burton Power Station (Comp/M.2675, 20.12.2001).

it appropriate to use elasticities of 0.15 (low), 0.40 (best guess), and 1.00 (high) for our modelling below.

Cement. There are five certified types of cement—Portland cement, Portland blast furnace cement, sulphate-resisting cement, masonry cement, and Portland pulverized fuel ash cement—which we group together because they are manufactured with essentially the same process (Environment Agency, 2005). The cement market definition is complex, mainly because land-based transport is expensive, while sea-based transport is relatively cheap.[24] Nevertheless, it is a fair assumption that large portions of the European cement industry do not face strong international competition. Indeed, since over 90% of the cement consumed in the UK is also manufactured there, we again define the relevant market as the UK.

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

Estimates of the price elasticity of demand for cement in the UK do not seem to be readily available. La Cour and Møllgaard (2002) provide an estimate of 0.27 for demand in Denmark. However, there is only one Danish cement producer, Aalborg Portland, with 85% market share, so this estimate appears to be somewhat low. In the United States, there are several dozen firms and Jans and Rosenbaum (1997) find an average elasticity of demand of 0.80. More recently, Ryan (2005) finds an elasticity 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. In the absence of UK data, we employ price elasticities of 0.30 (low), 0.80 (best guess) and 3.00 (high) in our modelling, based on the estimates for other countries.

Newsprint. Newsprint producers face more international competition than the previous two sectors, with some 15% of consumption being supplied from outside

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

the EU. According to an EU competition case, there are 19 European firms in the industry with at least six other international firms, but the five leading firms have a combined share of around 70–80% of the market.[25] UPM-Kymmene, Norske Skog and Stora Enso each have around 15–20% of the market. We assume the largest market share is 20% in our modelling. Because market shares otherwise appear to be distributed fairly evenly between firms, we estimate the Herfindahl index to be 0.12.

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

Coated sheet steel. Rapid structural changes have occurred in the steel industry over the past few years, with a clear trend towards increasing concentration.[26] Steel product markets are defined as European markets, and some of these markets have a relatively high import penetration, reducing the applicability of our theoretical model. For this reason, we examine European data on 'coated sheet steel', where imports comprise only 7% of the market. Coated sheet steel is used in a variety of products, including cars, trucks, buildings, and storage containers. As the name suggests, it is coated with a metal alloy or organic material designed to increase resistance to corrosion.

Data provided by the European Federation of Iron and Steel Industries (2006) for the year 2004 indicates that there were 12 firms supplying the European market for coated sheet steel.[27] The largest firm has a market share of 37% and the Herfindahl index is 0.19. The only available reference on price elasticities in the steel industry is Lord and Farr (2003) who report an estimate of 0.62. We thus employ a range of 0.30 (low), 0.60 (best guess), 1.00 (high) in our modelling.

The industry data are summarized in Table 1.

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

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

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

Table 1: Industry data

	Electricity	Cement	Newsprint	Steel
Market definition	UK	UK	Europe	Europe
Number of firms	16	8	19	12
Highest market share	16%	40%	20%	37%
Herfindahl Index	0.09	0.28	0.12	0.19
Price elasticity (low)	0.15	0.30	0.15	0.30
Price elasticity (best)	0.40	0.80	0.30	0.60
Price elasticity (high)	1.00	3.00	0.50	1.00

5.3   Estimates of profit-neutral grandfathering

This section provides empirical estimates of the amount of grandfathering needed to make firms and industries indifferent to the introduction of an emissions trading scheme such as the current EU ETS.

Price elasticity approach

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

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

at the firm-level (from Proposition 4) and

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

at the industry-level (from Proposition 8). Note that $N > 1/\eta$ is required for price to increase (and output and pollution to decrease) with the introduction of emissions trading, which we assumed in the theoretical model (see (11)). This condition is satisfied throughout by the data in all four industries.

It is of particular interest to see if the findings that both individual firms and an industry as a whole could be worse off have any empirical relevance. Since inverse demand is everywhere convex, we know from Proposition 5 that larger firms (those with higher σ_i^*) require a higher level of grandfathering to ensure profit-neutrality. We therefore report both the highest firm-level $\tilde{\gamma}_i$ as well as the industry-level $\tilde{\gamma}$.

The results for electricity, cement, newsprint and steel respectively are summarized in Table 2.

For the electricity generator industry (in the UK), the results in Table 2 show that the highest firm-level amount of grandfathering is no greater than 70%. Interestingly, this figure is higher near the *lower* end of the range of price elasticities where cost pass-through is *higher* (in fact, implied to be over 170%). However, closer to our best guess and the upper end of the elasticity estimates, around 20–30% grandfathering is sufficient for profit-neutrality—and much less for the smaller firms. Indeed, estimates of industry-level grandfathering are *negative* for a significant range of elasticities considered, and are near-zero otherwise. Our model therefore indicates that emissions trading may indeed have increased *total* operating profits in the electricity industry. This finding seems to be in line with the widespread claims that the UK electricity generators have benefitted substantially from the introduction of the EU ETS.[28]

The UK cement industry is much more heavily concentrated than any of the other industries we consider. The results in Table 2 indicate that it seems possible that the largest firm might be worse off under full grandfathering and requires up to around 150% for profit-neutrality. This finding holds for a range of elasticity estimates associated with higher rates of cost pass-through. It corresponds to the scenario discussed in Section 4 where a substantial (absolute) increase in profit margins helps smaller firms disproportionately. Estimates of profit-neutral grandfathering at the industry-level indicate that around 30–65% are sufficient, and are so for a very wide range of elasticities. Overall, these results suggest that the UK cement industry as a whole is also better off under full grandfathering.

The estimates we obtain for the European newsprint industry share a similar pattern with those for newsprint but are uniformly somewhat lower. Again, the results suggest that the market leader may be worse off under full grandfathering if price elasticities are near the lower end (which is 0.15 in this case). At the higher end, profit-neutrality for the largest firm requires something closer to 40–60% grandfathering. At the industry-level, our estimates indicate that grandfathering of 15–35% of allowances is sufficient for profit-neutrality, which means that (on average) the industry is substantially better off under a scheme like the current EU ETS.

Our estimates of profit-neutral grandfathering for the European coated sheet steel industry are comparable to those for cement and newsprint. Once again, we find

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[28]For instance, see the analysis conducted for the UK Department of Trade and Industry by IPA Energy Consulting (2005).

that more than full grandfathering *might* be required. In particular, profit-neutral grandfathering for the largest firm is found to be as high as 145%, and no lower than 60%. For the industry as a whole, our estimates of profit-neutral grandfathering are rather stable across the range of price elasticities considered. They show that grandfathering of around 25–35% of permits is sufficient, suggesting that the industry as a whole also benefits significantly under full grandfathering.[29]

Table 2: Profit-neutral grandfathering and price elasticity

Industry	Elasticity	Highest firm-level $\tilde{\gamma}_i$	Industry-level $\tilde{\gamma}$
Electricity	0.15 (low)	0.674	–0.246
	0.40 (best)	0.293	0.003
	1.00 (high)	0.208	0.059
Cement	0.30 (low)	1.543	0.651
	0.80 (best)	0.696	0.376
	3.00 (high)	0.470	0.303
Newsprint	0.15 (low)	1.281	0.336
	0.30 (best)	0.626	0.205
	0.50 (high)	0.435	0.167
Steel	0.30 (low)	1.451	0.371
	0.60 (best)	0.823	0.266
	1.00 (high)	0.625	0.233

Cost pass-through approach

Our second empirical approach considers the amount of profit-neutral grandfathering required as a function of the rate of pass-through from marginal cost onto prices. Given the absence of empirical data on pass-through in the four industries considered, we report estimates of profit-neutral grandfathering consistent with rates of cost pass-through ranging from 1% to 200%. It seems unlikely that any of the *actual* rates of cost pass-through in the four industries lie outside the wide range of values that we report.[30] With this approach, we do not restrict attention to constant

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[29]For the newsprint and steel industries, the presence of significant international competition may mean that our estimates of profit-neutral grandfathering are biased downwards. On the other hand, the adoption of abatement technologies pushes the level of profit-neutral grandfathering towards zero, thus typically implying an upward bias in our estimates (see the Appendix).

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

elasticity demand, and hence pass-through does not have to exceed 100%. This approach is best seen as a robustness check.[31]

As before, we are interested in the highest firm-level amount of grandfathering as well as the industry-level of profit-neutral grandfathering. Recall from Propositions 10 and 11 respectively that these can be written in terms of cost pass-through as

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

at the firm-level and

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

at the industry-level. We know from Proposition 5 that a 'one-size-fits-all' policy is optimal when $E(Q^*) = 0$ and hence $dP^*/dt = N/(N+1) < 1$. With non-linear demand, $\tilde{\gamma}_i$ is highest for the largest (smallest) firm when inverse demand is convex (concave). The highest firm-level amount of grandfathering, denoted $\max_i\{\tilde{\gamma}_i\}$, therefore is that for the largest firm whenever $dP^*/dt > N/(N+1)$ (equivalently, demand is convex) and for the smallest firm whenever $dP^*/dt < N/(N+1)$ (equivalently, demand is concave). Given that reliable data on market shares is much more difficult to obtain for very small firms, we report the results for the smallest firm assuming a market share of 2.5%.

The results on profit-neutral grandfathering as a function of cost pass-through for all four industries are reported in Table 3.

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[31]The *implied* rates of cost pass-through using the 'best guess' estimates of elasticity (see Table 2) are approximately 119% for electricity and cement, 121% for newsprint and 116% for steel respectively. All of the implied cost pass-through rates in the elasticity approach are within the range 104–172%.

Table 3: Profit-neutral grandfathering and cost pass-through[a]

dP^*/dt	Electricity $\max_i\{\tilde{\gamma}_i\}$	$\tilde{\gamma}$	Cement $\max_i\{\tilde{\gamma}_i\}$	$\tilde{\gamma}$	Newsprint $\max_i\{\tilde{\gamma}_i\}$	$\tilde{\gamma}$	Steel $\max_i\{\tilde{\gamma}_i\}$	$\tilde{\gamma}$
1%	1.584	0.555	1.782	–0.235	1.510	–0.276	1.683	–0.275
20%	1.285	0.466	1.445	–0.136	1.225	–0.200	1.365	–0.186
40%	0.970	0.372	1.090	–0.032	0.925	–0.120	1.030	–0.092
60%	0.655	0.278	0.735	0.072	0.625	–0.040	0.695	0.002
80%	0.340	0.184	0.380	0.176	0.325	0.040	0.360	0.096
100%	0.160	0.090	0.400	0.280	0.200	0.120	0.370	0.190
120%	0.304	–0.004	0.720	0.384	0.600	0.200	0.932	0.284
140%	0.448	–0.098	1.040	0.488	1.000	0.280	1.494	0.378
160%	0.592	–0.192	1.360	0.592	1.400	0.360	N/A	0.472
180%	0.736	–0.286	1.680	0.696	1.800	0.440	N/A	0.566
200%	0.880	–0.380	N/A	0.800	N/A	0.520	N/A	0.660

[a]N/A indicates that the implied rate of profit-neutral grandfathering exceeds 2, which is not compatible with a firm's second-order condition for profit-maximization in our model (see Proposition 7).

The estimates of industry-level grandfathering, $\tilde{\gamma}$, are linear in dP^*/dt and increasing or decreasing according to industry concentration, that is (by Proposition 11), whether $H > 2/(N+1)$ or $H < 2/(N+1)$. Only the electricity industry satisfies the condition that $H < 2/(N+1)$, so that $\tilde{\gamma}$ decreases with cost pass-through. Furthermore, since $N = 16$ and $H = 0.09$ (see Table 1), $\tilde{\gamma}$ for electricity has an upper bound of $2 - NH = 0.56$ (see the comments following Proposition 11).

The estimates of the highest firm-level profit-neutral grandfathering are *piecewise* linear in dP^*/dt, with a kink where $dP^*/dt = N/(N+1)$—for the four industries we consider, this is between 80% and 100%. Since the smallest firm cannot be above average, $\max_i\{\tilde{\gamma}_i\}$ initially decreases in dP^*/dt (using Propositions 5 and 10). If the largest firm has a market share $\sigma_1^* > 2/(N+1)$ (and this is indeed true of all four industries considered), then $\max_i\{\tilde{\gamma}_i\}$ increases in dP^*/dt when $dP^*/dt > N/(N+1)$.

Table 3 gives a wider range of estimates of profit-neutral grandfathering than similar estimates obtained using the elasticity approach. This is not surprising since the cost pass-through approach encompasses a far greater range of demand curves. A useful benchmark case to understand the results occurs when the rate of cost pass-through is exactly 100% (and $E(Q^*) = 1$), implying that each firm's profit margin remains constant. Then $\tilde{\gamma}_i = \sigma_i^*$ and $\tilde{\gamma} = H$, so *partial* grandfathering is always sufficient for profit-neutrality. If so, it is immediate from the industry data that

firm-level grandfathering of 16% to 40% and industry-level grandfathering of 9% to 28% is sufficient for profit-neutrality.

More generally, the estimates indicate that full grandfathering is more than sufficient for all firms if the rate of cost pass-through in a particular industry is (approximately) between 50% and 130%.[32] Small firms in all industries may be worse off if pass-through is lower, while large firms may be worse off when pass-through is higher. As with the previous elasticity approach, and for any rate of cost pass-through between 1% and 200%, no industry as a whole requires full grandfathering to achieve profit-neutrality.

In summary, and bearing in mind the potential limitations of our empirical approaches, the following results appear to be relatively robust. Larger firms and industries as a whole generally require some *partial* grandfathering to ensure profit-neutrality. We find no evidence at all that any industry as a whole could be worse off under full grandfathering. However, our estimates do not rule out that some large firms (in cement, newsprint and steel) might be worse off under the EU ETS, even with full grandfathering, while other firms in the same industry are likely to have benefitted substantially from its introduction. Lastly, the observed distribution of market shares in these industries often does not support the common presumption that a higher rate of cost pass-through implies a lower level of profit-neutral grandfathering, either at the firm- or industry-level.

6   Conclusions and policy implications

This paper has examined the amount of grandfathering required to ensure profit-neutrality of emissions trading at the firm- and industry-level. We summarize here the most important conclusions from the theoretical analysis and the empirical findings, before teasing out the policy implications.

There are four main conclusions from our theoretical analysis. First, in some circumstances, full grandfathering may not be enough to protect the profits of all firms or indeed an industry as a whole, and thus does not necessarily lead to 'windfall profits'. Second, however, under other circumstances *negative* grandfathering is necessary for profit-neutrality; in this case, firms will be better off even if they had to buy all their allowances at auction. Third, the theory suggests that firm

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[32]Sijm et al. (2006) obtain estimates of CO_2 pass-through rates for electricity in Germany and The Netherlands of 60–117% and also find that firms benefit from a fully grandfathered ETS.

asymmetries are important: A 'one-size-fits-all' policy of grandfathering the same proportion of allowances to all industries, or all firms, may have a very different impact on individual firms' profits. Fourth, the common presumption that a higher rate of cost pass-through helps firms (and thus lowers profit-neutral grandfathering) is unreliable. Overall, the theoretical results suggests that general conclusions about the impact of emissions trading are not readily available; results depend upon the details of the market structure and demand conditions.

The empirical section applied the theory to the electricity, cement, newsprint, and steel industries. There are two main conclusions. First, none of these industries *as a whole* is likely to be worse off after fully grandfathered emissions trading. Our results suggest that the electricity industry appears to require zero or even negative grandfathering. In contrast, the cement industry appears to need between around 30–65% grandfathering for profit-neutrality, while the values for newsprint and steel are around 15–35%. Second, industry-level results may mask important differences between firms. In particular, larger firms may need more grandfathering, and it cannot be ruled out that the largest firms *might* be worse off under full grandfathering.

These theoretical and empirical results have three important policy implications. First, it would seem sensible for EU Member States to auction the full 10% of the allowances permissible in Phase 2. Second, the inclusion of new sectors (such as aviation) in the EU ETS should be accompanied by careful economic analysis to determine the profit-neutral allocation of allowances. In general, it should not be taken for granted that full grandfathering, or full auctioning, is appropriate. Third, in climate policy arrangements post-2012, a proportion of allowances—in most cases probably more than 50%—should be auctioned. The impact of emissions trading depends on an industry's market structure and demand conditions and consequently the arrangements to guarantee profit-neutrality may well differ across industries.

Appendix

In the main body of the paper, we assume that the introduction of emissions permits with a market price of $t > 0$ per permit causes the marginal cost of each firm to increase by t. In particular, this means that firms' production possibilities do not allow for a reduction in marginal emissions. If emissions abatement is possible, the increase in marginal cost is potentially lower than the price of a permit. In this case, it seems reasonable to expect that the limiting level of profit-neutral grandfathering

then will also be lower than that obtained when abatement is ignored. We can confirm this intuition with a simple modification of our model.

Assume that the market price of a permit is $s > 0$. Given this price, firm i optimally chooses a technology that minimizes its marginal cost. Its new marginal cost with emissions trading is $c_i + \phi(s)$, where ϕ is a continuous and strictly increasing function with $0 < \phi(s) \leq s$ and $\phi(0) = 0$. Adapting equation (18), the profit neutral proportion of grandfathering for firm i, $\gamma_i(s)$, must satisfy

$$\Pi_i^*(\phi(s)) + \gamma_i(s)sq_i^* = \Pi_i^*(0). \tag{41}$$

The limiting level of profit neutral grandfathering is given by $\tilde{\gamma}_i \equiv \lim_{s \to 0} \gamma_i(s)$. Our assumptions on ϕ guarantee that it has an inverse ϕ^{-1} and that $\lim_{t \to 0} \phi^{-1}(t) = 0$. Denoting the increase in marginal cost by $t = \phi(s)$, it is clear that $\tilde{\gamma}_i = \lim_{t \to 0} \gamma_i(\phi^{-1}(t))$. Substituting $t = \phi(s)$ into (41) we obtain

$$\Pi_i^*(t) + \gamma_i(\phi^{-1}(t))\phi^{-1}(t)q_i^* = \Pi_i^*(0). \tag{42}$$

Suppose that $A \equiv \lim_{s \to 0} s/\phi(s)$ exists; A is the limiting ratio of the permit price to the increase in marginal cost it causes. Since $s \geq \phi(s)$, we have $A \geq 1$. Note also that $A = \lim_{t \to 0} \phi^{-1}(t)/t$. Taking the Taylor expansion of $\Pi_i^*(t)$ around $t = 0$, we now obtain

$$\tilde{\gamma}_i = \lim_{t \to 0} \gamma_i(\phi^{-1}(t)) = \frac{1}{A}\left[-\frac{1}{q_i^*}\frac{d\Pi_i^*}{dt}(0)\right]. \tag{43}$$

Comparing this expression with (19), we see that taking abatement into account changes the limiting level of profit-neutral grandfathering by a factor of $1/A \leq 1$. Whenever profit-neutral grandfathering is non-negative (i.e., $\tilde{\gamma}_i \geq 0$), it is therefore lower with abatement than without, thus confirming our intuition. (Note that for a monopolist we simply have $\tilde{\gamma}_M = 1/A$.) All the formulae for firm- and industry-level profit-neutral grandfathering obtained in the main body of the paper thus remain valid in a model with abatement, provided they are modified by a factor of $1/A$.

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