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CONTENTS

Contents continued on the outside back cover

Includes the Journal of Energy Finance and Development

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Energy Economics 34 (2012) 1143–1152

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The impact of power market structure on CO_2 cost pass-through to electricity prices under quantity competition – A theoretical approach

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ABSTRACT

We present a theoretical analysis of the impact of power market structure on the pass-through rate (PTR) of CO_2 emissions trading (ET) costs on electricity prices. Market structure refers in particular to the number of firms active in the market and the intensity of oligopolistic competition as measured by the conjectural variation, as well as to the functional form of the power demand and supply curves. In addition, we analyse briefly the impact of other power market-related factors on the PTR of carbon costs to electricity prices. These include in particular the impact of ET-induced changes in the merit order of power generation technologies and the impact of pursuing other market strategies besides maximising generator profit, such as maximising market shares or sales revenues of power companies. Each of these factors can have a significant impact on the rate of passing-through carbon costs to electricity prices.

1. Introduction

During the first phase of the EU Emissions Trading Scheme (ETS; 2005–2007), the impact of the scheme on electricity prices became a major political and academic issue (Sijm et al., 2005, 2008). In general, the impact of carbon trading on power prices depends first of all on the price of a CO_2 emission allowance and the carbon intensity of the power sector, especially of the generation technologies setting the electricity price at different levels of power demand. These two factors, i.e., allowance price times carbon intensity, determine the (marginal) carbon costs of power generation.

In addition, however, the impact of emissions trading on electricity prices depends also on the extent to which the CO_2 allowance costs of power generation are passed through to these prices. This so-called '*pass-through rate*' (PTR) is determined largely by the structure of the power market.[1] By structure, we refer in particular to the interaction of the following three elements:

1. The number of firms active in the market (N), indicating the level of *market concentration* or *market competitiveness*. Depending on this number of firms, the market structure is called either monopolistic ($N=1$), duopolistic ($N=2$), oligopolistic ($N=$small) or competitive ($N=$large).
2. The shape of the demand curve, notably whether the (inverse) demand curve is linear or iso-elastic.[2]

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[1] Another factor that might affect the pass-through rate of emissions trading costs to electricity prices is the method of allocating emission allowances, notably whether free allocations are regularly updated to incumbents and/or new entrants (Sijm et al., 2008).

[2] A linear demand function can be expressed as $Q=r-sP$, and an iso-elastic demand function as $Q=tP^{-\varepsilon}$ ($\varepsilon>0$), where Q is quantity, P is price, s is the slope of the linear demand curve, ε is the constant demand elasticity, while r and t are constants. On the other hand, the so-called *inverse* demand curves can be expressed as $P=w-vQ$ and $P=zQ^{-1/\varepsilon}$, respectively, where w and z are constants, while v ($=1/s$) is the slope of the inverse linear demand curve.

3. The shape of the supply (or marginal cost) curve, in particular whether the marginal costs are constant – i.e., a flat, horizontal line of perfectly elastic supply – or variable, i.e., sloping upward in either a linear or iso-elastic way.[3]

The main purpose of this paper is to analyse the impact of power market structure on the pass-through rate of CO_2 emissions trading costs to electricity prices from a theoretical point of view, including graphical illustrations and mathematical proofs. It builds on Section 3 – including the Appendix – of an article by the authors (Chen et al., 2008), making the following additional contributions:

- The results herein are more general in that we distinguish between cases of constant versus non-constant marginal costs and discuss the implications of this distinction for the derivation of the PTR under these cases.
- The implications of ETS-induced changes in the so-called *merit order* of power generation technologies for the PTR of carbon costs to electricity prices are analysed. These changes account for much of the ETS-caused decreases in emissions, but a general analysis of their implications for the PTR of CO_2 costs to power prices has not previously been presented.
- The effects of oligopolistic competition, considering a full range of conjectural variations, including special cases of Bertrand (perfect competition), Allaz–Vila competition, Nash–Cournot competition, and perfect collusion.
- We discuss briefly the implications of other, market-related factors for the pass-through of emissions trading costs to power prices. These factors include in particular the incidence of (i) market regulation, (ii) market imperfections, and (iii) other market strategies besides maximising profits, such as maximising market shares or sales revenues.

In the literature on the electricity sector, several approaches are generally used for modelling competition such as Cournot–Nash models, the 'supply function' approach and the 'auction' approach.[4] In this paper, we predominantly apply the so-called 'conjectural variations' approach, of which the Cournot–Nash model is a special case, to analyse the impact of different market structures on the pass-through of CO_2 emissions trading costs to electricity prices. The basic assumption of this approach is that quantity, i.e., output generated, is the decision variable of rival electricity producers. Whereas the Cournot model is based on the conjecture that rivals will not react to a production change by changing their output, the conjectural variation models are flexible with regard to the conjectures on the response of competitors. By parametrically changing the assumed supply response, different degrees of competitive intensity can be modelled, ranging from pure (Bertrand) competition (infinitely large positive quantity response by rivals to price increases), to oligopolistic Cournot competition (no response), and even collusion (which can be simulated by a negative quantity response to price increases). An intermediate case is Allaz-Vila competition which, under some assumptions, implies that a unit change in output by one firm is believed by that firm to stimulate a 0.5 change in output in the other direction by rival firms (Murphy and Smeers, 2010). Positively sloped conjectured supply functions (CSFs) also represent different degrees of competitive intensity between the Cournot and Bertrand cases (Day et al., 2002; Hansen, 2010).

Recently, Gulli et al. have used an alternative approach – the so-called 'auction' approach – to analyse the impact of market structures on CO_2 cost pass-through to electricity prices (see Bonacina and Gulli, 2007; Chernyavs'ka and Gulli, 2008; and Gulli, 2008). More specifically, by using a dominant firm facing a competitive fringe model, they analyse the short-run impact of CO_2 emissions trading on wholesale electricity spot markets where the pricing mechanism is a uniform, first-price auction. Their main finding is that the impact of carbon trading on power prices significantly depends on the structure of the electricity market. Under perfect competition, electricity prices fully internalise the carbon opportunity costs. Under market power, however, the extent to which these costs is passed through into electricity prices depends on several factors, including (i) the degree of market concentration, (ii) the plant mix operated by either the dominant firm or the competitive fringe, (iii) the carbon price, and (iv) the available capacity in the market, i.e., whether there is excess capacity or not.[5] Our results confirm (i) for the case of Cournot and, more generally, conjectural variation competition.

The remainder of the paper is structured as follows. Sections 2 through 5 discuss the PTR of carbon costs to electricity prices under different power market structures, in particular under different levels of market competitiveness (competitive, Cournot, and monopoly) and different combinations of shapes for power demand and supply (marginal cost) curves. Section 6 generalizes some of these results for oligopolies using conjectural variation competition, while Section 7 discusses two bounding cases of linear demand and supply under competitive markets. Subsequently, Section 8 analyses the implications of ETS-induced changes in the merit order of power generation technologies for the PTR of carbon costs to prices. Next, Section 9 discusses the implications of other, market-related factors for the pass-through of emissions trading costs to power prices, such as the effect of company strategies other than profit maximization. Finally, Section 10 summarizes our major findings.

2. Constant marginal costs and linear demand

Fig. 1 illustrates the pass-through of carbon costs for two polar cases, monopoly ($N=1$) versus full competition ($N=\infty$), both characterised by linear demand and a constant marginal cost curve (i.e., perfectly elastic supply). More generally, under these assumptions and Nash–Cournot competition, the extent to which carbon costs are passed through to power prices, i.e., the pass-through rate (PTR) is given by the formula:

$$\mathrm{PTR} = dP/dMC = N/(N+1) \qquad (1)$$

where dP/dMC is the rate of change of price with respect to marginal cost, and N is the number of firms active in the market (the proof is provided in Appendix A.6). Note that under these conditions the change in power price due to emissions trading depends only on the number of firms, but not on the elasticities of power demand or supply.[6]

The implications of this formula are somewhat counterintuitive: a monopoly ($N=1$) passes through only 50% of any increase in carbon costs. However, if a sector is more competitive (i.e., the number of firms increases) and competition is a la Cournot, the pass-through rate rises until it is close to 100%. Hence, under linear demand and

[3] Throughout this paper, we use the term 'supply curve' although in the context of oligopoly models, the more precise term would be 'marginal cost curve', since a unique supply function (as a function of price) does not generally exist for non-competitive markets. The inverse supply curve can be expressed as $MC=a+uQ$ if it is linear, or as $MC=kQ^b$ if it is iso-elastic, where MC is marginal costs, Q is quantity, a is a constant, u is the slope of the linear supply curve, k is a scaling factor, and $1/b$ (> 0) is the constant supply elasticity of the (non-inverse) iso-elastic supply curve.

[4] For a discussion of these and other approaches of modeling power market competition – including classifications of various proposed approaches – see, for instance, von der Fehr and Harbord (1998), Stoft (2002) or Hansen (2010).

[5] For more findings and further details, both theoretically and empirically, see Bonacina and Gulli (2007), Chernyavs'ka and Gulli (2008), and Gulli (2008).

[6] The formula is based on the assumption that the companies operating in the market are all affected by the cost change. In the case of the power sector affected by the EU ETS, this is a reasonable assumption as all major companies operating in EU power markets are covered by the scheme (although the cost change varies across these companies as they have different technologies and, hence, different emission rates). However, in the case of significant competition in the form of imports by external companies not covered by the scheme, the formula for the cost PTR becomes $X/(N+1)$, where X is the number of companies affected by the cost change and N the number of companies operating in the market (Oxera, 2004; Sijm et al., 2005; Smale et al., 2006).

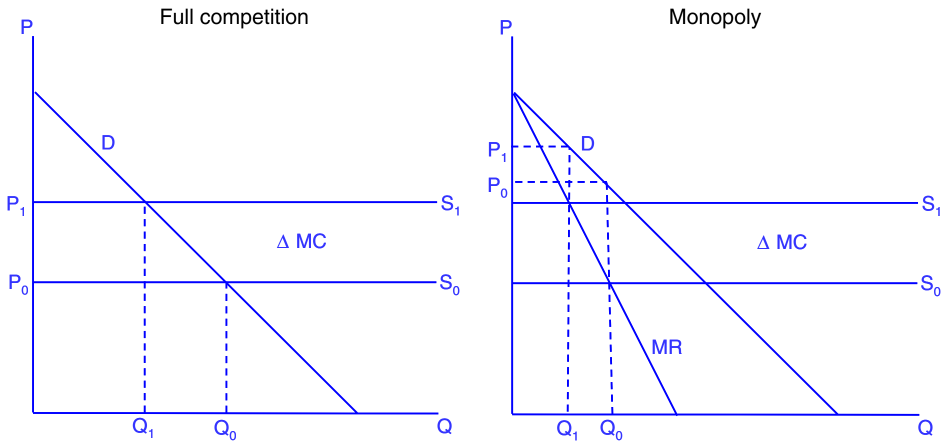

Fig. 1. Pass-through of carbon costs under full competition versus monopoly, facing constant marginal costs and linear demand. Note: S_0 is the supply (i.e., marginal cost) curve excluding carbon costs, while S_1 includes carbon costs. D is the demand curve, while MR is the marginal revenue curve.

constant marginal cost, the more competitive the industry, the greater the PTR. Or, in other words, the greater the degree of market concentration, the smaller the proportion of carbon costs passed through (see Chen et al., 2008; Oxera, 2004; Sijm et al., 2005; ten Kate and Niels, 2005; Varian, 2003).

This apparently counterintuitive result can be explained by the fact that as an industry becomes more competitive, prices become more aligned with marginal costs. In competitive markets, where producers are assumed to maximise their profits, this results in an equilibrium condition that marginal costs equal marginal revenues and also equal market prices (i.e., $MC = MR = P$). Hence, *ceteris paribus*, carbon costs will be fully transmitted into higher prices. On the other hand, in less competitive markets – where prices are higher than marginal cost due to a so-called 'mark-up' – less than 100% of the change in carbon costs is expected to transmit into power prices as (profit-maximising) producers in such markets still equate marginal costs and marginal revenues. That is, as these producers can influence market prices by changing their output, their marginal revenues – and, hence, their marginal costs – deviate from their output prices (see Fig. 1 where the slope of the *MR* curve of a monopolist is twice the magnitude of the slope of the demand curve *D*, resulting in a cost PTR of 50%).[7]

3. Constant marginal costs and iso-elastic demand

Fig. 2 shows the pass-through of carbon costs for the cases of monopoly versus perfect competition, both characterised by constant marginal costs of power production and an iso-elastic demand curve, i.e., demand is related to price with a constant elasticity ($-\varepsilon$, with $\varepsilon > 0$). For in-between situations with Cournot competition among N firms, the PTR of carbon costs to power prices is given by the formula:

$$\text{PTR} = dP/dMC = N\varepsilon/(N\varepsilon - 1) \quad (2)$$

where ε ($\varepsilon > 0$) is the price elasticity of demand, and $N\varepsilon$ is assumed > 1 (see Appendix A.3). The formula implies that under less competitive market structures the pass-through rate is determined by the demand elasticity, and that this rate is higher than 100%. For a monopolist facing constant marginal costs and an iso-elastic demand curve, the PTR formula corresponds to $\varepsilon/(\varepsilon - 1)$. Since a monopolist operates only where the marginal revenue is positive and, hence, the demand curve is elastic ($\varepsilon > 1$), this implies that under these market conditions changes in (power) prices are larger than changes in marginal (carbon) costs (Smale et al., 2006; Varian, 2003). For instance, in Fig. 2, ε is 2, implying that in the case of a monopoly the PTR is 200%. This rate, however, declines towards 100% when demand is more price-responsive and/or markets become more competitive. Thus, the PTR depends strongly on whether demand is assumed to be linear or iso-elastic.

4. Variable marginal costs and linear demand

In the previous sections, the marginal costs of power generation were assumed to be constant, regardless of the level of output production, and hence a change in marginal costs due to emissions trading is equal to the (change in) carbon costs concerned. However, if the marginal costs of power generation excluding carbon costs vary, and demand is price responsive, this equality between a change in marginal costs due to emissions trading and carbon costs no longer holds and, hence, the numerator of the PTR has to be clearly defined when discussing or estimating the pass-through of carbon costs.

This issue can be illustrated by Fig. 3 which presents the pass-through of carbon costs for the cases of monopoly versus perfect competition, both characterised by linear demand and a linear upward-sloping marginal cost curve.[8] Due to emissions trading, the supply or marginal cost curve increases from S_0 to S_1 by the amount c of carbon costs (assuming the same emission factor or carbon costs per unit production). Under perfect competition, prices are equal to marginal costs. Hence, if marginal costs increase due to emissions trading, prices in perfectly competitive markets increase accordingly. However, if demand is price responsive, quantity demanded decreases when prices increase. Less quantity demanded implies less supply, but also lower marginal costs as these costs are increasing with output level. Therefore, in the case of variable marginal costs and linear (price-responsive) demand, the increase in (net) marginal costs due to emissions trading is lower than the increase in carbon costs and, hence, the pass-through to power prices is also lower (as part of the increase in carbon costs is compensated by a decrease in the other components of marginal costs).[9]

In the left panel of Fig. 3, this difference between the increase in (net) marginal costs and carbon costs is illustrated for the case of

[7] In an oligopolistic or more competitive market structure, the slope of the *MR* curve is relatively less steep, i.e., it approaches the slope of the demand curve, implying that under linear demand, the PTR falls somewhere between the polar cases of monopoly (50%) and perfect competition (100%), and that it increases up to 100% if the degree of market concentration decreases.

[8] In Fig. 3, the sloping supply curve is linear. The same discussion would apply, however, if this curve would slope upwards in an iso-elastic or other non-linear manner.

[9] See also ten Kate and Niels (2005) who make a similar distinction between gross and net cost changes in the case of variable marginal costs and elastic demand.

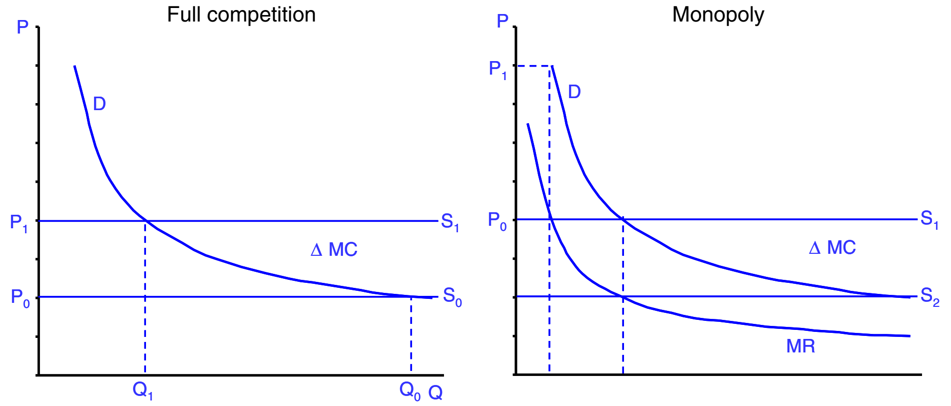

Fig. 2. Pass-through of carbon costs under full competition versus monopoly, facing constant marginal costs and iso-elastic demand.

perfect competition. The carbon cost of emissions trading equals c, the increase in (net) marginal costs due to emissions trading is designated by f, while the difference in increase between these carbon and marginal costs equals $g = c - f$. Under perfect competition and linear demand, the ETS-induced increase in competitive power prices ($P_0 - P_1$) is lower than the carbon costs.

It can be shown that in the case of variable marginal costs and linear demand, the pass-through of carbon cost to power prices is lower if demand is more price-responsive, or if supply is less elastic, i.e., less responsive to price or cost changes (see also Appendices A.4 and A.5). In the case of variable marginal costs, however, the value of the PTR depends upon the specific definition of this rate. If the PTR is defined as dP/dCC (where dCC is the change in carbon costs), it is, *ceteris paribus*, lower in the case of linear demand and increasing (rather than constant) marginal costs as power price increases are lower under increasing marginal costs. On the other hand, if the PTR is defined as dP/dMC – where $dMC = dCC + (dMC_o/dQ)(dQ/dCC)$ refers to the change in (net) marginal costs due to emissions trading, including changes in the non-carbon marginal cost MC_0 due to reduced demand – it is 100% in the case of perfect competition and linear demand, regardless of whether the marginal costs are variable or constant. As the term $(dMC_o/dQ)(dQ/dCC)$ is always negative, dP/dCC is always lower than dp/dMC.

Similarly, it can be shown that in the case of monopoly and linear demand, the PTR defined as dP/dCC is, *ceteris paribus*, always lower if the marginal costs are variable rather than constant, while the difference in PTR under variable versus constant marginal costs depends on the slopes of the demand and supply curves (compare, for instance the right panels of Figs. 3 and 1, respectively). However, if the PTR is defined as dP/dMC (as in the previous paragraph), it is 50% for a monopolist facing linear demand in the case of both variable and constant marginal costs, regardless of the slopes of the demand and supply curves, as the slope of the marginal revenues curve is always twice as steep as the slope of the demand curve.

More generally, in a market structure characterised by linear demand and Cournot competition among N firms, the PTR defined as dP/dCC is always lower if the marginal costs are variable (rather than constant), while the difference in PTR under variable versus constant marginal costs depends on the slopes of the demand and supply curves. On the other hand, if the PTR is defined as dP/dMC, it is equal to $N/(N+1)$ for all market structures characterised by linear demand, regardless of the slopes of the demand and supply curves, and regardless of whether the marginal costs are constant or variable. Moreover, these findings also hold regardless of whether the variable marginal costs are sloping upwards in a linear or non-linear way.

Turning to a case of variable and nonlinear supply, Appendix A.4 provides the derivation of the pass-through rate for market structures characterised by N firms facing linear demand and iso-elastic supply. Under these conditions, the PTR, defined as dP/dCC, is given by the formula:

$$PTR = \frac{dP}{dCC} = \frac{1}{1 + \frac{1}{N} + \varepsilon b} \tag{3}$$

where N is the number of Cournot firms active in the market, ε is absolute value of the demand elasticity at the competitive equilibrium before emissions trading (Q_0, P_0), and b is the (constant) elasticity of the supply function. In general, as supply elasticity increases, the PTR increases, if demand elasticity $\varepsilon < 1$.

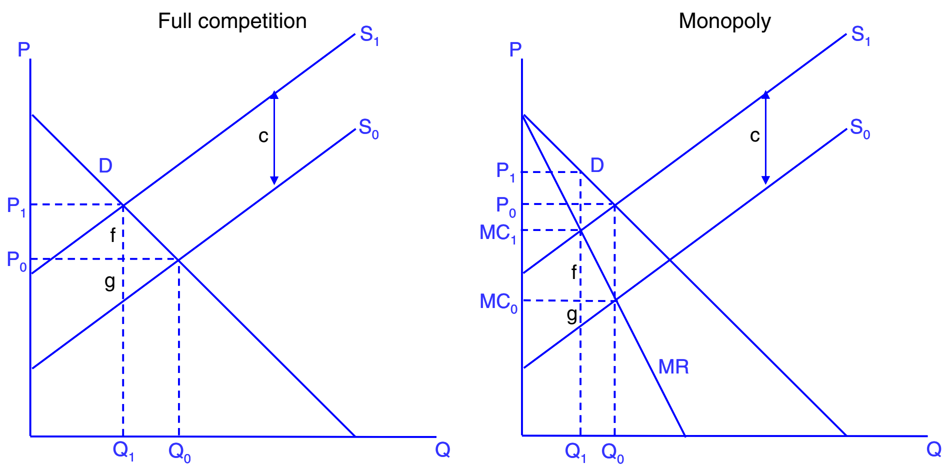

Fig. 3. Pass-through of carbon costs under full competition versus monopoly, facing variable marginal costs and linear demand.

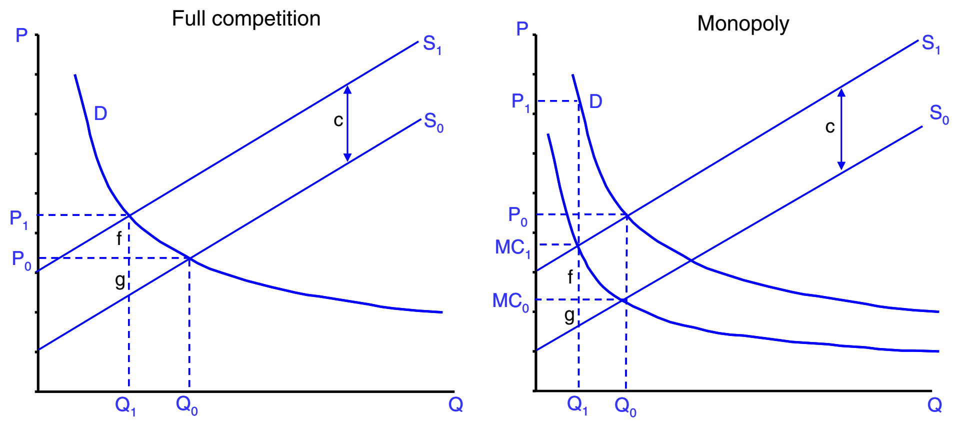

Fig. 4. Pass-through of carbon costs under full competition versus monopoly, facing variable marginal costs and iso-elastic demand.

5. Variable marginal costs and iso-elastic demand

Fig. 4 presents the pass-through of carbon costs for the two polar cases of monopoly versus perfect competition, both characterised by variable marginal costs and iso-elastic demand. As alluded to in the previous section, in a market structure characterised by iso-elastic demand and N active Cournot firms, the PTR defined as dP/dCC is always lower than dp/dMC if the marginal costs are upward sloping (rather than constant) as the increase in prices is lower in the case of variable marginal costs. This difference in PTR under variable versus constant marginal costs depends on the slopes of the demand and supply curves: it is larger – i.e., the PTR under variable marginal costs is lower – if demand is more elastic or supply is less elastic.

On the other hand, if the PTR is defined as dP/dMC, it is similar to the formula for the case of constant marginal costs and iso-elastic demand (i.e., $\text{PTR} = N\varepsilon/(N\varepsilon - 1)$), where ε is the constant demand elasticity ($\varepsilon > 0$). This formula applies to all market structures characterised by linear demand, regardless of the slopes of the demand and supply curves, as well as whether the marginal costs are constant or variable. Moreover, these findings also hold regardless of whether the variable marginal costs are sloping upwards in a linear or non-linear way.

Appendix A.1 presents the derivation of the PTR for market structures characterised by N Cournot firms facing iso-elastic demand and iso-elastic supply. Under these conditions, the PTR formula, defined as dP/dCC, is given by the formula:

$$PTR = \frac{dP}{dCC} = \frac{1}{\left(1 - \frac{1}{N\varepsilon}\right)(1 + b\varepsilon)} \tag{4}$$

with all notation having been defined earlier. For example, in the cases of perfect competition ($N = \infty$) and monopoly, with $\varepsilon = 1.5$ and $b = 1.2$, the PTR is 36% under full competition and 107% under monopoly. Note that under these conditions the PTR is higher if (i) demand is less price responsive, (ii) supply is more elastic, or (iii) markets are less competitive.[10]

6. More general oligopoly models: conjectural variations

Cournot competition is the most frequently used framework to represent oligopolistic competition in electricity models (see, e.g., the surveys in Day et al. (2002) and Ventosa et al. (2005)). However, other frameworks have also been used. One is the conjectural variations model (Fudenberg and Tirole, 1989) in which each producer f assumes that rivals will adjust their output Q_{-f} in response to firm f changing its Q_f. Quantity is still the strategic variable. Equivalent variants of this approach that have been applied to power markets include the conjectured price response (Centeno et al., 2007) and conjectured supply response models (Day et al., 2002). Cournot competition results from one particular parameterization of the conjectural variation model.

Another approach is supply function models, in which the strategic variable is each firm's bid function, showing the amount that each firm is willing to supply at all possible prices (e.g., Green and Newbery, 1992). Under many conditions, the supply function model's solution is not unique and difficult to compute, but its upper bound is known to be the Cournot model result.

The models of this paper are readily generalized to the conjectural variations case, resulting in particularly simple relationships when demand is assumed to be of the iso-elastic form. These are derived in Appendices A.1 and A.2, and the results are discussed below.

In particular, the conjectural variation model generalizes the Cournot model by assuming that each firm believes that marginal revenue takes the following form:

$$\begin{aligned} MR &= \frac{d\left(PQ_f\right)}{dQ_f} = P + \frac{dP}{dQ_f}Q_f = P + \frac{dP}{dQ}\frac{d\left(Q_f + Q_{-f}\right)}{dQ_f}Q_f \\ &= P + \frac{dP}{dQ}(1+\theta)Q_f \end{aligned} \tag{5}$$

The conjectural variation parameter θ describes how each firm f anticipates that the rest of the market's output will respond to a change in firm f's output, dQ_{-f}/dQ_f. The larger this parameter is, the less competitive the market outcome. We assume that this parameter is the same for all f, although more general models are possible. Some particular cases of this model include Bertrand/perfect competition ($\theta = -1$), Cournot competition ($\theta = 0$), and perfect collusion ($\theta = \text{N} - 1$, equivalent to each of the other firms matching f's quantity change). The idea of conjectural variations is sometimes criticized because the parameter θ can be viewed as the reduced form result of a more complicated dynamic game, which can change if the market structure changes. As an example, two-stage Allaz and Vila (1993) competition represents a closed-loop game in which firms first make forward quantity commitments (contracts), anticipating the effects on the outcomes in the Cournot second-stage spot market game. Under certain simplifying assumptions, this reduces to a conjectural variations game with $\theta = -1/2$, with price and quantity outcomes between the competition and Cournot results (Murphy and Smeers, 2010).

Appendix A generalizes the models discussed in Sections 2–6 above to the conjectural variation case. For the iso-elastic demand

[10] More specifically, under monopoly ($\varepsilon > 1$), the PTR is $\varepsilon/(\varepsilon - 1)$ times higher than under full competition. In other cases when $\varepsilon \leq 1$, the PTR under monopoly is not well defined. For example, the PTR is equal to infinity when $\varepsilon = 1$. In Appendix A, we limit most of the discussion to these cases where $1 - 1/(\text{N}\varepsilon) > 0$. See also Varian (2003).

case, the results are the same, except that price elasticity is modified – basically, the effect of demand elasticity is magnified by the factor $1/(1+\theta)$. With iso-elastic demand and supply, we get (Appendix A.1):

$$PTR = \frac{1}{\left(1 - \frac{1+\theta}{N\varepsilon}\right)(1+b\varepsilon)} \tag{6}$$

When iso-elastic demand is instead paired with linear supply case, we obtain instead (Appendix A.2):

$$PTR = \frac{1}{1 - \frac{1+\theta}{N\varepsilon} + uP^{-\varepsilon-1}} \tag{7}$$

where u is the slope of the supply curve. Generalizations for the linear demand case with either iso-elastic supply (Appendix A.4) or linear supply (Appendix A.5) give, respectively:

$$PTR = \frac{1}{1 + \varepsilon b + (1+\theta)/N} \tag{8}$$

$$PTR = \frac{1}{1 + u/v + (1+\theta)/N} \tag{9}$$

where v is the absolute value of the slope of the linear demand curve.

The effect of the conjectural variation parameter is as follows. If demand is iso-elastic, then as the market becomes less competitive (increases from −1 (perfectly competitive) to 0 (Cournot) to positive (some degree of collusion/quantity matching)), the PTR increases. This is similar to the effect of shrinking N, which also decreases the competitiveness of the market. But in the case of linear demand, the effect of decreasing competitiveness (either by increasing θ or decreasing N) has the opposite effect: PTR shrinks.

7. Two bounding cases of linear demand and supply under competition

Fig. 5 presents two specific cases of carbon costs pass-through under competitive markets facing linear demand, where the left and right panels show the case of perfectly inelastic and perfectly elastic demand, respectively. Note that the right panel of Fig. 5 represents not only the case of perfectly elastic demand but also other situations in which output prices are fixed, e.g., stringent price regulation or outside competition setting the price.

In the case of competitive markets and perfectly inelastic demand, the increase in power prices due to emissions trading is equivalent to the increase in marginal generation costs, i.e., the opportunity costs of carbon allowances needed to cover the CO_2 emissions of the production of an additional unit of power. Hence, the PTR under these conditions is 100%, independent of allocation method or functional form of the supply curve, i.e., no matter whether the marginal generation costs, excluding carbon costs, are constant or variable.

Moreover, since under perfectly inelastic demand, the level of demand and supply does not change while the carbon costs are fully passed through to electricity prices, the producer surplus of power generators does not change, assuming that producers must buy all their allowances at an auction. As indicated by the left panel of Fig. 5, before emissions trading the producer surplus is equal to the triangle *rst*. After emissions trading, in the case of auctioning, the producer surplus amounts to the triangle *tvw*. The areas *tvw* and *rst* are equal, and there is no change in producer surplus. In the case of perfect free allocation and perfectly inelastic demand, however, the new producer surplus amounts to *rsvw* i.e., it increases exactly by the full market value – or economic rent – of the free allowances represented by the quadrangle *rsvu*.

On the other hand, in the case of perfectly elastic demand, the pass-through rate is by definition 0 (as prices are fixed), regardless of the shape of the supply curve (provided that the price intercept of the upward sloping supply curve is less than P_0 so that supply and demand intersect at a positive quantity; see right panel of Fig. 5). However, both the supply response and the producer surplus depend on the slope of the supply curve and the method of allocation. In the case of auctioning and grandfathering-based allocation, profit-maximising producers adjust their output level until marginal revenues (i.e., fixed prices) are equal to marginal costs, considering the opportunity costs of emissions trading. In the right panel of Fig. 5, this situation is indicated by a reduction in output from Q_0 before emissions trading to Q_1 after emissions trading. As a result, the producer surplus decreases from *rst* before emissions trading to *rxvt* in the case of grandfathering allocation and even to *zvt* in the case of auctioning.

Therefore, even if the pass-through of carbon cost is zero (for instance, due to perfectly elastic demand, price regulation or outside competition), producers still consider the full opportunity costs of emissions trading in their output decisions when maximising profit by adjusting their production until price equals marginal cost, including the opportunity costs of CO_2 allowances. Compared to the situation before emissions trading, this yields a reduction of output and producer surplus in the case of auctioning. In the case of grandfathering allocation, the reduction in output is similar to the case of auctioning while –

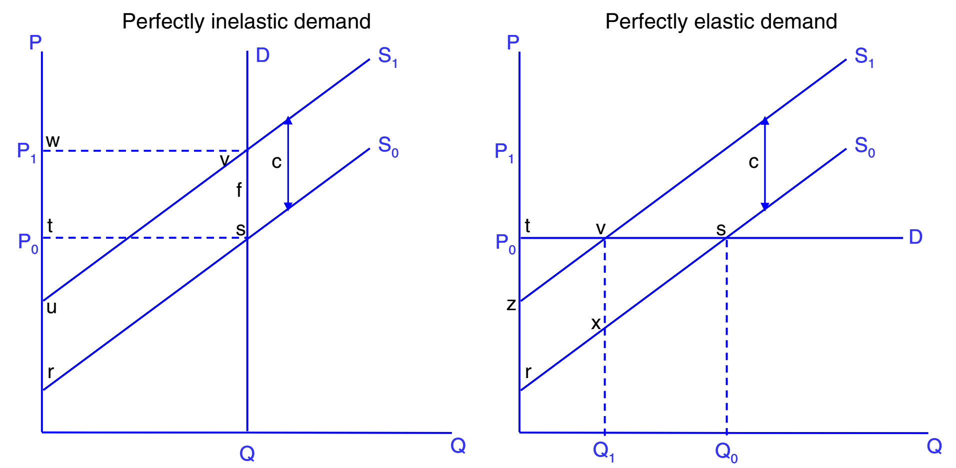

Fig. 5. Pass-through of carbon costs under full competition facing perfectly inelastic versus perfectly elastic demand.

depending on the slope of the supply curve and the share of allowances allocated for free – the reduction in producer surplus may be either partially, fully or more than fully compensated by the lump-sum subsidy of the free allowances.[11]

However, in the case of partial grandfathering allocations – such as updating or benchmarking based on actual output – the *net* opportunity costs of emissions trading are lower compared to auctioning (due to the implicit output subsidy from updating the allocation). Hence, the reductions in output and producer surplus are also lower. In the right panel of Fig. 5, this case can be illustrated by shifting the supply curve S_1 downwards to S_0.[12]

8. Changes in the merit order

In the previous sections, the analysis is based upon graphic approaches using continuous and differentiable curves. However, for power systems with multiple generators having fixed capacities and differing marginal costs, these supply curves are better represented by increasing, step-wise functions where each step represents a specific technology, with the width of each step showing the capacity of the technology and the height indicating its marginal cost. In the short term, these costs are largely determined by the fuel costs, including the fuel efficiencies and – in the case of emissions trading – the carbon costs of the technologies concerned. In the power sector, this ranking of the cheapest to the more expensive technologies is called the *merit order*.

Moreover, in the previous sections, the emissions rate – and, hence, the carbon costs – per unit production was assumed to be similar for each technology or level of output. In practice, however, these costs generally vary significantly among plants with different generation technologies and fuel efficiencies. In addition, these costs may change substantially over time depending on the evolution of the actual carbon price. As a result, the merit order of power generation technologies may shift over time, depending on the dynamics and interaction of the actual carbon and fuel costs of the plants. Assuming that electricity prices are set by the marginal generation technology, this implies that the pass-through of carbon costs – and, hence, the impact of these costs on electricity prices – can change if the merit order of power production changes.

The impact of a change in the merit order on carbon cost pass-through to power prices is illustrated in Fig. 6 for the case of a competitive market facing perfectly inelastic demand.[13]

The figure presents a simple merit order for only two technologies with different characteristics. Technology A is characterised by low marginal (fuel) costs before emissions trading and a high emission factor, while technology B has opposite characteristics, i.e., high fuel costs and a low emission factor. Hence, before emissions trading, technology A is the cheapest technology (in terms of variable costs), setting the price during the off-peak period ($P_{offpeak0}$), while the more expensive technology B determines the price during the peak period (P_{peak0}).

After emissions trading, the merit order and the carbon cost pass-through depend on the carbon price. As long as the carbon price is relatively low, the order does not change (left side of Fig. 6). Under these conditions, as discussed in the previous section, the PTR is 100%, resulting in power prices P_{peak1} and $P_{off\text{-}peak1}$ during the peak and off-peak periods, respectively.

If the carbon price becomes sufficiently high, however, the merit order of generation technologies changes, as illustrated in the right panel of Fig. 6. This implies that the magnitude of the PTR depends on its definition. On the one hand, the (marginal) PTR can be defined as the impact of emissions trading on the power price, *dP*, divided by the difference between the marginal costs of the price-setting production technology after and before emissions trading, *dMC*, i.e., PTR = *dP*/*dMC*.[14] Defined this way, the PTR is and remains 100% under the conditions of competitive markets facing perfectly inelastic demand (as in Section 7 above).[15]

Alternatively, the (marginal) PTR can be defined as the impact of emissions trading on the power price, *dP*, divided by the carbon costs of the marginal production unit after emissions trading, *dCC*, i.e., PTR = *dP*/*dCC*.[16] Defined this way, the PTR can deviate substantially from 100% if the merit order changes due to emissions trading, even under competitive markets with perfectly inelastic demand and perfectly elastic supply, depending on the carbon intensity of the marginal production unit after emissions trading.

For instance, as illustrated by Fig. 6, the off-peak power price before emissions trading ($P_{off\text{-}peak0}$) is set by technology A at 2 €/MWh, while after emissions trading – when carbon prices are relatively high – the off-peak power price ($P_{off\text{-}peak2}$) is determined by technology B at 9 €/MWh. Hence, the increase in power prices due to emissions trading, *dP*, is 7 €/MWh. As the carbon costs (*dCC*) of technology B are 4 €/MWh, this results in a PTR – defined as *dP*/*dCC* – of 175%. Similarly, under emissions trading with relatively high carbon prices, the peak power price increases from P_{peak0} to P_{peak2} ($dP = 10 - 5 = 5$ €/MWh), while carbon costs of the marginal technology setting the peak price after emissions trading (i.e., A) amounts to 8 €/MWh. Hence, in this case, the PTR – defined as *dP*/*dCC* – is 5/8 or 63%. Therefore, in the case of a change in the generation merit order due to emissions trading, the resulting pass-through may vary significantly from 100% even under competitive markets and perfectly elastic demand, depending on the definition of the pass-through rate

[11] The perfect ('ideal' or 'textbook') type of grandfathering allocation is characterized by:

1) A one-off initial allocation of free allowances to existing installations (incumbents), usually for a long time frame, based on (i) a fixed baseline or historic reference period of actual emissions at the installation level ('grandfathering'), or (ii) a standard emission factor multiplied by an ex-ante fixed quantity or activity level, for instance a certain input, output or capacity level ('benchmarking' with an absolute or fixed cap).
2) When plants are retired, they retain their allowances.
3) New entrants do not receive allowances for free, but have to buy them on the market.

The implications of auctioning versus (perfect/imperfect) grandfathering allocation for electricity prices and power generators' profits are discussed in Sijm et al. (2008), while implications for long run generation mix are explored in Zhao et al. (2010).

[12] Moreover, it can be shown in the right panel of Fig. 5 that if sufficient allowances are grandfathered to new entrants to cover their production costs, investments in additional capacity will take place when *P* covers at least the variable and fixed costs (excluding carbon costs), while in the case of auctioning or perfect free allocation these investments are only implemented if *P* covers at least all long run costs (including carbon costs).

[13] Based on the findings of the previous sections, a similar reasoning can be followed for other, less competitive markets and, other, more elastic demand curves in order to illustrate the impact of a change in the merit order on carbon cost pass-through to power prices for these cases.

[14] This way of defining the (marginal) PTR seems to be more appealing from a theoretical point of view as long as one intends to consider the overall change in marginal costs due to emissions trading and its impact on power prices (Bonacina and Gulli, 2007; Sijm et al., 2005).

[15] For example, before emissions trading, the power price during the peak period (P_{peak0}) equals the marginal cost of technology A (excluding carbon costs), while after emissions trading this price (P_{peak2}) is set by the marginal cost of technology B (including carbon costs). The difference between the marginal costs after and before emissions trading, *dMC*, is just equal to the difference in power price, *dP*, i.e., the PTR is 100%.

[16] This way of defining the (marginal) PTR follows the more conventional notion of carbon cost pass-through to power prices and seems to be more appropriate from an empirical point of view as, in practice, it may be rather complicated to determine empirically the difference between the (total) marginal costs of the marginal production unit after and before emissions trading (or after and before a certain change in carbon prices), in particular if the merit order of the generation technologies changes due to emissions trading or a change in carbon prices.

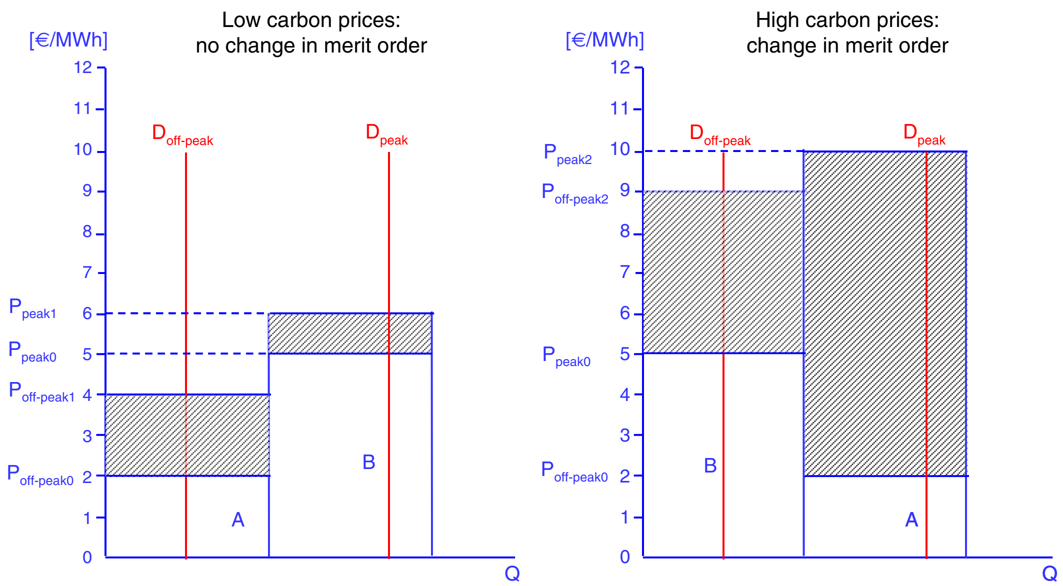

Fig. 6. Pass-through of carbon costs in a competitive market facing perfectly inelastic demand during peak and off-peak hours, including a change in the merit order. Note: Technology A is characterised by low marginal (fuel) costs before emissions trading and a high emission factor, while technology B has opposite characteristics, i.e., high marginal costs before emissions trading and a low emissions factor. The shaded areas represent carbon costs per technology, depending on their emission factor and the actual carbon price.

and the carbon intensity of the marginal production technology after emissions trading.[17]

9. Other market factors affecting carbon cost pass-through

In addition to the factors outlined in the previous sections, there could be other, market-related factors that influence the pass-through of emission costs to power prices. These include strategy, regulation, and market imperfections, each of which are briefly discussed below.

9.1. Market strategy

The above results are based on the assumption that power companies pursue profit maximisation. This assumption may be largely valid for analysing short-term operations in the wholesale power market, or it may adequately reflect the objectives of private company shareholders in the short or medium run. In practice, however, there may be trade-offs between maximising profits and other company objectives in the short or long run. Further, the objectives of firm's shareholders may diverge to some extent from the objectives of firm's managers, or company objectives may differ between private versus public utilities.

Moreover, it may not be possible for managers to determine the profit-maximising strategy in bulk or retail power markets, due to a lack of information on the exact shape of the demand curve in the short, medium and long-term for different categories of electricity end-users (including power-intensive industries, small and medium firms, public institutions and private households characterised by different income levels or other factors determining consumption patterns). Therefore, in practice, companies' managers may pursue other short- or medium-term strategies besides profit maximisation (such as maximising market shares or sales revenues) or operate by simple rules of thumb, particularly for retail market transactions. An example of such a rule is cost-plus or mark-up pricing in which a mark-up is added to the average unit cost of production in order to meet a satisfying level of producer surplus (Smale et al., 2006).

[17] The effects of merit order changes in an actual power system are quantified in Chen et al. (2008).

Vivid Economics (2007) has analysed the implications of different firm strategies for cost pass-through to output prices.[18] In particular, it considers cost pass-through under so-called 'strategic delegation', with objectives such as maximising either sales revenue (PQ_i for firm i) or market share (Q_i/Q_{tot}; see also Ritz, 2007).[19] A remarkable feature of the cost PTR under these alternative objectives is that it has a lower bound, i.e., regardless of the shape of the demand curve, the PTR is always higher than 50% in cases with sales revenue objectives and higher than 33% in cases with market share objectives.

According to Vivid Economics (2007), the intuition for these results is that firms under strategic delegation act as if they face more rivals than they actually do, thus pushing cost pass-through towards 100%, the level under perfect competition. It is important to note, however, that the difference is not due to managers' treatment of opportunity costs under free allocation (rather than actual costs from buying allowances). Although it is possible that firms under strategic delegation are more likely to treat opportunity costs of freely allocated allowances as 'soft costs' that they absorb to undercut their competitors, the authors of Vivid Economics (2007) are not aware of any evidence that this is the case. Hence, they retain the assumption that all firms exhibit maximising behaviour regardless of whether carbon costs are actual or opportunity costs.

9.2. Market regulation

The extent to which carbon costs are passed-through to power prices may be affected by the presence of market regulation, including regulation of wholesale or retail power prices. Although firms

[18] Vivid Economics (2007) used this analysis for a study to estimate ticket price changes when, as proposed, the aviation sector is introduced in the EU ETS, but it can be applied also to other sectors such as the power industry. It is based on work by Hepburn et al. (2006) and Ritz (2007).

[19] Strategic delegation refers to the case where a firm's shareholders delegate decision-making to managers whose compensation is based on, for instance, a combination of firm profits and sales revenue (or a combination of firm profits and market share). As a result, these managers do not solely maximise profits but trade off between maximising profits and sales revenues (or between maximising profits and market shares). Intuitively, placing some weight on sales revenue (market share) leads to a manager acting as if his/her firm's (marginal) costs are lower than they actually are, and thus favouring a relatively higher output level. In acting as if marginal costs are lower, it results in setting lower prices, selling higher volumes and achieving a higher market share (Vivid Economics, 2007).

exhibit maximising behaviour regardless of whether carbon costs are actual or opportunity costs, regulators may treat the pass-through of these costs differently depending on whether they are opportunity costs (in the case of free allocations) or actual cash outlays (in the case of auctioning or market purchases of allowances).

If regulators forbid and can indeed prevent any cost pass-through on retail power markets in the case of free allocations, the PTR is by definition zero. However, as discussed in Section 7 even if the pass-through of carbon costs is zero, optimising power producers still include the opportunity costs of carbon allowances in their price bidding and other operational decisions, resulting in less output, depending on the specifics of the free allocations and the slope of their marginal cost curves. Moreover, less output implies more scarcity, leading to higher power prices in the spot market (or serious risks of other ways of demand rationing). In addition, price regulation in some Member States of an ETS holds prices to below marginal cost, leading to more (price-responsive) power consumption in these countries and, hence, to more emissions and an upward pressure on carbon prices, resulting in higher power prices in other Member States. Hence, as a policy option to avoid the pass-through of the opportunity costs of carbon allowances, the regulation of power prices may be ineffective or have negative side effects.

While the incidence of power price regulation is decreasing or even absent in a growing number of power markets in the EU, the pass-through of the opportunity costs of grandfathering allowances may still be affected by so-called 'regulatory threats', including the threat of reinstating price controls, of taxing windfall profits resulting from the pass-through of carbon opportunity costs, or of other less favourable energy policies. These threats may be implicit or explicit. As a result, power companies may be reluctant to pass through such costs. This applies particularly for companies in countries characterised by either a monopoly, a dominant firm or a small oligopoly of power producers, as such companies run the risk of being accused of 'abusing their market position'. However, predicting the extent to which power companies could pass through the cost of allowances requires assumptions about how regulators would react, assumptions that would be highly arbitrary.

9.3. Market imperfections other than market power

A final category of factors affecting carbon cost pass-through refers to the incidence of market imperfections other than the existence of market power. While we addressed the impact of imperfect competition on carbon cost pass-through above, we have assumed other market conditions to be more or less perfect, including full and free information of energy and carbon market performance, no risks or uncertainties, low adjustment costs, insignificant time lags, etc. In practice, however, power production, trading, pricing and other generators' decisions are affected by all kinds of market imperfections, including the incidence of (i) risks, uncertainties or lack of information and (ii) other production constraints, such as the presence of 'must-run' constraints on operation, high costs of start-up or shut-down costs, or a lack of liquid and flexible fuel (gas) markets, resulting in a lack of production flexibility and high costs of short-term production adjustments. Although it may be difficult to estimate the size (or even, occasionally, the direction) of the impact of these market imperfections on the carbon cost PTR, it is obvious that they could affect this rate.

10. Summary and conclusion

A major factor affecting the impact of emissions trading on electricity prices is the structure of the power market. This structure refers primarily to the interaction of three elements:

- The number of firms active in the market (N), indicating the level of market competitiveness or market concentration.
- The shape of the demand curve, notably whether this curve is linear or iso-elastic.
- The shape of the supply curve, particularly whether the marginal costs before emissions trading are constant – i.e., a flat, horizontal line – or variable, i.e., sloping upward in either a linear or iso-elastic way.

Table 1 gives an overview of the cost pass-through formulas for different market structures, assuming profit maximisation among Cournot producers. The table makes a distinction between two definitions of the pass-through rate (PTR), i.e., $PTR_1 = dP/dMC$ (where dP is the change in price and dMC the total change in marginal costs, including carbon costs) and $PTR_2 = dP/dCC$ (where dCC refers to the change in carbon costs only). If the supply function is perfectly elastic (i.e., marginal costs are constant) PTR_1 is similar to PTR_2. However, if the marginal costs are variable (i.e., sloping upwards linearly or iso-elastically), the two rates are no longer similar, with $PTR_1 > PTR_2$.

Based on Table 1, our findings regarding the impact of market structure on cost pass-through include:

- If demand is perfectly elastic, i.e., the price is given, then the PTR is zero. This outcome applies also to cases of outside competition – when prices are set by competitors outside the ETS – or price regulation, in particular when the cost pass-through of freely allocated allowances is not accepted.
- If demand is perfectly inelastic, i.e., demand is fixed and unresponsive to price changes, then the PTR is always 100% (in the case of competitive markets), regardless of the shape of the supply function, assuming no change in the merit order of generating plants.
- If supply is perfectly elastic, i.e., marginal costs are constant, the PTR depends on the shape of the demand curve and the number of firms active in the market (N). If demand is linear, the PTR is significantly

Table 1
Overview of cost pass-through formulas for different market structures, assuming profit maximisation among Cournot producers, and different definitions of the pass-through rate.

Demand function					
		Perfectly elastic	Perfectly inelastic	Linear	Iso-elastic
Definition of PTR/Supply function	First definition: $PTR_1 = \frac{dP}{dMC}$				
	All supply functions	0	1.0	$\frac{N}{N+1}$	$\frac{N\varepsilon}{N\varepsilon-1}$
	Second definition: $PTR_2 = \frac{dP}{dCC}$				
	Perfectly elastic	N.A.	1.0	$\frac{N}{N+1}$	$\frac{N\varepsilon}{N\varepsilon-1}$
	Linear	0	1.0	$\frac{1}{1+1/N+u/v}$	$\frac{1}{\left(1-\frac{1}{N\varepsilon}\right)+uP^{-\varepsilon-1}}$
	Iso-elastic	0	1.0	$\frac{1}{1+1/N+\varepsilon b}$	$\frac{1}{\left(1-\frac{1}{N\varepsilon}\right)(1+b\varepsilon)}$

Note: PTR is pass-through rate, dP is the change in price, dMC is the change in marginal costs, dCC is the change in carbon costs, N is the number of firms active in the market, $1/b$ is the price elasticity of supply ($b>0$), $-\varepsilon$ is the price elasticity of demand ($\varepsilon>0$), $v>0$ is the absolute value of the slope of the inverse, linear demand function, and $u>0$ is the slope of the inverse, linear supply function.

lower than 100% when N is small (for instance, it is 50% in the case of monopoly, i.e., $N=1$) but increases when markets become more competitive (it approaches 100% in the case of perfect competition, when $N=\infty$). If demand is iso-elastic, however, the PTR may be substantially higher than 100% when N is small (and demand is less elastic), but decreases towards 100% when markets become more competitive (or demand becomes more price-responsive). Therefore, if supply is perfectly elastic, the PTR always tends towards 100% when the number of firms becomes large and, hence, markets approach the case of full competition, regardless of the shape of the demand function.
- If supply is not perfectly elastic, i.e., marginal costs are variable, the PTR should be carefully defined, distinguishing between $PTR_1 = dP/dMC$ and $PTR_2 = dP/dCC$. When using the first definition, the pass-through rate (i.e., PTR_1) under variable marginal costs is similar to the PTR under constant marginal costs (as discussed above). However, when applying the second definition, the pass-through rate (i.e., PTR_2) under variable marginal costs is always lower than the PTR under constant marginal costs. Moreover, the PTR_2 under variable costs decreases when supply becomes less elastic or demand becomes more elastic.

The distinction between the two definitions of the pass-through rate is also relevant in the case of ETS-induced changes in the merit order of the power supply curve (i.e., changes in the ranking of generation technologies according to their marginal costs, including carbon costs). For instance, if the PTR is defined as dP/dMC (where dMC refers to the difference between the marginal costs of the price-setting production technology after and before emissions trading), its value is and remains 100% in competitive markets, regardless of whether the merit order changes or not. However, if the PTR is defined as dP/dCC (where dCC refers to the carbon costs of the production unit that becomes marginal after emissions trading), the PTR can deviate substantially from 100% (either >1.0, or <1.0) if the merit order changes, even under competitive markets with perfectly inelastic demand and perfectly elastic supply, depending on the carbon intensity of the marginal generation technology after emissions trading.

In addition, there are additional factors related to the power market that influence the pass-through of carbon costs to power prices, including:

- *Market strategy.* Besides profit maximisation (as assumed above), firms may pursue other objectives such as maximising market shares or sales revenues. These differences in market strategy affect the PTR, regardless of whether carbon costs are actual cash outlays or opportunity costs.
- *Market regulation.* However, in the case of market regulation (or 'regulatory threat') public authorities (or firms) may treat the actual, real costs of purchased allowances differently than the opportunity costs of freely obtained allowances, resulting in different levels of cost pass-through to power prices.
- *Market imperfections.* The pass-through of carbon costs to power prices may be affected by the incidence of market imperfections such as (i) risks, uncertainties or lack of information, and (ii) other production constraints, including 'must run' limits, highly non-convex operating cost functions (such as high start-up costs), lack of flexible fuel markets, and time lags.

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