Modelling the short-run impact of 'carbon trading' on the electricity sector with endogenous market power

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Abstract. *Why do power prices seem to be correlated with the carbon price in some markets and in others not? Why do power firms pass-through into power prices in some cases more and in others less than the carbon opportunity cost? What is the relationship between the pass-through and the structure of the power market? What is the influence of the technology mix and of the available generation capacity? How can market power in power market affect the pass-.through and vice versa? Can "carbon trading" determine a rise rather than a decline in carbon emissions of the power system, at least in the short and medium run? In this paper we attempt to anwer these questions by modelling the impact of "carbon trading" on the electricity sector in the short and medium runs. The analysis shows that under imperfect competition the extent to which the carbon cost is passed through into power prices depends on several structural factors of the power market: i) the degree of market concentration; ii) the technology mix; iii) the available capacity (whther there is excess capacity or not); iv) the allowance prices and v) the level of power demand (peak vs. off-peak hours). Depending on these factors, the marginal pass-through rate can be either above or below 1, i.e. the increase in price under market power can be either higher or lower than that under perfect competition. Also, under certain conditions, the impact on power prices can be even slightly negative (at least, in principle), i.e. the ETS can involve a decrease rather than an increase in prices. Market power, therefore, would determine a significant deviation from the "full pass-through" rule but we can not know the sign of this deviation, a priori, i.e. without before taking carefully into account the structural features of the power market. Furthermore, the paper highlights that the ETS causes a change in the degree of market power in the sense that, after the introduction of the trading scheme, the time (the number of hours in the year) over which power firms prefer to bid the maximum price (e.g. the price cap) increases or decreases depending (again) on the structural factors of the power market. This means not only that the ETS can amplify or lessen the* *existing distortions in the output market but also that it might determine a rise rather than a decrease in carbon emissions, namely when the change in market power significantly expands the production share of the most polluting plants. However, this does not necessarily imply that perfect competition is preferable to market power from the environmental point of view but simply that under imperfect competition, and provided that certain conditions are satisfied, it might be more difficult to reach the environmental targets.*

1. Introduction

This paper studies the impact of "carbon emissions trading" (trading of CO_2 emissions allowances) on the electricity sector, focusing on the European Emissions Trading Scheme (EU ETS). Started in 2005, the EU ETS [1] covers several sectors of which power generation is the largest one. Therefore, on the one hand, the performance of the trading scheme largely depends on the efficacy in inducing power industry to reduce CO_2 emissions in a significant way in the short and long run. On the other hand, it might have a considerable impact on the consumers' surplus and firms' profits and competitiveness. Either the performance of the EU ETS or its impact on social welfare depends on how and to what extent the CO_2 price is passed through into power prices.

This study focuses on this latter issue, attempting to provide a better understanding of how a CO_2 price could impact on electricity pricing[2] and carbon emissions.

The economic literature on emissions trading is enough wide and covers several fields[3]. However existing studies have been mainly concerned with design issues rather than with the impact on correlated (product) markets. Concerning the electricity sector, only recently specific research effort has been made to study the effects of the ETS on product prices but studies generally assume purely competitive frameworks which are far from the reality of electricity markets. These, in fact, are more or less concentrated markets where one or more firms are able to exercise market power. Thus the need of extending

[1] For a detailed decription of the EU ETS and its implications, see Chernyavs'ka (2008).

[2] Indeed, this is a very recent question. Currently, in Europe there is a very controversial debate on whether (and up to which extent) the rise in power prices is due to the pass-through of the carbon opportunity cost.

[3] Main contributions deal with (1) comparative studies of alternative policy tools (Bohm and Russell 1985), (2) analysis of static and dynamic efficiency, (3) studies of the effects of uncertainty and risk (Montero 2004) as well as of (4) market power (Hahn, 1984; Malueg, 1990; Eshel, 2005) and (5) transaction costs (Stavins, 1995).

the study to imperfect competition arises and in particular the need of answering three important questions:

(1) How does the impact of the ETS on electricity pricing depend on electricity market structures?

(2) What role does market power in electricity markets play, in this respect[4]?

(3) How does the ETS impact on carbon emissions in the short run?

Studies aimed at answering these questions do exist but they provide a very controversial framework.

Sijm et al. (2005) and Wals and Rijkers (2003), by using a game theoretical simulation model based on the theory of Cournot competition and Conjecture Supply Funcions[5], find that the electricity price in a competitive scenario increases more than under market power, on both percentage and absolute basis. They attribute this result to the assumption of linear demand function they adopt. Surprisingly, however, Lise (2005) achieves the opposite result (electricity price increases more under market power) even though the author uses the same model. Reinaud (2003), relying on price competition, and Newbery (2005), by assuming constant price elasticity, state that electricity prices are likely to increase more under market power.

Moreover the question of how the ETS can affect emissions is not less controversial. All authors agree that emissions are highest under the most competitive scenarios. Nevertheless some contributions (Sijm et al., 2005 and Lise, 2005) show that emission reductions are lowest under perfect competition while others (Lise, 2006) state that generally higher emission reductions are achieved in the case without market power.

This controversial framework also highlights that results significantly depend on the choice of competition models[6]. In the economic literature on the electricity sector several

[4] This question is important also for another reason. The impacts of the ETS on electricity prices influences power demand and consequently the environmental performance of the market. Many authors deal with the link between market structure and environmental issues. For a survey, see Requate (2005).

[5] The COMPETES model. For details on this model, see Day et al. (2002), Hobbs and Rijkers (2004a; 2004b).

[6] In particular price elasticity choice is very important in simulating the impact of the ETS and can undermine the effectiveness of a model. For example, the existence of Nash equilibria within the Cournot model requires substantial negative price elasticity. This is the case, for example, of the COMPETES model cited above. Whereas completely inelastic demand seems to be more appropriate for the power industry, at least in the short-run. Moreover, Bolle (1992) proves that in this latter case no equilibrium exists in the supply-function model.

approaches are generally used for modelling competition and several classifications are proposed[7]. Examining recent developments in the literature on electricity spot markets, von der Fehr and Harbord (1998) distinguish three groups of approaches: the standard oligopoly models[8]; the "supply function" approach[9]; the "auction" approach[10].

In the present work we will follow the suggestion of authors who argue in favor of the "auction" approach. In fact, several electricity spot markets have characteristics which make standard models not well-suited to their analysis. In particular in these markets pricing mechanism is a uniform, first price auction. Furthermore, since we have to isolate the effect of the environmental regulation, in the form of a typical *cap and trade* regulation (namely, a market of carbon emissions allowances), we do not account for the problem of capacity witholding, grid congestion and contract market which, in the opinion of some authors (Borenstein et al., 1999), can be better investigated by using the standard oligopoly models.

The paper proceeds as follows. Section 2 summarizes the assumptions underlying the model and in particular those concerning power demand and supply, electricity market and allowance market regulations. Section 3 describes the impact of the ETS on power generation costs, a fundamental step for further evaluations. The competitive outcome is illustrated in section 4. It provides a benchmark for the subsequent analysis. Section

[7] See Borenstein et al. (1998), von der Fehr and Harbord (1998) and Smeers (1997, 2005).

[8] Among these models the authors include the "capacity-constrained, Bertrand competition" approach and the "repeated interaction, price collusion" approach. Other authors (Borenstein et al., 1998) emphasize the usefulness of the Cournot-Nash approach considered flexible in order to incorporating other institutional aspects of the electricity markets (bilateral trading, startup costs, ramping rate, transmission constraints, etc.) as well as useful to study the capacity witholding problem.

[9] This group is based on competition with supply functions which means that producers can select their strategies from a space with an infinite number of dimensions. One of the main advantages of a supply function equilibrium model is that it seems to be suited to the characteristics of the actual electricity markets. The general formulation of this model was introduced by Klemperer and Meyer (1989). Bolle (1992) and Green and Newbery (1992) provide applications to the UK electricity market. For an interesting comment about the results of this latter contribution, see von der Fehr and Harbord (1993, 1998). Recent works using the supply-function approach have extended the previous analyses in order to include contract market and contestable entry (Newbery, 1998).

[10] Many contributions use the "auction" approach in order to model competition in the electricity markets. Among them, we have to recall the former contribution by von der Fehr and Harbord (1993). This approach has been recently extended in order to study the discriminatory or "pay your bid" electricity auctions (von der Fehr et al., 2006).

5 simulates the impact of the ETS under market power in electricity market[11], by using a dominant firm facing a competitive fringe model. We will present various scenarios by altering the following factors: (1) the leader's share of the total capacity in the market; (2) the plant mix operated by either the dominant firm or the competitive fringe; (3) the allowance price (above or below the so-called "switching price"); (4) the available capacity in the market (whether there is excess capacity or not). In section 6 a quantitative simulation is carried out by using plausible variable costs and emission rates. This simulation provides useful insights about the pass-through rate under perfect and imperfect competition. Section 7 shows the analysis of how the ETS impacts on aggregate carbon emissions in the short and medium run. Finally, section 8 summarizes the main results of the analysis.

Consistently with major economic remarks, the model confirms that the ETS causes a rise in power prices due to the pass-through of the carbon opportunity cost. However, the main finding of the analysis is that the impact of the ETS significantly depends on electricity market structures (other than on other factors). The carbon opportunity cost is fully included in energy prices when the electricity market is assumed to be perfectly competitive. Under impefect competition prices may increase more or less than under competition depending on the structural features of power markets. Furthermore, the analysis highlights that under market power the ETS always determines a decrease in emissions except for the case in which there is excess capacity in the market and under specific technological conditions.

Before proceeding it is important to underline that, throughout the paper, we will focus on short-term issues, i.e. we will analyse the ETS impact on electricity pricing in the short run leaving the question of how the ETS can affect investment decisions for further research.

2. The model: basic assumptions

This subsection describes the structure of the model detailing the main assumptions on the regulation of the electricity and carbon markets.

Concerning power demand, consistently with most contributions on this topic, we assume power demand is inelastic[12], predictable with certainty and given by a typical

[11] The model presented in this section is an extension of that carried out by Bonacina and Gullì (2007).

[12] Most contributions using auction models assume inelastic demand (e.g. von der Fehr and Harbord,

load duration curve $D(H)$, where H is the number of hours (the reference time unit adopted here) in the reference time period (e.g. the year) that demand is equal to or higher than D, where $0 \leq H \leq H_L$. $D_L = D(H_L)$ is the base-load demand (the minimum level) and $D_M = D(0)$ is the peak-load demand (the maximum level). Note that the assumption on the price elasticity of demand (inelastic demand) will be abandoned in section 8 when we will attempt to asseess the impact of the ETS on carbon emissions.

With regard to power supply, we model technologies by means of two distinctive elements: variable costs (essentially, fuel costs) and CO_2 emission rates (emissions per unit of electricity generated).

In particular, the CO_2 emission rate is $e \geq 0$ and variable cost of production is $v \geq 0$ for production levels less than capacity, while production above capacity is impossible (i.e. infinitely costly).

Since we simulate a uniform, first price auction, it is enough to focus on technologies which have a positive probability of becoming the marginal operating unit. This allows us to neglect, without loss of generality, those technologies suited to meet the base-load demand (i.e. nuclear and large hydropower plants, renewable technologies, and so on) or which are inelastically supplied.

Given these premises, we restrict the analysis to two groups of plants, a and b, and assume that each group includes a very large number n of homogeneous generating units[13] such that

$$K_j = \sum_{i=1,2..n} k_j^i = nk_j,\ j = a, b \text{ and } v_j^i = v_j; e_j^i = e_j, \forall i, j$$

where K_j is the total capacity of the group j, $v_j^i = v_j > 0$ and $k_j^i = k_j > 0$ are the variable cost and the capacity of the i-th unit belonging to the group j, respectively. Thus

1993; von der Fehr at al., 2006; Crampes and Creti, 2005). In this paper this hypothesis mainly reflects the fact that hourly demand forecasts announced by the market operator are fixed quantities. Indeed, the aggregate demand should exhibit some elasticity, to the exetent that eligible customers are allowed to announce demand bids. Nevertheless, actually observation highlights that the price elasticity of demand is very low (Crampes and Creti, 2005). Furthermore, a reasonable way (even if not optimal) to justify this assumption is to consider the short term.. However, it is important to underline that focusing on the short term implies not considering mid and long-term strategies of utilities in managing their fuel and hydro reserves, and therefore may not represent correctly their bidding strategies. This may explain to a certain extent the difference between empirical and simulated results.

[13] Assuming that each group includes the same number n of units implies that k_j depends on K_j. This is an arbitrary assumption which does not undermine, however, the significance of the analysis.

K_a and K_b are the installed capacity of groups a and b, respectively.

Furthermore, we assume $v_a < v_b$ and $K_a + K_b = K_T = D_M$, i.e. the units of a and b are sufficient to meet the peak demand, and consider two scenarios: Scenario 1 in which there is trade-off between variable costs and emission rates (hereafter "trade-off in the plant mix"), i.e. the technology with lower variable cost is the worse polluter ($v_a < v_b$ and $e_a > e_b$, a typical relevant example is given by coal plants (a) versus CCGT -combined cycle gas turbine- technologies (b)); Scenario 2 in which there is not such a trade-off, i.e. the technology with lower variable cost is also the cleaner technology ($v_a < v_b$ but $e_a < e_b$, a typical relevant example is given by CCGT plants (a) versus gas-fired steam cycle plants (b)).

Emission abatement is supposed to be impossible or, equivalently, abatement cost infinitely costly. This hypothesis is consistent with the time horizon of the analysis (short term analysis of the ETS impact).

Concerning the wholesale market, we assume a typical day ahead market. Before the actual opening of the market (e.g. the day ahead) the generators simultaneously submit bid prices for each of their units on hourly basis. We neglect the existence of technical constraints such as start-up costs. The auctioneer (generally the so-called market operator) collects and ranks the bids by applying the merit order rule. The bids are ordered by increasing bid prices and form the basis upon which a market supply curve is carried out.

If called upon to supply, generators are paid according to the market-clearing spot price (the system marginal price, equal to the highest bid price accepted). All players are assumed to be risk neutral and to act in order to maximize their expected payoff (profit). Production costs, emission rates as well as the installed capacity of the plants are common knowledge.

Given the regulatory framework described above, it is straightforward that price equilibria will depend on the power demand level. Since this latter varies continuously over time, an useful way of representing the price schedule is carrying out the so-called price duration curve $p(H)$, where H is the number of hours in the year that the power price is equal to or higher than p.

With regard to the allowance market, we suppose this market is very large (consistently with the extent of the European ETS) and that firms are price takers[14]. Therefore, the allowance price, p^{tp}, is given exogenously. Carbon emissions allowances are allocated free of charge and on the basis of the amounts emitted in a base period (typical grandfathering) or on the basis of the expected emissions in the future[15].

Finally, we assume that firm's offer prices are constrained to be below some threshold level, $\widehat{p}$, which can be interpreted in several ways.

It may be a (regulated) maximum price, $\overline{p}$, as officially introduced by the regulator or we can suppose that it is not introduced officially, but simply perceived by the generators, i.e. firms believe that the regulator will introduce (or change) price regulation if the price rises above the threshold. This latter interpretation is well-suited to the topic analysed here. In fact, firms might decide to bring bid prices down not only to avoid regulation in the wholesale electricity market but also to avoid change in allowance allocation (e.g. under allocation) or change in taxation [16]. For these reasons we think that it is acceptable assuming that the price cap is insensitive to the CO_2 price.

Alternatively, we can suppose that there is so much generation that price never is above the marginal cost of a peaker. In order to simulate this situation, we introduce a third technology, c, such that $v_c > \max[v_a,\ v_b]$ and whose capacity is great enough, $K_c = \overline{K}_c$, that the dominant firm does not try to let it all run and drive the price up to the price cap. Instead, $K_c = 0$, is useful to simulate the situation in which there is not excess capacity in the market and prices can reach the price cap, $\overline{p}$. Finally, we assume that $e_a > e_c > e_b$ in the Scenario 1 and $e_c > e_b > e_a$ in the Scenario 2. These latter assumptions are crucial for our analysis but not arbitrary. Technology c, in fact, can

[14] The electricity sector accounts for basically 50% of the EU ETS. Therefore, in principle it has a certain power to influence prices in the carbon market. However, in our analysis, what is important is the ability to do this in the single electricity firm. This ability is relatively low if we consider the entire European carbon market. Moreover, most studies on carbon ETS assume the firms behave as price-takers in the carbon market. This assumption is acceptable when there are other firms outside the oligopolistic industry (other output industries or other power industries) that operate on the same permit market (Requate, 2005). This is the case for the European carbon market which is the largest multi-country and multi-sector ETS.

[15] For a comparative analysis of the different allocation methods, see Harrison and Radov (2002) and Burtraw et al. (2001).

[16] Under allocation and change in firm's taxation are some of the options taken into consideration for the second phase of the EU ETS in some countries in order to reduce the so-called (and supposed) windfall profits.

be interpreted as a typical peaking technology (old oil-fired plants or gas turbine plants) whose electrical efficiency is generally much lower than that of the CCGT. Furthermore, this technology is generally more polluting than CCGT (or gas-fired steam cycle plants) but cleaner than coal plants.

In brief, we will consider two scenarios (Scenario 1 and Scenario 2, with and without "trade-off in the plant mix", respectively) and, for each of them, two cases of available capacity in the market, namely excess capacity ($K_c = \overline{K}_c$) and scarcity of generation capacity ($K_c = 0$).

3. THE IMPACT ON POWER GENERATION COSTS

The first step of the analysis is to evaluate how the carbon ETS can affect power generation costs.

Definition 1. *The carbon opportunity cost of the i-th generating unit belonging to the group j of plants is equal to the price of the CO_2 allowance, p^{tp}, multiplied by its emission rate, e_j^i.*

Given this definition and in line with economic theory, the marginal cost of production is expected to include the full carbon opportunity cost, regardless of whether allowances are allocated free of charge or not,

$$MC_j^i = v_j^i + p^{tp} e_j^i \tag{1}$$

where MC_j^i is the marginal cost of the i-th unit belonging to the group j of plants.

This will be a central issue within the study and suggests the set up of the following definitions.

Definition 2. *For the purpose of this analysis, the generating units belonging to the group j of plants are the most (least) efficient units if their marginal cost (including the carbon opportunity cost) is lower (higher) than that of the units belonging to the other group.*

Definition 3. *The "switching price", p^{tp*}, is the allowance price such that the marginal cost of the plants of the group a, MC_a, is equal to that of the plants of the group b, MC_b, i.e. $p^{tp*} = (v_b - v_a)(e_a - e_b)$*

Definition 4. *For the purpose of the paper and given Definition 3, the allowance price is low if $p^{tp} \leq p^{tp*}$, high otherwise.*

Obviously, thse two latter definitions are valid only for the Scenario 1.

4. Perfect competition

Although the case of perfect competition lacks of realism, it is a good, paradigmatic, benchmark for evaluating the consequences of market power in the wholesale spot market.

The generation system includes $2n$ (where n is very large) independent generators belonging to the two categories of plants presented above.

Definition 5. *The marginal carbon opportunity cost is the price of the CO_2 emissions allowance multiplied by the emission rate of the marginal production unit.*

Given equation 1 and Definition 3 we can characterize the perfectly competitive Nash-equilibria. Results are illustrated in the following Proposition.

Proposition 1. *(i) Under perfect competition, electricity prices fully internalize the marginal carbon opportunity cost. (ii) Let $\overline{MC}$ and $\underline{MC}$ be the marginal costs of the least and most efficient plants, respectively and let $\widehat{p}$ the price threshold. Then the price equilibria are as follows*

$$p = \begin{cases} \widehat{p} & \text{for } D = D_M \\ \overline{MC} = \max\{MC_a;\ MC_b\} & \forall D \in]D_M; \underline{K}] \\ \underline{MC} = \min\{MC_a;\ MC_b\} & \forall D \in]\underline{K}; D_L] \end{cases}$$

where $\widehat{p} = \begin{cases} \overline{p} & \text{for} \quad K_c = 0 \\ MC_c & \text{for} \quad K_c = \overline{K}_c \end{cases}$ *and* $\underline{K} = \begin{cases} K_a & \text{if} \quad p^{tp} \leq p^{tp*} \\ K_b & \text{if} \quad p^{tp} > p^{tp*} \end{cases}$

Proof. The market clearing price is the highest bid price accepted. Therefore, under perfect competition it equals the marginal cost of the marginal unit which fully includes the carbon opportunity cost. In the Scenario 1, for low (high) price of allowances, the marginal unit will belong to the group b (a) whenever demand is above K_a (K_b) and to the group a (b), otherwise. In the Scenario 2, whatever p^{tp} the marginal unit will belong to the group b whenever demand is above K_a and to the group a, otherwise. Figure 3.1 presents this result graphically (for the case of $K_c = \overline{K}_c$). ■

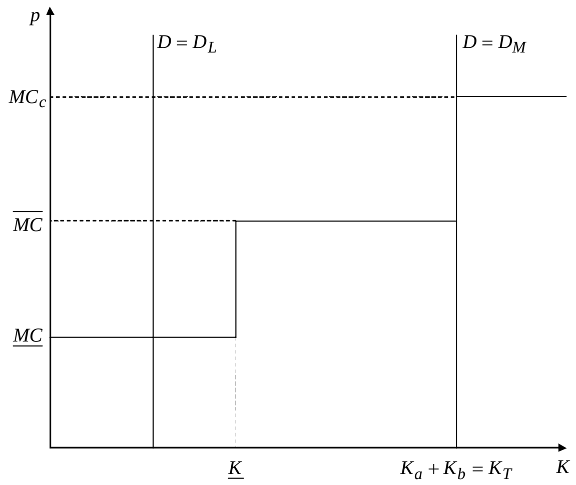

Figure 1: Perfectly competitive prices ($K_c = \overline{K}_c$)

In Figure 3.2 the price duration curves, $p(H)$, are reported (before and after the ETS), for the Scenario 1. We can observe that when $p^{tp} \leq p^{tp*}$ (low allowance prices) the impact of the ETS on the volume-weighted average electricity price, $\triangle p_{av} = \int_0^{H_L} \Delta p(H) dH$, equals the volume-weighted average marginal opportunity cost. When $p^{tp} > p^{tp*}$ (high allowance prices), the volume-weighted marginal opportunity cost exceeds $\triangle p_{av}$.

These results suggest the following definition.

Definition 6. *The marginal pass-through rate (MPTR) is the ETS impact on electricity prices, Δp, divided by the difference between the marginal production costs of the marginal unit (under perfect competition) after and before the ETS*[17]*, ΔMC, i.e. $MPTR = \Delta p / \Delta MC$.*

Applying Definition 6, we get a 100% MPTR under perfect competition.

5. Imperfect competition

We are now able to simulate the impact of market power[18] on power pricing. For this purpose, we adopt a dominant firm facing a competitive fringe model rather than the usual

[17] This way of defining the marginal pass-through rate seems to be more appropriate from a theoretical point of view as long as one intends to consider the overall change in marginal prices due to the ETS. See Sijm et al. (2005).

[18] Throughout the paper, we consider that there is market power when firms are able to set prices above the level which would arise under perfect competition.

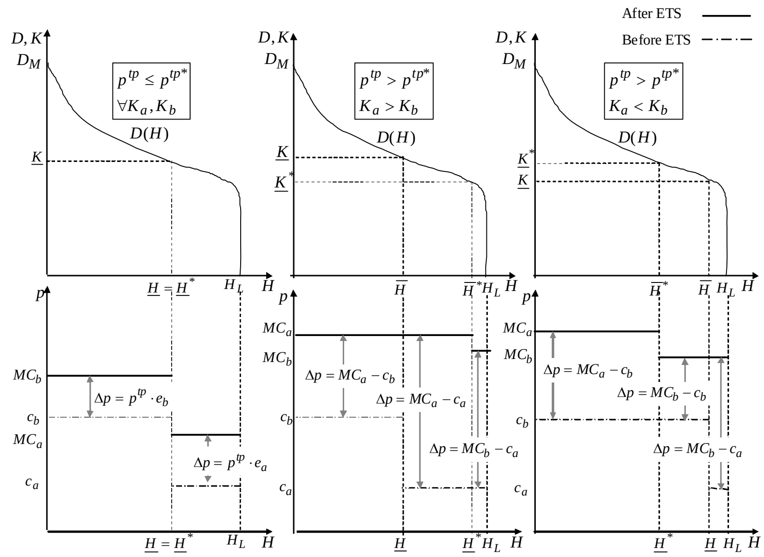

Figure 2: The impact of the ETS on electricity prices under perfect competition: Scenario 1

dupolistic-oligopolistic framework. This choice is due to several reasons, either methodological or practical. On the methodological side, the attraction of this characterization is that it avoids the implausible extreme of perfect competition and pure monopoly, at the same time escaping the difficulties of characterizing an oligopolistic equilibrium (Newbery, 1981). This does not mean, however, that it is only a useful benchmark. It is also useful on the practical side, as long as is suited to represent the reality of several electricity markets. We especially refer to those markets emerging from restructuring processes where the incumbent is obliged to sell a portion of his capacity to different firms and new independent producers meet the rise in power demand over time.

The general formulation of the model assumes that the dominant firm owns and operates $z \in [0; 2n]$ units of both group a and b while the remaining units are operated by $2n - z$ firms behaving as a competitive fringe. Obviously, $z = 0$ corresponds to the case of pure competition while $z = 2n$ to that of pure monopoly.

In order to derive the price schedule in the form of a price duration curve, we introduce the following parameters.

The first parameter is $\delta \in [0; 1]$ representing the share of the total power capacity

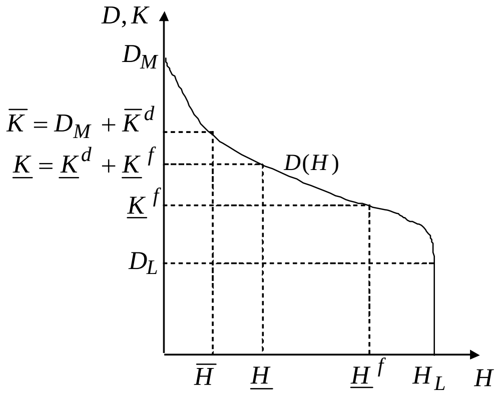

Figure 3: An example of supply configuration

in the market operated by the dominant firm. Complementary, the competitive fringe operates the share $(1-\delta)$ of the total power capacity. Thus, δ can be interpreted as a measure of the degree of market concentration.

The other parameters are $\underline{\mu}^d \in [0;1]$ and $\underline{\mu}^f \in [0;1]$ representing the share of own power capacity that the strategic operator and the competitive fringe get in most efficient plants, respectively. By complement, $\overline{\mu}^d = (1-\underline{\mu}^d)$ and $\overline{\mu}^f = (1-\underline{\mu}^f)$ are the shares in the least efficient ones.

By facing the competitive fringe, the dominant firm has two alternative strategies: (1) bidding the price threshold $(\widehat{p})$ and so accommodating the maximum production by the fringe or (2) competing *à la Bertrand* with the rivals in order to maximize his market share.

Let $\underline{K}^f$ be the installed capacity in most efficient plants operated by the competitive fringe. Thus $\underline{K}^f = \underline{\mu}^f(1-\delta)K_T$, and $\underline{H}^f = D^{-1}(\underline{K}^f)$.

Similarly, let $\overline{K} = D_M - \overline{K}^d$ be the peak demand minus the dominant firm's capacity in least efficient plants $(\overline{K}^d)$. Given that $D_M = K_T$, then we assume that $\overline{K} = \left(1-\delta\overline{\mu}^d\right)K_T$, and $\overline{H} = D^{-1}(\overline{K})$.

Finally, $\underline{K} = \left[\underline{\mu}^d\delta + \underline{\mu}^f(1-\delta)\right]K_T$ is the total capacity in most efficient plants, already introduced in the previous section.

It is important to note that δ determines not only the degree of market concentration but also the total share of most efficient plants in the market, $\underline{K}$. In particular, increasing δ implies increasing $\underline{K}$ if $\underline{\mu}^d > \underline{\mu}^f$, and vice versa if $\underline{\mu}^d < \underline{\mu}^f$.

Figure 3.3 shows an (generic) example of possible power supply configuration.

The following Lemma describes the shape of the price duration curve.

Lemma 1. *There exists* $\widehat{D} \in \left]\overline{K}; \underline{K}^f\right]$ *such that the system marginal prices equal the price threshold* $\widehat{p}$ *when* $D \geq \widehat{D}$ *and the marginal cost of the least efficient plants* $(\overline{MC})$ *when* $D < \widehat{D}$. *When* $D < \underline{K}^f$*, pure Bertrand equilibria (first marginal cost pricing) arise and prices equal the marginal cost of the most efficient plants* $(\underline{MC})$*, where*

$$\widehat{D} = \begin{cases} \widetilde{D}\left(\delta, \underline{\mu}^d, \zeta\right) = \left[\underline{\mu}^d \delta\zeta + (1-\delta)\right] K_T & \text{for } \widehat{D} > \underline{K} \text{ case } i) \\ \widetilde{\widetilde{D}}\left(\delta, \underline{\mu}^f, \zeta\right) = (1-\delta)\left[\dfrac{(1-\mu^f)}{(1-\zeta)} + \underline{\mu}^f\right] K_T & \text{for } \widehat{D} \leq \underline{K} \text{ case } ii) \end{cases}$$

$$\text{and } \zeta = \frac{\left(\overline{MC} - \underline{MC}\right)}{\widehat{p} - \underline{MC}} \text{ with } \widehat{p} = \begin{cases} \overline{p} & \text{for } K_c = 0 \\ MC_c & \text{for } K_c = \overline{K}_c \end{cases}$$

Proof. See the Appendix. ■

Therefore, two price duration curves are possible, depending on whether the discontinuity is at $\widetilde{H} = D^{-1}(\widetilde{D})$ or $\widetilde{\widetilde{H}} = D^{-1}(\widetilde{\widetilde{D}})$. The following Proposition identifies the critical value of δ that discriminates between these two cases.

Proposition 2. *Under market power, there exists* $\underline{\delta}(\underline{\mu}^d, \underline{\mu}^f, v_j, e_j, p^{tp})$ *such that*

$$p = \begin{cases} \widehat{p} & \forall D \in \left[0; \widehat{D}\right] \\ \overline{MC} & \forall D \in \left]\widehat{D}; \underline{K}^f\right] \\ \underline{MC} & \forall D \in \left]\underline{K}^f; D_L\right] \end{cases}$$

$$\text{where: } \widehat{p} = \begin{cases} \overline{p} & \text{for } K_c = 0 \\ MC_c & \text{for } K_c = \overline{K}_c \end{cases} ; \widehat{D} = \begin{cases} \widetilde{D} & \text{if } \delta < \underline{\delta} \text{ case } i) \\ \widetilde{\widetilde{D}} & \text{if } \delta \geq \underline{\delta} \text{ case } ii) \end{cases} \text{ and } \underline{\delta} = \frac{\underline{\mu}^f - 1}{\underline{\mu}^f - 1 + \underline{\mu}^d(\zeta - 1)}$$

Proof. See the Appendix. ■

By differentiating $\widetilde{D}$ and $\widetilde{\widetilde{D}}$ with respect to $\underline{\mu}^d$ and $\underline{\mu}^f$, we find that the degree of market power (which decreases in $\widehat{D}$) is an increasing function of $\underline{\mu}^f$, when $\delta > \underline{\delta}$, and a decreasing function of $\underline{\mu}^d$, when $\delta < \underline{\delta}$ (see the Appendix). In other words, by intuition,

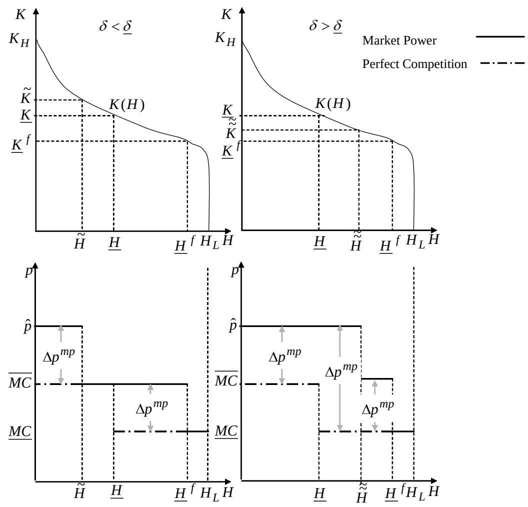

Figure 4: The impact of market power on electricity prices (symmetric plant mix: $\underline{\mu}^d = \underline{\mu}^f$; $\widehat{p}$: price threeshold)

if the demand is high enough, the dominant firm maximizes its profit by bidding the price cap (accommodating so the maximum production by the fringe and behaving as a residual monopolist) rather than by bidding the marginal cost of the least efficient plant (maximizing so its production). The level of demand above which this occurs ($\widehat{D}$) increases in the share of most efficient plants operated by the dominant firm ($\underline{\mu}^d$) and in the marginal cost difference between the two kinds of technologies (the numerator of ζ). Such a level, instead, decreases in the fringe's share of most efficient plants ($\underline{\mu}^f$).

Finally some remarks on the impact of market power on electricity prices, $\triangle p^{mp}$, which results from the comparison of the price duration curves under market power and those under perfect competition.

Figure 3.4 presents the outcome graphically. Proposition 2 distinguishes two possible cases. When $\delta < \underline{\delta}$, the effect of market power on electricity prices is relatively slight and concentrated in the periods of high and medium-low demand, whereas there is no distortion in periods of medium and very low demand. When $\delta > \underline{\delta}$, the outcome is quite different. This time, the largest distortions occur in medium-load demand hours.

Lemma 1 highlights that the degree of market power depends on ζ. Since this latter depends on the carbon price, the environmental regulation is able to modify the degree of market power in the output market. Indeed, according to the definition adopted in this analysis, the dominant firm exerts his market power not only when it bids the price threshold ("first market power effect") but also when it is able to set prices just below the marginal cost of the least efficient plants whereas under perfect competition prices would converge to the marginal cost of the most efficient plants. In what follows we neglect this "second effect" and consider $\widehat{D}$ as a proxy of market power. Note that this choice is reasonable since the "second market power effect" depends on $\underline{K}^f$ which does not depend on the allowance price.

Given this assumption, the following proposition describes how and under which conditions the environmental regulation can affect the degree of market power.

Lemma 2. *$\widehat{D}$ is non-increasing in p^{tp} if $(e_b - e_a)(\widehat{v} - v_a) < (\widehat{e} - e_a)(v_b - v_a)$, under low allowance prices, and if $(e_a - e_b)(\widehat{v} - v_b) < (\widehat{e} - e_b)(v_a - v_b)$, under high allowance prices, where: (i) $\widehat{e} = e_c$ and $\widehat{v} = v_c$, with excess capacity, and (ii) $\widehat{e} = 0$ and $\widehat{v} = \overline{p}$, without excess capacity.*

Proof. For the formal proof, see the Appendix. Intuitively, the environmental regulation can increase market power when the change in the cost structure between the technologies makes more profitable bidding the price threshold rather than the marginal cost of the least efficient plants, i.e. when the proportional increase (decrease) in the difference between the price threshold and the marginal cost of the most efficient plants is higher (lower) than the proportional increase (decrease) in the difference between the marginal cost of the least efficient and the most efficient plants. Namely, this occurs when $(e_b - e_a)(\widehat{v} - v_a) < (\widehat{e} - e_a)(v_b - v_a)$, if .$p^{tp} \leq p^{tp*}$, and when $(e_a - e_b)(\widehat{v} - v_b) < (\widehat{e} - e_b)(v_a - v_b)$, if $p^{tp} > p^{tp*}$. Under 'trade-off in the plant mix' and excess capacity, this condition always (never) is satisfied if $p^{tp} \leq p^{tp*}$ (if $p^{tp} > p^{tp*}$) . Without 'trade-off in the plant mix' it is never satisfied if there is a scarcity of capacity. Otherwise, it is satisfied only under certain values of v_j and e_j. ■

Corollary 1. *The sensitivity of market power to the carbon price increases (decreases) in μ_a^d (μ_a^f), if $p^{tp} \leq p^{tp*}$. Vice versa, if $p^{tp} > p^{tp*}$, under "trade-off in the plant mix".*

Proof. See the Appendix. ■

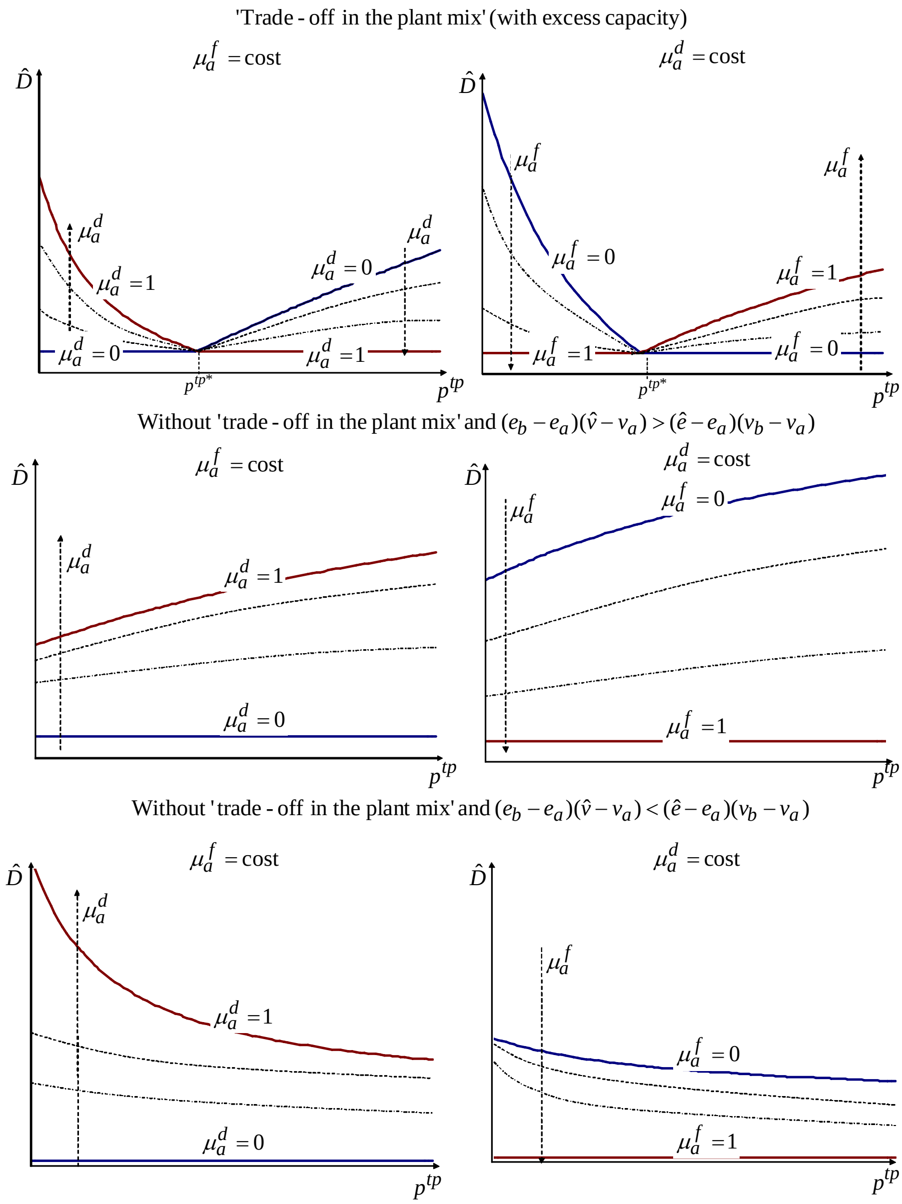

Figure 5: Examples of change in market power due to the ETS

Figure 3.5 shows graphically the results described by Lemma 2 and Corollary 1. As can be noted, the level of demand over which the dominant firm prefers to bid the threshold can either decrease or increase in the allowance price depending on three factors: 1) the plant mix operated by either the dominant firm or the competitive fringe; 2) the allowance price (whether above or below the "swithcing price"); 2) the power capacity in the market (whether there is excess capacity or not).

Finally, some numerical examples help us to have an idea about the extent of this effect.

	Allowance price (Euro/tCO_2)					
	0	20	40	60	80	100
With trade-off (excess capacity)						
$\widehat{p} = MC_c$, $\delta = 0.7$						
$\mu_a^d = 1$, $\mu_a^f = 0$	0.640	0.398	0.300	0.300	0.300	0.300
$\mu_a^d = \mu_a^f = 0.5$	0.442	0.349	0.303	0.341	0.384	0.430
$\mu_a^d = 0$, $\mu_a^f = 1$	0.300	0.300	0.300	0.383	0.468	0.560
With trade-off (without excess capacity)						
$\widehat{p} = \overline{p}$, $\delta = 0.7$						
$\mu_a^d = 1$, $\mu_a^f = 0$	0.347	0.325	0.300	0.300	0.300	0.300
$\mu_a^d = \mu_a^f = 0.5$	0.325	0.313	0.301	0.317	0.343	0.387
$\mu_a^d = 0$, $\mu_a^f = 1$	0.300	0.300	0.300	0.334	0.386	0.473
Without trade-off (excess capacity)						
$\widehat{p} = MC_c$, $\delta = 0.7$						
$\mu_a^d = 1$, $\mu_a^f = 0$	0.806	0.727	0.664	0.612	0.581	0.560
$\mu_a^d = \mu_a^f = 0.5$	0.553	0.513	0.482	0.456	0.440	0.430
$\mu_a^d = 0$, $\mu_a^f = 1$	0.300	0.300	0.300	0.300	0.300	0.300
Without trade-off (without excess capacity)						
$\widehat{p} = \overline{p}$, $\delta = 0.7$						
$\mu_a^d = 1$, $\mu_a^f = 0$	0.360	0.402	0.466	0.572	0.732	0.852
$\mu_a^d = \mu_a^f = 0.5$	0.330	0.351	0.383	0.436	0.516	0.576
$\mu_a^d = 0$, $\mu_a^f = 1$	0.300	0.300	0.300	0.300	0.300	0.300

Table 3.1 $\widehat{D}/D_M$ as function of the allowance price (change in market power)

Table 3.1 reports the results corresponding to the situations with and without "trade-off in the plant mix" under either excess or scarcity of generation capacity. These results are obtained by using emission rates and variable costs reported in Table 3.3 in Appendix. Three combinations of μ_a^d and μ_a^f are simulated: the extreme situations and the case of perfect symmetry (μ_a^d=μ_a^f $= 0.5$). As can be noted, the time (the number of hours) over which the dominant firm prefers to bid the price threshold ($\widehat{H}$, the inverse of $\widehat{D}$) changes only slightly if the share of most efficient plants operated by the dominant firm (μ_a^d) is low or, under high allowance prices, if μ_a^d is high. Otherwise, the change in market power is significant especially when there is excess capacity in the market.

From this outcome the following implications arise. First, when we try to estimate to what extent the carbon price is passed through into power prices, we have to take into account also that change in price may be amplified or lessened by change in market power. Second (and most important), the change in market power due to the ETS might significantly affect the amount of emissions as it can modify the share of production by the different kinds of plants (favouring the most or least polluting plants). This effect may be able to influence greatly the cost of achieving the emissions target, i.e. the effort to pursue the reduction in carbon emissions.

6. The impact on power prices: market power versus perfect competition

As pointed out before, under perfect competition the MPTR is always equal to 1 (see Definition 6). Thus, by estimating the MPTR we are able to know whether the impact of the ETS on power prices under imperfect competition is higher ($MPTR > 1$) or lower ($MPTR < 1$) than that under perfectly competitive scenarios.

In order to carry out the MPTR curve (i.e. how the MPTR is distributed over time), we have to depict the price and marginal cost (of the marginal unit) duration curves before and after the ETS distinguishing between low ($0 < p^{tp} \leq p^{tp*}$) and high ($p^{tp} > p^{tp*}$) allowance prices (only for Scenario 1). Table 3.2 shows different expressions of MC_c, $\overline{MC}$, $\underline{MC}$, $\underline{\mu}^d$, $\underline{\mu}^f$ corresponding to the situations after and before the ETS. We will use the superscript star (*) in order to address the critical threshold of D, H, and δ when $p^{tp} \neq 0$ (i.e. the situation after the ETS).

In what follows, we will present some relevant examples of marginal pass-through rate curves corresponding to different scenarios in terms of available capacity, market concentration and plant mix. For the sake of simplicity, we will illustrate only the outcome under low allowance prices while that under high allowance prices is reported in the

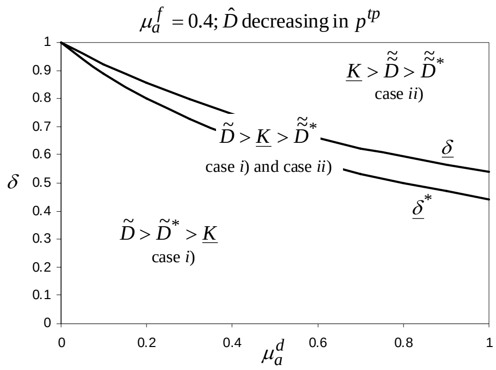

Figure 6: Possible combinations of $\widehat{D}$ and $\widehat{D}^*$: Scenario 1

Appendix.

	Before ETS	Scenario 1		Scenario 2
	$p^{tp} = 0$	$p^{tp} \leq p^{tp*}$	$p^{tp} > p^{tp*}$	$\forall p^{tp}$
MC_c	v_c	MC_c	MC_c	MC_c
$\overline{MC}$	v_b	MC_b	MC_a	MC_b
$\underline{MC}$	v_a	MC_a	MC_b	MC_a
$\underline{\mu}^d$	μ_a^d	μ_a^d	μ_b^d	μ_a^d
$\underline{\mu}^f$	μ_a^f	μ_a^f	μ_b^f	μ_a^f

Table 3.2 Parameter expressions before and after the ETS

6.1. Scenario 1 ("trade-off in the plant mix"): low allowance prices. In this case, $\widehat{D}$ always decreases in p^{tp} under excess capacity, whereas it may either decrease or increase under scarcity of generation capacity (see proof of Lemma 2). In both situations (excess and scarcity of generation capacity), we analyse only the case in which $\widehat{D}$ decreases in p^{tp} (increasing market power) because this is the most likely situation given plausible plant mix in the market: coal plants (a), CCGT (b) and oil-fired plants (c). In fact, by using the emission rates and variable costs of these technologies (Table A1 in the Appendix), we get $(e_b - e_a)(\overline{v} - v_a) < (\overline{e} - e_a)(v_b - v_a)$, regardless of the available capacity in the market (i.e. regardless of whether there is excess capacity or not).

Decreasing $\widehat{D}$ implies that we may face three combinations of $\widehat{D}$ and $\widehat{D}^*$ depending on whether the degree of market concentration is above or below the critical values indentified

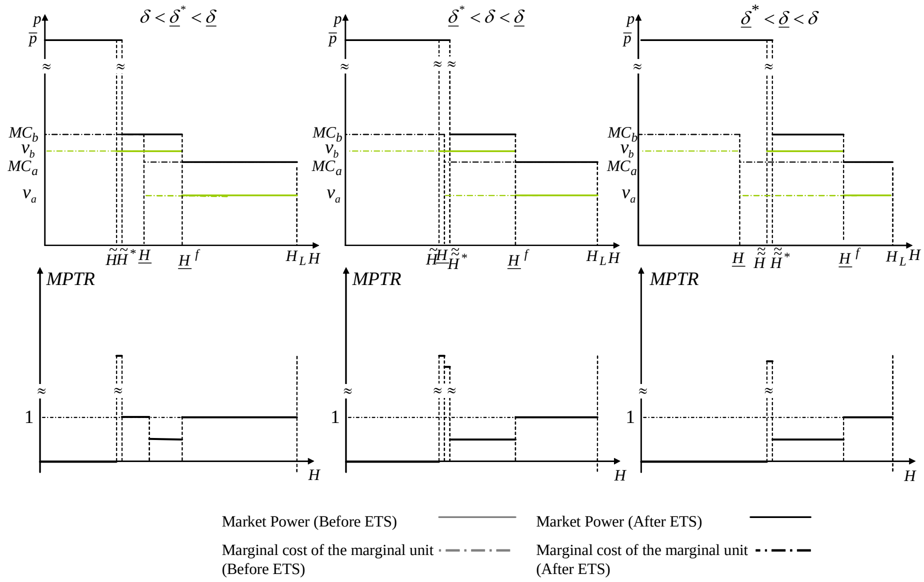

Figure 7: Marginal pass-through rate (MPTR) curve (Scenario 1): low allowance prices and without excess capacity ($\underline{\mu}^d = \underline{\mu}^f$)

in Proposition 2, i.e. $\underline{\delta}$ (before the ETS) and $\underline{\delta}^*$ (after the ETS). In Figure 3.6, by using the expression of $\underline{\delta}$ (Proposition 2), we have depicted $\underline{\delta}$ and $\underline{\delta}^*$ as function of μ_a^d (assuming $\mu_a^f = 0.4$, without loss of generality). As can be noted, the critical value after the ETS ($\underline{\delta}^*$) is always lower than that before the ETS ($\underline{\delta}$). Thus, from Lemma 1 and Proposition 2, the possible combinations of $\widehat{D}$ and $\widehat{D}^*$ are: 1) $\widetilde{D} > \widetilde{D}^* > \underline{K}$ if $\delta < \underline{\delta}^* < \underline{\delta}$ (case i) for both $p^{tp} = 0$ and $p^{tp} \neq 0$); 2) $\widetilde{D} > \underline{K} > \widetilde{\widetilde{D}}^*$ if $\underline{\delta}^* < \delta < \underline{\delta}$ (case i) for $p^{tp} = 0$ and case ii) for $p^{tp} \neq 0$); 3) $\underline{K} > \widetilde{\widetilde{D}} > \widetilde{\widetilde{D}}^*$ if $\underline{\delta}^* < \underline{\delta} < \delta$ (case ii) for both $p^{tp} = 0$ and $p^{tp} \neq 0$).

Figures 3.7 and 3.8 illustrate the MPTR curves obtained by dividing the change in prices by the change in marginal production cost of the marginal unit[19]. For the sake of simplicity and without loss of generality, we assume that the dominant firm and the competitive fringe operate the same share of most efficient plants ($\underline{\mu}^d = \underline{\mu}^f$)[20].

[19] Without any loss of generality, curves are carried out by assuming 20 €/tonCO_2, which is consistent with the average values in 2005 and 2006.

[20] The reason for this latter choice is that we intend to separate the effect of market concentration and that of plant mix. In fact, as pointed out previously, increasing degree of market concentration implies increasing total capacity in most efficient plants if $\underline{\mu}^d > \underline{\mu}^f$, and inversely if $\underline{\mu}^d < \underline{\mu}^f$. Instead, if $\underline{\mu}^d = \underline{\mu}^f$ the overall plant mix does not depend on δ, so making more simple the economic interpretation.

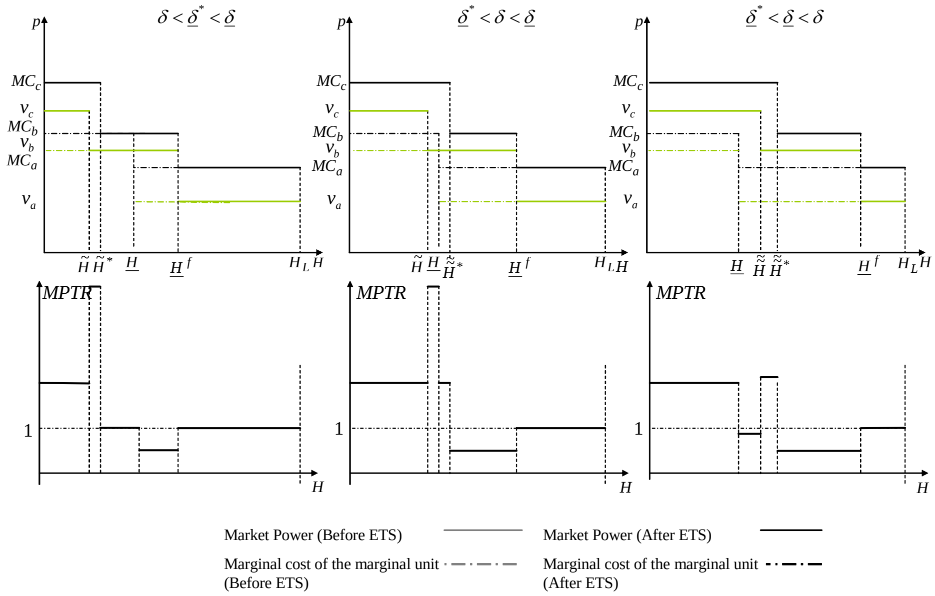

Figure 8: Marginal pass-through rate (MPTR) curve (Scenario 1): low allowance prices and excess capacity ($\underline{\mu}^d = \underline{\mu}^f$)

Figures clearly show that results largely depend on the power demand level (peak vs. off-peak hours) and on the available capacity in the market.

In the peak hours, there would not be any CO_2 cost pass-through under scarcity of generation capacity (provided that δ is high enough) whereas, under excess capacity, the MPTR would be more than 1.

In the off-peak hours power prices can include the full marginal carbon cost but even much less if the share of most polluting plant in the market is high enough. This is more likely to occur under excess capacity than under scarcity of generation capacity.

Note that the differences between competition and market power are due to the disparity in emission rates. In fact, there would be no difference if $e_a = e_b = e_c$, regardless of either the plant mix or the degree of market concentration.

Then, the impact of emission rate differences can be interpreted as the combination of two components. On the one hand, it determines a different degree of opportunity cost internalization (the "pass-through component" which is the prevalent effect). On the other hand, it alters the degree of market power ("market power component") because of the shift from $\widetilde{H}$ to $\widetilde{H}^{*}$ (or from $\widetilde{\widetilde{H}}$ to $\widetilde{\widetilde{H}}^{*}$).

Under low allowance prices the "pass-through component" is more than 1 only when there is excess capacity and in the peak hours (Figure 3.8). The "market power component", instead, is always above 1 but moves from peak (high demand) towards off-peak hours (low demand) as long as the degree of market concentration increases. Therefore, under excess capacity, the probability that the volume-weighted average $MPTR$, $MPTR_{av} = \int_0^{H_L} MPTR(H)dH$, could be less than 1 increases in the degree of market concentration.

Similarly without excess capacity, but this time the time-period over which the rise in market power occurs is so short that the $MPTR_{av}$ might be below 1 even under relatively low degree of market concentration (Figure 3.7).

In addition, when $\delta < \underline{\delta}$ the $MPTR_{av}$[21] decreases in $\underline{\mu}^f$ and increases in $\underline{\mu}^d$. Inversely, when $\delta > \underline{\delta}$ it decreases in $\underline{\mu}^d$ and is low sensitive to $\underline{\mu}^f$.

Finally, if we remove the assumption that $\underline{\mu}^d = \underline{\mu}^f$ we have the following outcome moving from low to high degree of market concentration. If $\underline{\mu}^d > \underline{\mu}^f$, the share of the most polluting plants in the market increases by amplifying the impact of δ. Inversely, if $\underline{\mu}^d < \underline{\mu}^f$. In this latter case, the share of most polluting plants in the market declines, offsetting the effect of δ.

When allowance prices are high (higher than the "switching price"), the interpretation is a little bit more complex (Appendix). This time in fact we have also to account for the "switching effect" (due to the "switch" of the power producers' position on the merit order). This effect is equal to the difference in variable costs of the technologies a and b, $|v_b - v_a|$, and, because of the trade-off between variable costs and emission rates (in the technology set), it counterbalances the "pass-through component".

Figures A1 and A2 in Appendix shows how the "switching component" influences the MPTR curve. Under both relatively low and high degree of market concentration there is a higher probability (higher than in the case of low allowance prices) that the average MPTR is below 1. These effects seem to be even more evident when the hypothesis of excess capacity is removed.

[21] In fact, a rise in $\underline{\mu}^f$ determines decreasing $\underline{H}$ and $\underline{H}^f$ while $\widetilde{H}$ and $\widetilde{H}^{*}$ do not vary. At the same time, to the extent to $\underline{\mu}^d$ decreases, $\underline{H}$ moves slowly towards the low-load together with $\widetilde{H}$ and $\widetilde{H}^{*}$. The range of negative differential impact will tend therefore to disappear.

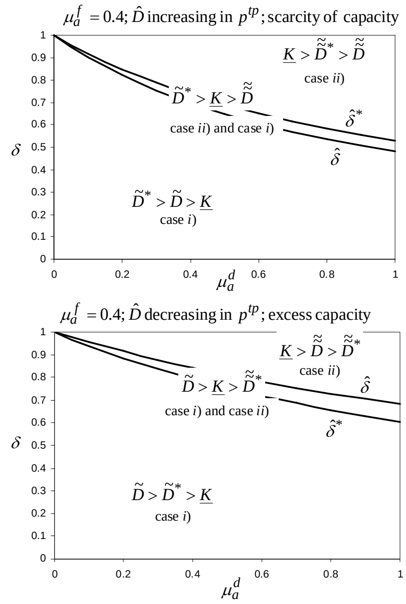

Figure 9: Possible combinations of $\widehat{D}$ and $\widehat{D}^*$: Scenario 2

6.2. Scenario 2 (without "trade-off in the plant mix"). In this scenario, as pointed out before (proof of Lemma 2), under excess capacity both cases, $\widehat{D} > \widehat{D}^*$ and $\widehat{D}^* > \widehat{D}$, are possible, whereas under scarcity of generation capacity market power always decreases in p^{tp} ($\widehat{D}^* > \widehat{D}$), regardless of v_j and e_j. This time a, b and c may be CCGT, gas-fired steam cycle plants and oil-fired steam cycle plants, respectively (plausible plant mix).

By using the emission rates and variable costs of these technologies (Table A1 in the Appendix), we get $(e_b - e_a)(\overline{v} - v_a) < (\overline{e} - e_a)(v_b - v_a)$, under excess capacity (i.e. increasing market power, decreasing $\widehat{D}$), and $(e_b - e_a)(\overline{v} - v_a) > (\overline{e} - e_a)(v_b - v_a)$, without excess capacity (i.e. decreasing market power, increasing $\widehat{D}$).

Increasing $\widehat{D}$ (scarcity of generation capacity) implies that we may face three possible combinations of $\widehat{D}$ and $\widehat{D}^*$ depending on whether the degree of market concentration is above or below the critical values identified in Proposition 2, i.e. $\underline{\delta}$ (before the ETS) and $\underline{\delta}^*$ (after the ETS). As above we have depicted $\underline{\delta}$ and $\underline{\delta}^*$ as function of μ_a^d (assuming $\mu_a^f = 0.4$, without loss of generality). As can be noted (Figure 3.9), this time the critical value after the ETS ($\underline{\delta}^*$) is always higher than that before the ETS ($\underline{\delta}$). Thus, from Lemma 1 and

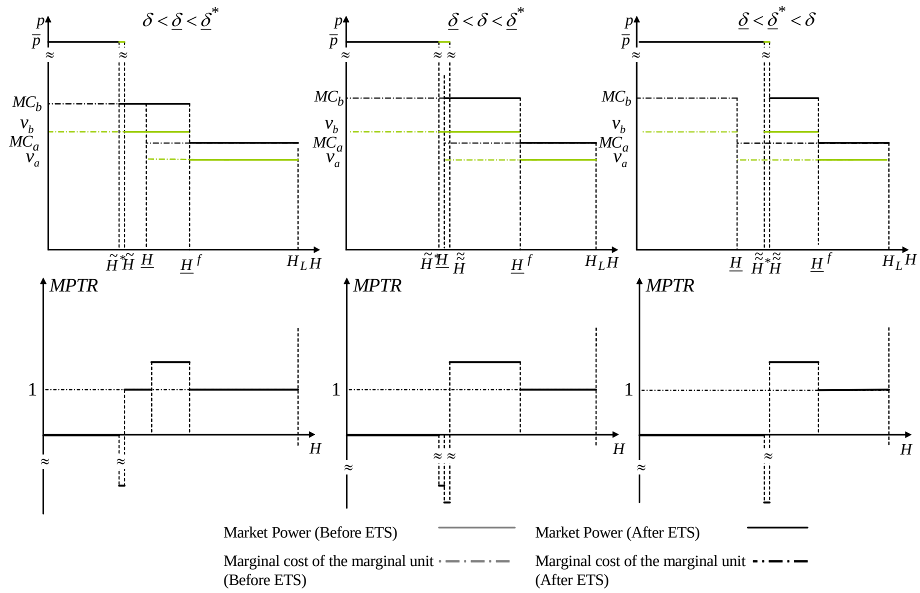

Figure 10: Marginal pass-through rate (MPTR) curve (Scenario 2): without excess capacity ($\underline{\mu}^d = \underline{\mu}^f$)

Proposition 2, the possible combinations of $\widehat{D}$ and $\widehat{D}^*$ are: 1) $\widetilde{D}^* > \widetilde{D} > \underline{K}$ if $\delta < \underline{\delta} < \underline{\delta}^*$ (case i) for both $p^{tp} = 0$ and $p^{tp} \neq 0$); 2) $\widetilde{D}^* > \underline{K} > \widetilde{\widetilde{D}}$ if $\underline{\delta} < \delta < \underline{\delta}^*$ (case ii) for $p^{tp} = 0$ and case i) for $p^{tp} \neq 0$); 3) $\underline{K} > \widetilde{\widetilde{D}}^* > \widetilde{\widetilde{D}}$ if $\underline{\delta} < \underline{\delta}^* < \delta$ (case ii) for both $p^{tp} = 0$ and $p^{tp} \neq 0$).

Decreasing $\widehat{D}$ (excess capacity) implies we face the same combinations already described for the Scenario 1: 1) $\widetilde{D} > \widetilde{D}^* > \underline{K}$ if $\delta < \underline{\delta}^* < \underline{\delta}$; 2) $\widetilde{D} > \underline{K} > \widetilde{\widetilde{D}}^*$ if $\underline{\delta}^* < \delta < \underline{\delta}$; 3) $\underline{K} > \widetilde{\widetilde{D}} > \widetilde{\widetilde{D}}^*$ if $\underline{\delta}^* < \underline{\delta} < \delta$.

In the peak hours (Figures 3.10 and 3.11), the results are similar to those emerging from the Scenario 1 (MPTR more than 1, under excess capacity, and less than 1, under scarcity of generation capacity).

In the off-peak hours, instead, the outcome is substantially different. This time power prices fully include the marginal carbon opportunity cost (and even much more in the mid-merit hours), regardless of the share of most (least) polluting plants in the market.

Consequently, under excess of generation capacity the $MPTR_{av}$ will be always more than 1. Furthermore, it is important to highlight that the ETS may determine a decrease

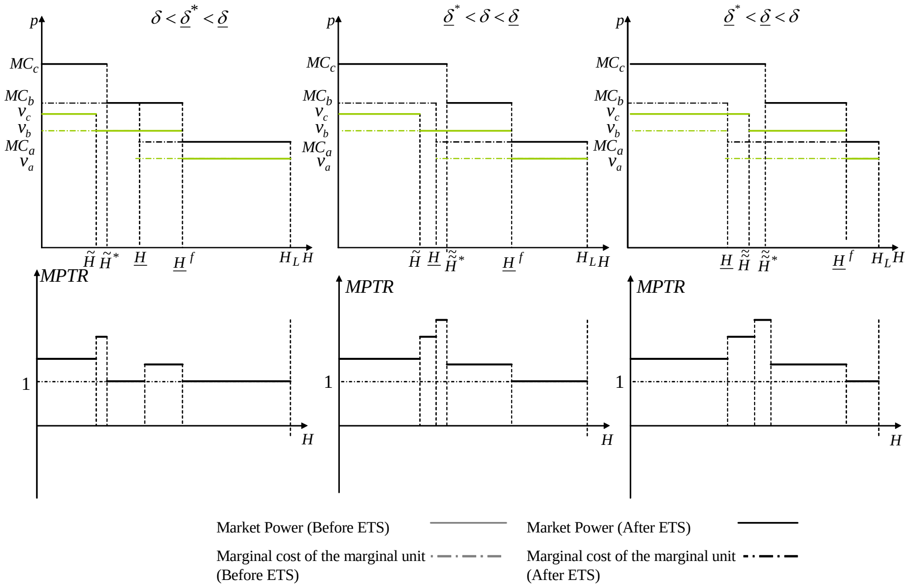

Figure 11: Marginal pass-through rate (MPTR) curve (Scenario 2): with excess capacity ($\underline{\mu}^d = \underline{\mu}^f$)

in the degree of market power implying that the $MPTR_{av}$ may be even negative if the degree of market concentration is high and there is scarcity of generation capacity.

7. Quantitative simulations

In this section the impact of emissions trading on the average electricity price is assessed. In particular, we calculate the volume-weighted average marginal pass-through rate (hereafter $MPTR_{av}$) which is given by $MPTR_{av} = \int_0^{H_L} MPTR(H)dH$.

For this purpose we adopt (Table A1 in the Appendix) plausible values (typical of the Italian electricity market) of variable costs, emission rates and price cap[22]. Notice that, within such setting, the "switching price", as labeled in Definition 3, rests around 40 €/tonCO_2. Concerning the allowance price, 20 €/tonCO_2 and 60 €/tonCO_2 are chosen to characterize the cases of low and the high allowance prices, respectively[23]. Finally,

[22] We assume $\overline{p} = 500$ €/MWh which is the value currently adopted for the Italian wholesale spot market.

[23] Indeed, 20 €/tonCO_2 is widely considered as the most likely price in the long run for the European market whereas 60 €/tonCO_2 is low plausible but not impossible. The EU-ETS, in fact, introduces two

without any loss of generality, we assume the load duration curve is a linear function of H[24].

Although either the low and the high allowance price scenarios yield interesting results, for analytical purposes we illustrate the former context exclusively and let the Appendix guides the reader throughout the other. Linkages (i.e. similarities and differences) between the two cases are here discussed.

Outcomes are presented in Figures 3.12 and 3.13 from which the following remarks can be drawn.

First, without excess capacity (Figure 3.12), market power always can lessen the impact of the ETS on electricity prices whatever the underlying technological structure (the plant mix) of the industry. Furthermore, what is important to underline is that, if there is not "trade off in the plant mix" the $MPTR_{av}$ can be even slightly negative, i.e. the ETS can determine a decrease rather than an increase in average power prices. This effect is due to the fact that the ETS, under certain conditions, can cause a decrease in market power.

This pattern does not extend to the case of excess capacity (Figure 3.13). Here $MPTR_{av} < 1$ only with "trade-off in the plant mix" and for certain range of parameter values. In particular, market power can lessen the impact of the ETS on electricity prices only when the share of most polluting plants in the market is enough large[25] (high μ_a^d combined with high δ or high μ_a^f combined with low δ). Instead when μ_a^d is sufficiently low, $MPTR_{av}$ never is below 1 whatever δ and μ_a^f[26]. Without "trade-off in the plant mix",

levels of excess emissions penalty in the case in which operators do not deliver sufficient allowances by 30 April each year to cover their emissions during the preceding year: 40 €/tonCO_2 in the first period and 60 €/tonCO_2 in the second period. Nevertheless these values must not be considered as possible maximum allowance prices (in the respective periods) because firms must deliver the allowances corresponding to the exceeding emissions in any case.

[24] In particular we set $D(H) = D_M + \theta H$, where $\theta = (D_L - D_M)/H_L < 0$ and $D_L = 0.3D_M$.

[25] Intuitively, under perfect competition prices include the carbon opportunity cost of the most polluting plants (a) in most hours whereas, under market power, firms pass through into prices the carbon cost of both the peking technology (c) and the least polluting plants (b) in a certain number of hours (increasing in δ).

[26] Intuitively, when δ is high (and regardless of μ_a^f) or both δ and μ_a^f are low, prices include the carbon cost of the least polluting plants (b) in most hours, under perfect competition. Under market power, instead, prices include the carbon cost of the peking technology (c) in a certain number of hours. When low δ are combined with high μ_a^f, firms pass through into prices the carbon cost of the most polluting plants (a) in most hours, under both perfect competition and market power. Nevertheless, there is a little

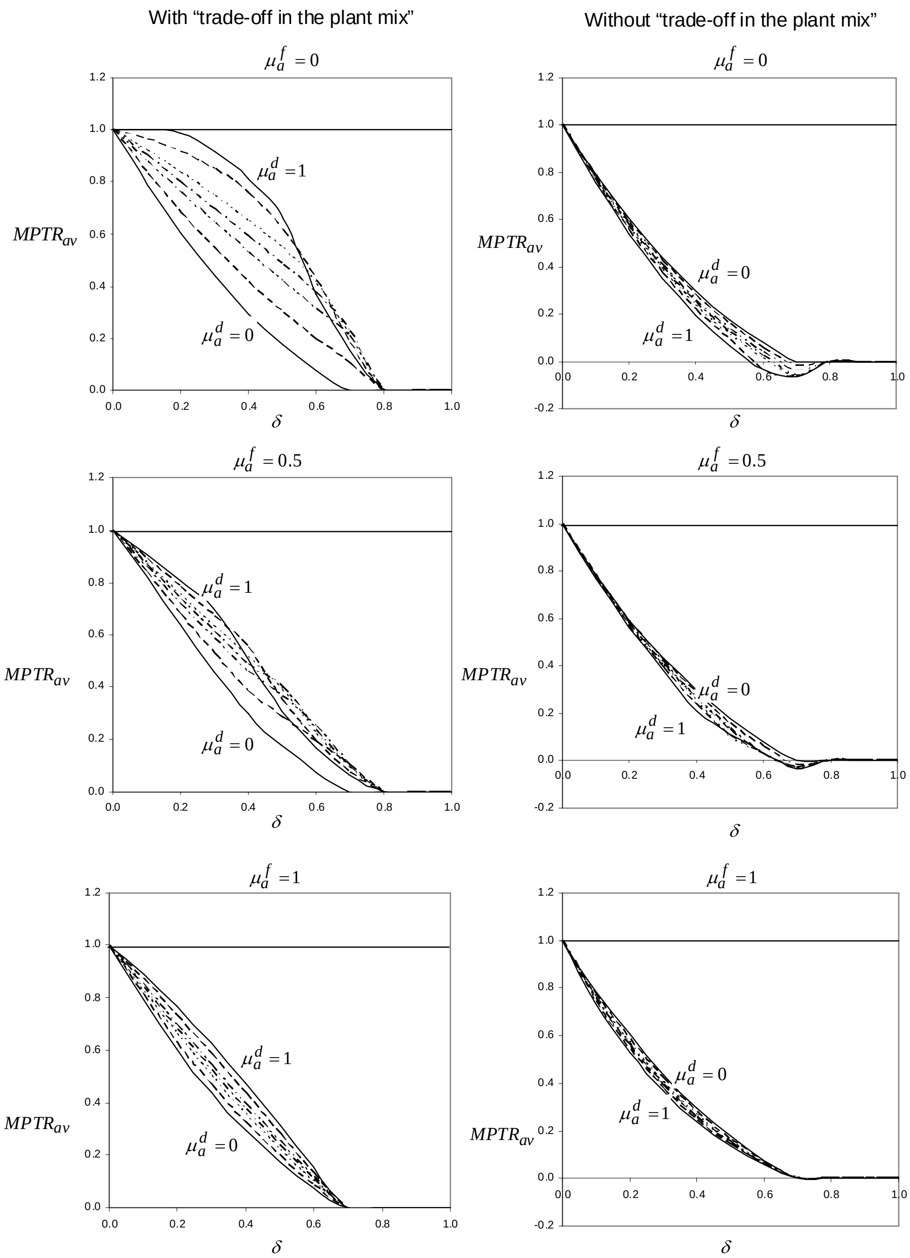

Figure 12: Volume weighted average marginal pass-through rate ($MPTR_{av}$): low allowance prices and without excess capacity

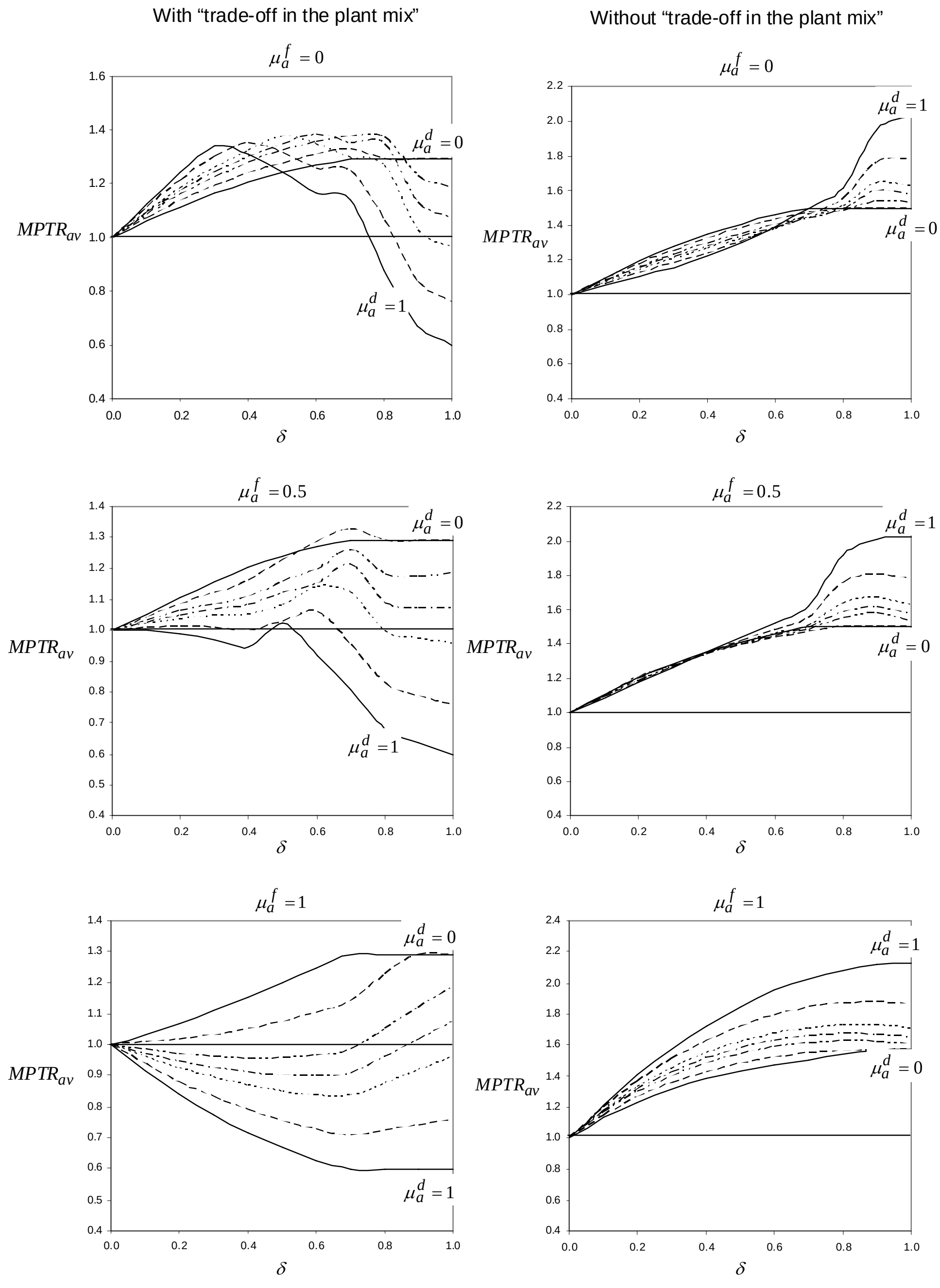

Figure 13: Volume weighted average marginal pass-through rate ($MPTR_{av}$): low allowance prices and excess capacity

the impact under market power is always more than that under perfect competition and increase in μ_a^d (except when μ_a^f and δ are low enough).

Therefore, quantitative simulations confirm the visual interpretation proposed in the previous section.

Second, the simulation highlights that the relative impact of market power may be relevant. The average MPTR ranges from 0.5 to 2.0 under excess capacity and from -0.1 to 1 without excess capacity.

Similar results arise in the case of high allowance prices (Figures A3 and A4 in the Appendix). This time, however, if there is "trade-off in the plant mix" and μ_a^f is enough large, $MPTR_{av}$ can be less than 1 even if δ and μ_a^d are low[27].

Overall, the ETS impact under imperfect competition is always less than that under perfect competition when there is scarcity of generation capacity in the market. Instead, when there is excess capacity the $MPTR_{av}$ is always more than 1 except for certain technological mix of the power system.

8. The impact on emissions

In order to estimate the impact of the ETS on emissions, we abandon the assumption of price inelasticity of demand and suppose, without loss of generality, that $D(p, H) = \alpha(H) - \beta p$, i.e. downward sloping linear demand whose slop does not depend on the time of consumption[28].

In the short run, the environmental regulation can modify the amount of pollutant emissions throughout two ways. On the one hand, it may determine a rise in power prices and consequently a decrease in power demand (and production). On the other hand, if the allowance price is above the "switching price", it may determine a switch in the merit order of the generation plants, drastically modifying the production by the different groups of plants (and consequently, total emissions).

In imperfectly competitive markets, other than the two above mentioned effects, we

number of (peak) hours in which prices converge to the marginal cost of the least polluting plants (b), in the former case, and to the marginal cost of the peaking technology (c), in the latter case.

[27] In this case, in fact, the increase in prices equals the carbon cost of the most polluting plants (a) in most hours, under perfect competition. Under market power, instead, the increase in prices is significantly less than the carbon cost of the most polluting plants in most hours, because of the "switching effect".

[28] Indeed, this assumption does not reflect what occors in the real power market where price elasticity changes during the rime of consumption.

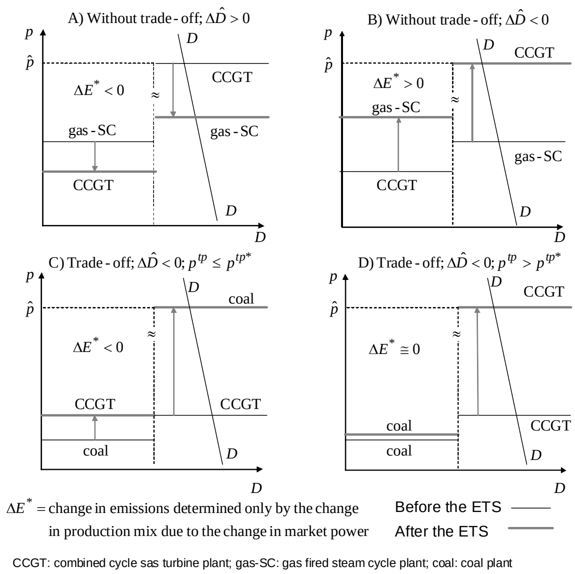

Figure 14: Change in market power and change in emissions: examples

have to take into account an additional effect, i.e. the impact of environmental regulation on the degree of market power.

To understand how change in market power may affect emissions, it is helpful to start by showing the simplified case in which the dominant firm operates only one group of generating plants and the fringe only the other one. Figure 3.14 illustrates how the change in market power modifies the production by the two groups of plants and consequently the total emissions by the power system in the reference period. Notice that in all cases we refer to power markets organized in the form of a uniform price auction.

The first graph (A) highlights what occurs when the degree of market power decreases ($\Delta\widehat{D} > 0$) and there is not "trade-off in the plant mix". We assume that the dominant firm operates only CCGT plants and the fringe only gas-fired steam cycle plants (gas-SC). Before the ETS, the dominant firm accomodates maximum production by the fringe (in gas-SC plants) and bids the price threshold by restraining its production (CCGT plants). After the ETS, this time the dominant firm prefers to maximize its production (CCGT plants) by bidding prices below the marginal cost of the fringe's plants (gas-SC plants). Therefore, since CCGT are less polluting than gas-SC, the change in market power determines a decrease in carbon emissions. Inversely, if the ETS causes a rise in market power (graph B).

Under "trade-off in the plant mix" and for allowance prices below the "switching price" the outcome is exactly the opposite (graph C), assuming that the dominant firm operates only coal plants and the fringe only CCGT plants. This time, the increase in market power determines a decrease in emissions. If the allowance price is above the "switching price", the change in pollutant emissions due the change in market power is marginal (graph D). However, this does not mean that there would not be any change in emissions. Instead, they strongly go down but this fall would be due to the switch in the merit order and not to the change in market power.

Once again, some numerical examples help us to appreciate the extent of these effects. As above, we assume that $D(p,H) = \alpha(H) - \beta p$ (with $\beta = 0.5$) and the extreme combinations of $\underline{\mu}^d$ and $\underline{\mu}^f$ together with the symmetric case ($\underline{\mu}^d$=$\underline{\mu}^f = 0.5$).

	Perfect competition				Impefect competition			
	p^{tp} (Euro/tCO$_2$)				p^{tp} (Euro/tCO$_2$)			
	0	20	40*	60	0	20	40*	60
	IN$^{(1)}$	%	%	%	IN$^{(1)}$	%	%	%
$\delta = 0.7$, $\beta = 0.5$								
With excess capacity ($\widehat{p} = MC_c$)								
$\mu_a^d = 1$, $\mu_a^f = 0$	100	-0.41	-12.38	-12.88	90.0	-9.70	-17.00	-17.19
$\mu_a^d = \mu_a^f = 0.5$	90.0	-0.27	-29.18	-29.57	87.7	-2.20	-21.53	-22.53
$\mu_a^d = 0$, $\mu_a^f = 1$	75.0	-0.05	-28.05	-28.36	75.0	-0.50	-0.06	-7.89
Without excess capacity ($\widehat{p} = \overline{p}$)								
$\mu_a^d = 1$, $\mu_a^f = 0$	100	-0.41	-12.38	-12.88	81.2	-1.10	-2.17	-2.17
$\mu_a^d = \mu_a^f = 0.5$	90.0	-0.27	-29.18	-29.57	85.3	-0.22	-18.44	-18.79
$\mu_a^d = 0$, $\mu_a^f = 1$	75.0	-0.05	-28.05	-28.36	75.0	0.00	0.00	-1.63

$^{(1)}$ IN: Index Number:$^{(*)}$ "switching price"

Table 3.3 Change in carbon emissions: numerical simulations ("trade-off in the plant mix")

	Perfect competition				Impefect competition			
	p^{tp} (Euro/tCO_2)				p^{tp} (Euro/tCO_2)			
	0	20	40*	60	0	20	40*	60
	IN(1)	%	%	%	IN(1)	%	%	%
$\delta = 0.7$, $\beta = 0.5$								
With excess capacity ($\widehat{p} = MC_c$)								
$\mu_a^d = 1$, $\mu_a^f = 0$	100	-0.23	-0.46	-0.69	88.3	1.11	2.11	3.03
$\mu_a^d = \mu_a^f = 0.5$	106.0	-0.27	-0.54	-0.81	92.5	-0.09	-0.10	-0.17
$\mu_a^d = 0$, $\mu_a^f = 1$	114.9	-0.28	-0.55	-0.82	100	-0.42	-0.84	-1.26
Without excess capacity ($\widehat{p} = \overline{p}$)								
$\mu_a^d = 1$, $\mu_a^f = 0$	100	-0.23	-0.46	-0.69	87.0	-0.28	-0.64	-1.14
$\mu_a^d = \mu_a^f = 0.5$	106.0	-0.27	-0.54	-0.81	94.7	-0.08	-0.17	-0.29
$\mu_a^d = 0$, $\mu_a^f = 1$	114.9	-0.28	-0.55	-0.82	100	0.00	0.00	0.00

(1) IN: Index Number; (*) "switching price"

Table 3.4 Change in carbon emissions: numerical simulations (without "trade-off in the plant mix")

Tables 3.3 and 3.4 report the change in emissions on percentage basis for both the perfectly and imperfectly competitive scenarios. Form these tables the following conclusions can be drawn.

First, under "trade off in the plant mix" and below the "switching price" the ETS determines a decrease in emissions which is higher under imperfect than under perfect competition in most cases. Vice versa, if the allowance price is above the "switching price".

Second, as expected, under "trade-off in the plant mix", total emissions strongly fall if the allowance price is above the "switching price". This effect is mostly due to the switch in the merit order and only partially to the decrease in demand and change in market power.

Third, in imperfectly competitive markets emissions may even increase if there is not "trade-off in the plant mix" and under excess of generation capacity, provided that the share of least polluting plants operated by the dominant firm is large enough.

Resuming, taking into account market structures is essential to evaluate how the ETS impacts on emissions in the short run. This analysis in fact demonstrates that under imperfect competition the ETS, by affecting the degree of market power, is able to significantly influence total emissions. In some cases, change in market power amplify the decrease in emissions. In other cases, instead, it can lessen or offset this effect, up to involving a rise in pollution. Thus, under certain conditions imperfect competition might make more difficult to achieve the environmental targets.

9. Conclusions

The analysis described in this paper highlights that the impact of the ETS on power prices significantly depends on electricity market structures. Under perfect competition, power prices fully internalize the carbon opportunity cost. Under market power the extent to which the carbon cost is passed through into power prices depends on several factors: *(i)* the degree of market concentration, *(ii)* the plant mix operated by either the dominant firm or the competitive fringe, *(iii)* the price of the CO_2 emissions allowances and *(iv)* the available capacity in the market (whether there is excess capacity or not).

In particular, the theoretical analysis points out that the pass-through under imperfect competition is always lower than under perfect competition if there is a scarcity of generation capacity in the market. Otherwise, the marginal pass-through rate is always above one, except for two cases with "trade-off in the plant mix: under low allowance prices (below the "switching price"), when a large share of most polluting plants operated by the dominant firm combines with a high degree of market concentration, and under high allowance prices, if the fringe's share of the least polluting plants is large enough. Furthermore, the average pass-through under market power can even be slightly negative (decreasing rather than increasing prices) if the ETS determines a decrease in the degree of market power. This can occur if there is not "trade-off in the plant mix" and under a scarcity of generation capacity provided that the degree of market concentration is high enough.

Finally, the ETS can determine a change in short-run emissions through three effects: *i)* a change in power demand due to a change in power prices; *ii)* a possible switch in the merit order and *iii)* a change in the degree of market power. The analysis highlights that this last effect can cause an increase in carbon emissions only when there is no "trade-off in the plant mix" and under excess capacity, provided that the leader's share of the least polluting (most efficient) plants in the market is large enough. Otherwise, the ETS always determines a decrease in emissions, generally lower under market power than under perfectly competitive scenarios, however. Thus, under certain conditions imperfect competition might make it more difficult to achieve the environmental targets.

10. Appendix

Proof of Lemma 1. It is immediately intuitive that when $D \geq \overline{K}$ the system marginal price equals $\overline{p}$ (for $K_c = 0$) or MC_c (for $K_c = \overline{K}_c$). When $D < \underline{K}^f$, pure Bertrand equilibria (first marginal cost pricing) arise and prices equal the marginal cost of the most efficient plants ($\underline{MC}$). In fact, on the one hand, whenever the demand is so high that both leader's and fringe's least efficient units can enter the market, the dominant firm would not gain any advantage by competing *à la Bertrand,* i.e. by attempting to undercut the rivals. Therefore, it will maximize its profit by bidding the price threshold[29]. On the other hand, whenever the power demand is lower than the fringe's power capacity in most efficient plants, competing *à la Bertrand* is the only leader's available strategy in order to have a positive probability of being dispatched. As a consequence prices will converge to the marginal cost of the most efficient plants.

It remains to identify the leader's optimal choice on $D \in \left]\overline{K}; \underline{K}^f\right]$[30]. Under the assumptions of the model, each generator in the competitive fringe has a unique dominant strategy whatever the market demand is: bidding according to its own marginal cost of production (which, after the implementation of the ETS, includes the carbon opportunity cost). By converse the best choice of the dominant firm might consist in (1) bidding the price cap ($\overline{p}$, if there is not excess capacity, i.e. $K_c = 0$) or the backstop price (MC_c, if there is excess capacity, i.e. $K_c = \overline{K}_c$) or in (2) bidding $\overline{MC}$[31].

Let π_1^d and π_2^d be the profits corresponding to the first and second strategies above, respectively. Whenever the least efficient units could enter the market (i.e. $D(H) > \underline{K}$), the profit the dominant firm earns by choosing the first strategy (i.e. $\forall H \in \left]\overline{H}; \underline{H}\right]$) is

[29] Strictly speaking, only offer prices of units that may become marginal units (i.e. units belonging to the group b) need to equal the price cap or the backstop price.

[30] Note that assuming a dominant firm with competitive fringe model, rather than an oligopolistic framework, assures that equilibria in pure-strategy do exist. For an explanation of why equilibria in pure strategies do not exist in the case of oligopolistic competition, see von der Fehr and Harbord (1993).

[31] Strictly speaking, bidding $\overline{MC}$ for units of kind b and $p \leq \overline{MC} - \epsilon$ (where $\epsilon \simeq 0^+$) for units of kind a.

$$\pi_1^d = (\widehat{p} - \underline{MC})\left[D(H) - K_T(1-\delta)\right] - \sum\nolimits_{i=1}^{z}\sum\nolimits_{j=a,b}\left(k_j^i f_j^i - p^{tp}\overline{E}_j^i\right) \tag{A1}$$

where f_j^i is the capital cost per unit of installed capacity of the i-th unit belonging to the group j of plants and $\overline{E}_j^i$ the amount of allowance allocated (free of charge) to the generic plant i belonging to the group j.

If the dominant firm chooses the second strategy, it earns

$$\pi_2^d = \left(\overline{MC} - \underline{MC}\right)\underline{\mu}^d \delta K_T - \sum\nolimits_{i=1}^{z}\sum\nolimits_{j=a,b}\left(k_j^i f_j^i - p^{tp}\overline{E}_j^i\right) \tag{A2}$$

where $\widehat{p} = \begin{cases} \overline{p} & \text{for } K_c = 0 \\ MC_c & \text{for } K_c = \overline{K}_c \end{cases}$

Therefore the leader's optimal strategy is bidding $\widehat{p}$ if and only if $\pi_1^d \geq \pi_2^d$, i.e. if and only if

$$D \geq \left[\underline{\mu}^d \delta\zeta + (1-\delta)\right]K_T = \widetilde{D}(\delta, \underline{\mu}^d, \zeta) \tag{A3}$$

where $\zeta = \dfrac{\left(\overline{MC} - \underline{MC}\right)}{\widehat{p} - \underline{MC}}$

When $D \in \left]\underline{K}; \underline{K}^f\right]$ (i.e. $H \in \left]\underline{H}; \underline{H}^f\right]$) the profit the dominant firm earns by choosing the first strategy is

$$\pi_3^d = (\widehat{p} - \underline{MC})\left[D(H) - K_T(1-\delta)\right] - \sum\nolimits_{i=1}^{z}\sum\nolimits_{j=a,b}\left(k_j^i f_j^i - p^{tp}\overline{E}_j^i\right) \tag{A4}$$

and by choosing the second strategy, the profit is

$$\pi_4^d = \left(\overline{MC} - \underline{MC}\right)\left[D(H) - K_T\underline{\mu}^f(1-\delta)\right] - \sum\nolimits_{i=1}^{z}\sum\nolimits_{j=a,b}\left(k_j^i f_j^i - p^{tp}\overline{E}_j^i\right) \tag{A5}$$

Thus the dominant firm will choose the first strategy (bidding the price cap or the backstop price) if and only if $\pi_3^d \geq \pi_4^d$, i.e. if and only if

$$D \geq (1-\delta)\left[\frac{(1-\underline{\mu}^f)}{(1-\zeta)} + \underline{\mu}^f\right]K_T = \widetilde{\widetilde{D}}(\delta, \underline{\mu}^f, \zeta) \tag{A6}$$

Therefore the leader's best reply is a function of power demand. We still have to demonstrate that the two critical values $\widetilde{D}$ and $\widetilde{\widetilde{D}}$ never work together, i.e. if $\widetilde{D} \in \left]\overline{K}; \underline{K}\right[$ then $\widetilde{\widetilde{D}} \notin \left]\underline{K}; \underline{K}^f\right[$ and vice versa.

Given that $\overline{K}^f = (1-\underline{\mu}^f)(1-\delta)K_T$, $\underline{K}^d = \underline{\mu}^d\delta K_T, K^f = (1-\delta)K_T$ and $\underline{K} = \left[\underline{\mu}^d\delta + \underline{\mu}^f(1-\delta)\right]K_T$, equation (A3) can be rewritten as

$$D\left(H\right) \geq \widetilde{D}(\delta, \underline{\mu}^{d}, \zeta) = \zeta \underline{K}^{d} + K^{f} \tag{A7}$$

and equation (A6) as

$$D\left(H\right) \geq \widetilde{\widetilde{D}}(\delta, \underline{\mu}^{f}, \zeta) = \frac{\overline{K}^{f}}{1-\zeta} + \underline{K}^{f} \tag{A8}$$

Let's assume for instance that $\widetilde{D} > \underline{K}$. From (A7) $\dfrac{\overline{K}^{f}}{(1-\zeta)} > \underline{K}^{d}$ and from (A8) $\widetilde{\widetilde{D}} > \underline{K}$. Thus, $\widetilde{\widetilde{D}} \notin \left]\underline{K}; \underline{K}^{f}\right[$.

Let's similarly suppose that $\widetilde{\widetilde{D}} < \underline{K}$. From (A8) $\underline{K}^{d} > \dfrac{\overline{K}^{f}}{1-\zeta}$ and from (A7) $\widetilde{D} < \underline{K}$. Thus, $\widetilde{D} \notin \left]\overline{K}; \underline{K}\right[$.

In addition, from (A7) and (A8), if $\widetilde{D} = \underline{K}$ then $\widetilde{\widetilde{D}} = \underline{K}$ and vice versa.

Finally, note that $\widetilde{D} < \overline{K}$ and $\widetilde{\widetilde{D}} > \underline{K}^{f}$.

Last some comparative statics,

$$\frac{\partial \widetilde{D}}{\partial \underline{\mu}^{d}} = \delta \zeta K_{T} > 0; \ \frac{\partial \widetilde{\widetilde{D}}}{\partial \underline{\mu}^{f}} = -(1-\delta)\frac{\zeta}{1-\zeta} K_{T} < 0$$

In fact, when $\delta > \underline{\delta}$, increasing fringe's share of most efficient plants implies that bidding the marginal cost of the least efficient plants becomes less profitable for the dominant firm compared to bidding the price cap or the backstop price (π_4^d in equation (A5) decreases whereas π_3^d in equation (A4) does not depend on $\underline{\mu}^{f}$). Inversely when we look at the case of $\delta < \underline{\delta}$ and at the rise of $\underline{\mu}^{d}$. This time increasing leader's share of most efficient plants implies that bidding the marginal cost of the least efficient plants becomes more convenient for the dominant firm (π_2^d in equation (A2) increases whereas π_1^d in equation (A1) does not depend on $\underline{\mu}^{d}$). Furthermore,

$$\frac{\partial \widetilde{D}}{\partial \zeta} = \underline{\mu}^{d} \delta K_{T} > 0; \ \frac{\partial \widetilde{\widetilde{D}}}{\partial \zeta} = \frac{(1-\delta)(1-\underline{\mu}^{f})}{(1-\zeta)^{2}} K_{T} > 0$$

Thus, market power is a decreasing function of ζ.

10.1. Proof of Proposition 2. This proposition follows directly from Lemma 1. Since $\widetilde{D}$ and $\widetilde{\widetilde{D}}$ never work together and provided that when $\widetilde{D} = \underline{K}$ then $\widetilde{\widetilde{D}} = \underline{K}$ (see the proof of Lemma 1 above), in order to identify the critical value of δ it sufficient to carry out the locus of points δ ($\underline{\widetilde{\delta}}$) that $\widetilde{D} = \underline{K}$ which is equal to the locus of points δ ($\underline{\widetilde{\widetilde{\delta}}}$) that $\widetilde{\widetilde{D}} = \underline{K}$

$$\underline{\widetilde{\delta}} = \underline{\widetilde{\widetilde{\delta}}} = \underline{\delta} = \frac{\underline{\mu}^f - 1}{\underline{\mu}^f - 1 + \underline{\mu}^d(\zeta - 1)}$$

Furthermore, note that $\widetilde{D} < \overline{K}$ and $\widetilde{\widetilde{D}} > \underline{K}^f$.

10.2. Proof of Lemma 2.

The derivative of $\widehat{D}$ with respect to p^{tp} can be written as

$$\frac{\partial \widehat{D}}{\partial p^{tp}} = \frac{\partial \widehat{D}}{\partial \zeta} \frac{\partial \zeta}{\partial p^{tp}} \tag{A9}$$

Since (from (A3) and (A6))

$$\frac{\partial \widetilde{D}}{\partial \zeta} = \underline{\mu}^d \delta K_T > 0 \text{ and } \frac{\partial \widetilde{\widetilde{D}}}{\partial \zeta} = \frac{(1-\delta)(1-\underline{\mu}^f)}{(1-\zeta)^2} K_T > 0 \tag{A10}$$

then, market power is a decreasing function of ζ.

By differentiating ζ with respect to p^{tp} we get

$$\frac{\partial \zeta}{\partial p^{tp}} = \begin{cases} \dfrac{(e_b - e_a)(v_c - v_a) - (e_c - e_a)(v_b - v_a)}{\left[(v_c - v_a) - p^{tp}(e_c - e_a)\right]^2} & \text{under excess capacity} \\ \dfrac{(e_b - e_a)(\overline{p} - v_a) + e_a(v_b - v_a)}{(\overline{p} - v_a - p^{tp} e_a)^2} & \text{without excess capacity} \end{cases} \quad \text{if } p^{tp} \leq p^{tp*}$$

$$\frac{\partial \zeta}{\partial p^{tp}} = \begin{cases} \dfrac{(e_a - e_b)(v_c - v_b) - (e_c - e_b)(v_a - v_b)}{\left[(v_c - v_b) - p^{tp}(e_c - e_b)\right]^2} & \text{under excess capacity} \\ \dfrac{(e_a - e_b)(\overline{p} - v_b) + e_b(v_a - v_b)}{(\overline{p} - v_b - p^{tp} e_b)^2} & \text{without excess capacity} \end{cases} \quad \text{if } p^{tp} > p^{tp*}$$

Consequently:

if $e_a > e_c > e_b$ and $p^{tp} \leq p^{tp*} \Longrightarrow \dfrac{\partial \zeta}{\partial p^{tp}} < 0$ and $\dfrac{\partial \widehat{D}}{\partial p^{tp}} < 0 \; \forall v_j, e_j$ under excess capacity

whereas under scarcity of capacity $\dfrac{\partial \widehat{D}}{\partial p^{tp}} < 0$ only when $(e_b - e_a)(\overline{p} - v_a) < -e_a(v_b - v_a)$;

if $e_a > e_c > e_b$ and $p^{tp} > p^{tp*} \Longrightarrow \dfrac{\partial \zeta}{\partial p^{tp}} > 0$ and $\dfrac{\partial \widehat{D}}{\partial p^{tp}} > 0 \; \forall v_j, e_j$ under excess capacity whereas under scarcity of capacity $\dfrac{\partial \widehat{D}}{\partial p^{tp}} < 0$ only when $(e_a - e_b)(\overline{p} - v_b) < -e_b(v_a - v_b)$;

if $e_c > e_b > e_a \Longrightarrow \dfrac{\partial \zeta}{\partial p^{tp}} < 0$ and $\dfrac{\partial \widehat{D}}{\partial p^{tp}} < 0$

$$\text{only when} \begin{cases} (e_b - e_a)(v_c - v_a) \; < (e_c - e_a)(v_b - v_a) & \text{under excess capacity} \\ (e_b - e_a)(\overline{p} - v_a) < -e_a(v_b - v_a) & \text{without excess capacity} \end{cases}.$$

From compative statics above, $\widetilde{D}$ and $\widetilde{\widetilde{D}}$ are increasing functions of ζ. Thus, if there is excess capacity and 'trade-off in the plant mix' market power always increases (decreases) in p^{tp} if $p^{tp} \leq p^{tp*}$ (if $p^{tp} > p^{tp*}$). Without 'trade-off in the plant mix' market power always decreases in p^{tp} if there is a scarcity of capacity. Otherwise the change on market power depends on on the relative values of variable costs and emission rates of the different kinds of technologies.

10.3. Proof of Corollary 1. By differentiating $\dfrac{\partial \widehat{D}}{\partial p^{tp}}$ with respect to μ_a^d and μ_a^f, we get (from (A9) and (A10))

$$\text{if } p^{tp} \leq p^{tp*} \Longrightarrow \frac{\partial^2 \widetilde{D}}{\partial p^{tp} \partial \mu_a^d} = \delta \frac{\partial \zeta}{\partial p^{tp}} K_T \text{ and } \frac{\partial^2 \widetilde{\widetilde{D}}}{\partial p^{tp} \partial \mu_a^f} = -\frac{1}{(1-\zeta)^2} \frac{\partial \zeta}{\partial p^{tp}} K_T$$

$$\text{if } p^{tp} > p^{tp*} \Longrightarrow \frac{\partial^2 \widetilde{D}}{\partial p^{tp} \partial \mu_a^d} = -\delta \frac{\partial \zeta}{\partial p^{tp}} K_T \text{ and } \frac{\partial^2 \widetilde{\widetilde{D}}}{\partial p^{tp} \partial \mu_a^f} = \frac{1}{(1-\zeta)^2} \frac{\partial \zeta}{\partial p^{tp}} K_T$$

Thus from comparative statics above (Proofs of Lemma 2) we get:

i) if $e_a > e_c > e_b$ and $p^{tp} \leq p^{tp*} \Longrightarrow \dfrac{\partial^2 \widetilde{D}}{\partial p^{tp} \partial \mu_a^d} < 0$ and $\dfrac{\partial^2 \widetilde{\widetilde{D}}}{\partial p^{tp} \partial \mu_a^f} > 0 \; \forall v_j, e_j$ under excess capacity whereas under scarcity of capacity $\dfrac{\partial^2 \widetilde{D}}{\partial p^{tp} \partial \mu_a^d} < 0$ and $\dfrac{\partial^2 \widetilde{\widetilde{D}}}{\partial p^{tp} \partial \mu_a^f} > 0$ only when $(e_b - e_a)(\overline{p} - v_a) < -e_a(v_b - v_a)$;

ii) if $e_a > e_c > e_b$ and $p^{tp} > p^{tp*} \Longrightarrow \dfrac{\partial^2 \widetilde{D}}{\partial p^{tp} \partial \mu_a^d} < 0$ and $\dfrac{\partial^2 \widetilde{\widetilde{D}}}{\partial p^{tp} \partial \mu_a^f} > 0 \; \forall v_j, e_j$ under excess capacity whereas under scarcity of capacity $\dfrac{\partial^2 \widetilde{D}}{\partial p^{tp} \partial \mu_a^d} > 0$ and $\dfrac{\partial^2 \widetilde{\widetilde{D}}}{\partial p^{tp} \partial \mu_a^f} < 0$ only when $(e_a - e_b)(\overline{p} - v_b) < -e_b(v_a - v_b)$;

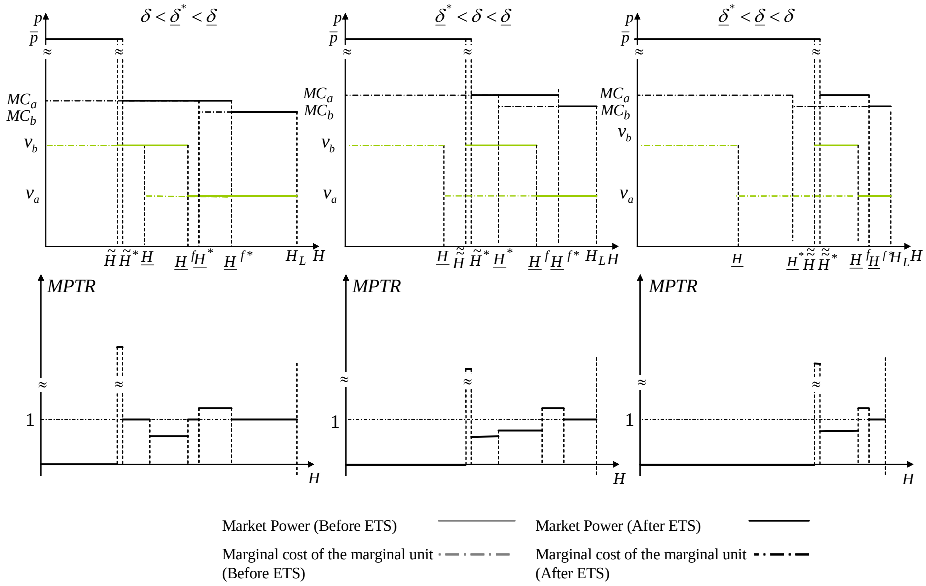

Figure 15: Figure A1. MPTR curves ($\underline{\mu}^d = \underline{\mu}^f$): high allowance prices and without excess capacity

iii) if $e_c > e_b > e_a$ and $(e_b - e_a)(\widehat{v} - v_a) > (\widehat{e} - e_a)(v_b - v_a) \Longrightarrow \dfrac{\partial^2 \widetilde{D}}{\partial p^{tp} \partial \mu_a^d} > 0$ and $\dfrac{\partial^2 \widetilde{\widetilde{D}}}{\partial p^{tp} \partial \mu_a^f} < 0$;

iv) if $e_c > e_b > e_a$ and $(e_b - e_a)(\widehat{v} - v_a) < (\widehat{e} - e_a)(v_b - v_a) \Longrightarrow \dfrac{\partial^2 \widetilde{D}}{\partial p^{tp} \partial \mu_a^d} < 0$ and $\dfrac{\partial^2 \widetilde{\widetilde{D}}}{\partial p^{tp} \partial \mu_a^f} > 0$;

10.4. High allowance prices. In this section, we report the figures referring to the high allowance price scenario. Figures A1 and A2 illustrates the MPTR curves and Figure A3 shows the results of quantitative simulations (the volume-weighted average MPTR). Comments to these figures are reported in the text of this chapter.

For the sake of simplicity, we report only examples referring to the Scenario 1. Figures A1 and A2 refer to an allowance price around 60 €/tonCO_2, just above the "switching price" between coal and CCGT plants. As can be noted, the outcome is very similar to that under low allowance prices (see subsection 2.3.)[32]. This time, however, it is more

[32] As pointed out in note 11, explaining how the ETS can impact on market power under high allowance

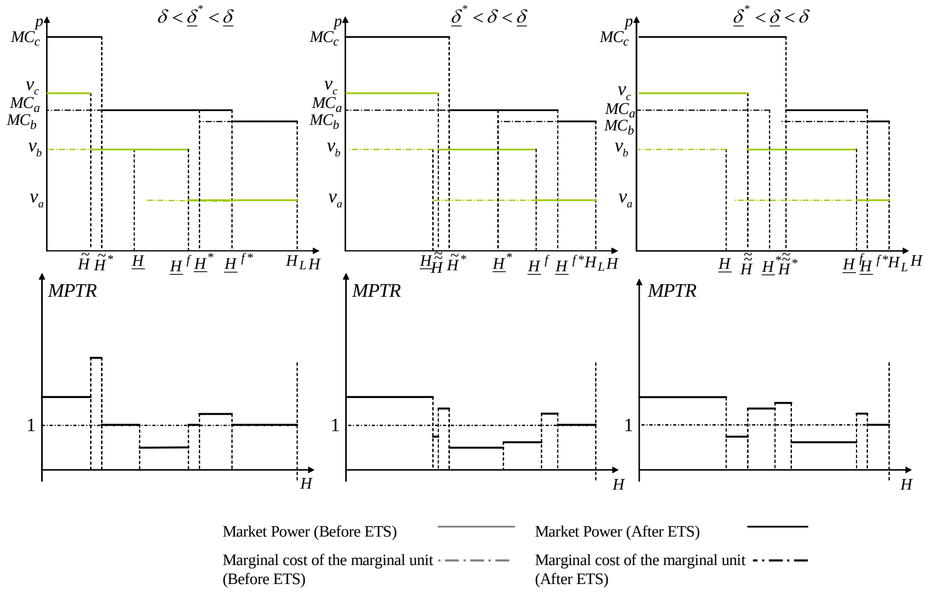

Figure 16: Figure A2. MPTR curves ($\underline{\mu}^d = \underline{\mu}^f$): high allowance prices and with excess capacity

likely that the MPTR could be less than 1 in the off-peak hours.

	Oil-fired steam cycle	Gas-fired steam cycle	CCGT	Coal plant	CHP-CCGT
Variable cost (v), €/MWh	60	56	42	25	33
CO_2 emission rate (e), kg/MWh	790	500	400	840	550
Efficiency (η)	0.35	0.40	0.50	0.40	0.70[(1)]

(1) Including heat (i.e. useful heat plus power divided by fuel consumption)

Table A1 Technical parameters of the power generating plants

prices is beyond the scope of this paper. However, it is possible to demonstrate that $\widehat{K} > \widehat{K}^*$ if the allowance price is not very high (even if above the "switching price). This is the case simulated in figs A1 and A2.

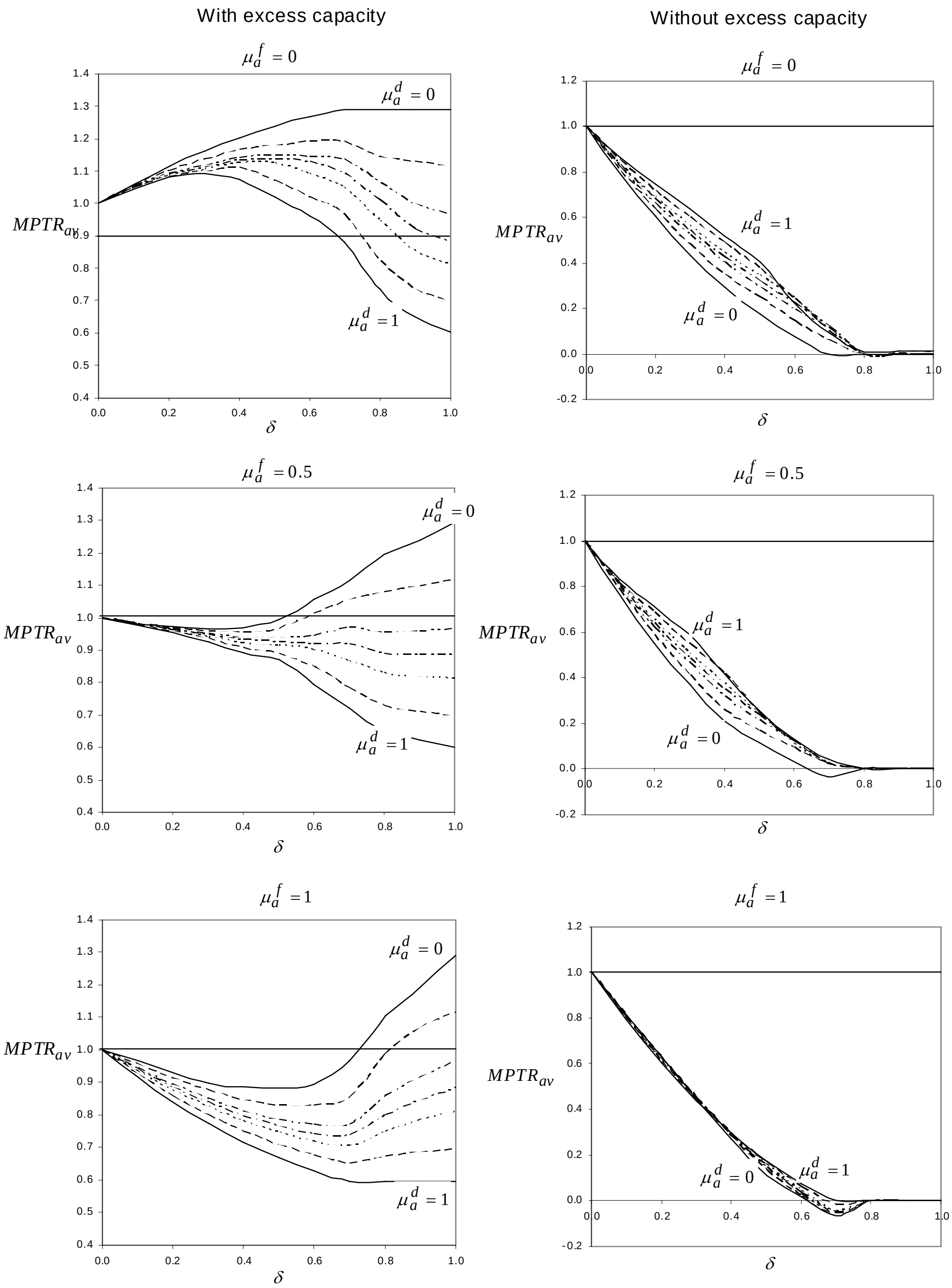

Figure 17: Figure A3. $MPTR_{av}$ with "trade-off in the plant mix" and high allowance prices

10.5. Technical parameters of power plants. Table 3.3 reports variable costs, emission rates and energy efficiencies of power generating technologies adopted throughout the paper.

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