Environmental taxation within electricity auctions with dominant firm

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Abstract. *Should we be confident about the possibility that pollution taxes will effectively reduce pollution? Just a few of papers of the economic literature on the environmental policy have tried to answer this question. Dealing with comparative static effects and relying on one-shot standard models of competition, these papers find that for particular tax-rate intervals taxation can in principle increase pollution if markets are imperfectly competitive, firms are sufficiently asymmetric and certain demand conditions are satisfied (extreme curvature). Focusing on what can actually occur in the electricity market, in which the pricing mechanism is a multi-shot price auction, this article strengthen this result. Increasing pollution is not only theoretically possible. Looking at the real technological conditions of power sectors, it is even very likely if the natural gas/coal price ratio is sufficiently high.*

1. Introduction

In the theoretical literature great effort has been directed to studying the environmental policy in presence of imperfect competition. Recently, Requate (2005) carried out a very useful and interesting survey from which the following framework arises.

First, most of contributions focus on emission taxes and tradable permits and are based on standard models of oligopolistic competition (one-shot Cournot and Bertrand frameworks). Second, just a few of them considers endogenous market structures[1]. Third, most of papers are mainly interested in the rules for determining the first or second-best levels of the control policy.

In line with this framework, this paper concentrates on emission taxes but deviates from it with regard to the other issues.

[1] Among them, see Requate (1993).

Firstly, we do not use one-shot standard models of competition but multi-shot and multi-unit first price auctions which are well suited to characterize the electricity market (one of the most important environmentally regulated market) where demand for service varies cyclically over time (for example on an hourly basis).

Secondly, in our analysis the endogenous variable is the degree of market power[2] and not the market structure. This choice is due to two reasons. On the one hand, the right way to measure the power market concentration is referring to the share of capacity (and not to the share of production). This latter can not be endogenous since it does not change over time, at least in the short and medium runs. On the other hand, when demand varies cyclically over time (e.g. hour by hour) and prices are constrained below a threshold (as in the case of electricity spot markets), the most important endogenous structural variable is the time over which prices are above the competitive level. This variable is is crucial for the estimation of the impact of taxation on aggregate emissions and is directly correlated to the degree of market power. Unfortunately, its effect can not be captured by the one-shot models, by definition[3] and therefore it is generally ignored by the current literature.

Finally, our analysis is not concerned with describing optimal rates of taxation but it focuses on comparative static effects. In fact, given the huge uncertainty about certain environmental damages[4], searching for the otimal level of the control policy might be less useful than exploring the effects of different levels of tax rates, if we mainly look at the policy implications of the analysis.

Just a few of authors focuses on comparative statics. Among them, Requate (2005) demonstrates that "if firms are sufficiently asymmetric, in the sense that their cost functions are sufficiently different, then it is possible that for particular tax-rate intervals aggregate emissions are increasing"[5]. For the last effect to arise, however, asymmetry of

[2] 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.

[3] By definition, one shot models can not account for how regulation can modify the time over which prices are above the competitive level. Therefore they ignore this impotant endogenous component of market power.

[4] We mainly refer to the marginal cost of carbon dioxide emissions and therefore to the carbon tax.

[5] Following Requate (2005) the intuition is that if the marginal cost differential between the firms is different from the difference in emission coefficients, taxation changes the cost structure between the firms. This can not only lead to a situation where one firm gains whereas the other firm suffers from a tax increase, but can also cause aggregate pollution to rise.

firms does not suffice. The inverse demand function must show an extreme curvature, i.e. it must be either sufficiently convex or sufficiently concave (Levin, 1985)[6].

Unfortunately, as pointed out before, these contributions rely on one-shot models which overestimates the effect on pollution due to imperfect competition since they focus on a single period, namely that period in which firms use market power. By contrast in the electricity markets the demand cycle is divided in several periods. In some of them strategic firms use their market power while in the remaining time they engage in different forms of competition with rivals. It is obivious that the environmental performance must be evaluated by accounting for what occurs in all periods of the demand cycle and not only in those in which firms use market power.

In this paper we prove that taxation can in principle increase pollution even when the pricing mechanism is a multi-shot price auction. Rather this article demonstates that increasing pollution is possible not only theoretically. Looking at the real technological conditions of power sectors, it is even very likely if the natural gas/coal price ratio is sufficiently high.

The article proceeds as follows. Section 2 focuses on the structure of the model used to characterize price equilibria under imperfect competition. Section 3 deals with how taxation can change the degree of market power. Section 4 focuses on how taxation can impact on pollution. Finally, section 5 summarizes the main results of the article.

2. The basic model

2.1. Assumptions. First of all, it is important to describe the structure of the model detailing the main assumptions on the regulation of the output market[7].

We assume that the demand function can be represented by the load duration curve $D(p, H)$ where H is the number of periods (e.g. number of hours) in the reference time period (e.g. the day or the year) that demand is equal to or higher than D, with $0 \leq H \leq H_L$. $D_L(p) = D(p, H_L)$ is the minimum demand and $D_M(p) = D(p, 0)$ is the maximum demand. Furthermore, for all (p, H), $-\infty < \dfrac{\partial D}{\partial p} < 0$, $\dfrac{\partial^2 D}{\partial p^2} < 0$ and $\dfrac{\partial D}{\partial H} < 0$.

To simulate market power we use a dominant firm facing a competitive fringe model

[6] Howerver, Requate (2005) also underlines that if the tax rate is set sufficiently high, so that each firm's output goes down, then aggregate emissions also have to go down, compared to the laissez-faire level.

[7] See also Bonacina and Gullì (2007), Chernyavs'ka and Gullì (2008) and Gullì (2008).

rather than the usual 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[8]. It is often used in the literature concerning environmental policy under imperfect competition[9]. On the practical side, it is well suited to simulate the structural features of several electricity markets.

The leader (d) and the competitive fringe (f) supply the market with capacity given by $S^d > 0$ and $S^f > 0$, respectively. We assume linear technologies whose variable cost of production is $c \geq 0$ and emission rate is $e \geq 0$ (emission per unit of output). Therefore pollution is proportional to output. Finally we assume that taxation is proportional to emissions. The tax rate, τ, is the charge per unit of pollutant emitted.

Without loss of generality, we restrict the analysis to two groups of technologies, a and b. Each of them includes a large number n of homogeneous units[10] such that

$$S_j = \sum_{i=1,2..n} s_j^i = ns_j,\ j = a, b \text{ and } c_j^i = c_j; e_j^i = e_j, \forall i, j$$

where $c_j^i = c_j \geq 0$, $e_j^i = e_j \geq 0$ and $s_j^i = s_j > 0$ are the variable cost, the emission rate and the capacity of the i-th unit belonging to the group j, respectively. Thus S_a and S_b are the installed capacity of groups a and b, respectively. We assume $c_a < c_b$ and $S_a + S_b = S_T = D_M$, i.e. the units of kind a and b are sufficient to meet the maximum demand. Furthermore, we consider two technological scenarios: *i)* 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 ($c_a < c_b$ but $e_a > e_b$), and *ii)* Scenario 2 in which there is not such a trade-off, i.e. the technology with lower variable cost is also the cleaner technology ($c_a < c_b$ and $e_a < e_b$).

[8] In particular, this model allows us to overcome the problem of possible inexistent equilibria in pure strategy. In their article on spot market competition in the UK electricity industry, using a typical duopolistic framework, von der Fehr and Harbord (1993) demonstrate that under variable-demands period (i.e. when the range of possible demands exceeds the capacity of the largest generator) there does not exist an equilibruim in pure strategy. Instead, there exist a unique mixed-strategy Nash equilibrium.

[9] See Innes (1991), Conrad and Wang (1993).

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

Given these assumptions, the marginal cost of the i-th unit belonging to the group j of plants is given by

$$MC_j^i = c_j^i + \tau e_j^i \tag{1}$$

From equation (1) and for the purpose of this analysis, the units belonging to the group j of plants are defined as the most (least) efficient units if their marginal cost is lower (higher) than that of the units belonging to the other group i.

Furthermore, if $e_a > e_b$ there exists a tax rate, the "switching tax" $\tau^* = (c_b - c_a)(e_a - e_b)$, 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. Then the tax rate is defined as low if $\tau < \tau^*$ and high if $\tau \geq \tau^*$. Finally, $\overline{MC} = \max\{MC_a = c_a + \tau e_a; MC_b = c_b + \tau e_b\}$ is the marginal cost of the least efficient plants and $\underline{MC} = \min\{MC_a = c_a + \tau e_a; MC_b = c_b + \tau e_b\}$ the marginal cost of the most efficient ones.

With regard to the organization of the electricity market, we consider a typical spot market in which the pricing mechanism is a multi-shot uniform price auction. Firms simultaneously submit bid prices for each of their units and for each period (each hour). The auctioneer 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, firms are paid according to the market-clearing spot 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 firms' installed capacity are common knowledge.

Finally, we assume that firm's offer prices are constrained 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. For instance firms believe that the regulator will introduce (or change) price regulation if the price rises above a certain threshold. Alternatively, firms may believe that the regulator will introduce or modify regulation when profit rises above a certain value. In this last case (profit target) we should talk about a (flexible) price threshold profile rather than a single price threshold.

Under an official price cap, it is appropriate to assume that the price threshold does not depend on the tax rate. In fact, given the very low price elasticity of demand, the price cap is generally so high that it does not worth to change it in order to account for the tax rate.

By contrast, under a profit threshold, taxation would determine a change in the dominant firm's profit. This change may be compensated by passing through the tax rate into the price threshold. Therefore it seems to be reasonable that the price threshold could depend on the tax rate and that the dominant firm could pass through less than the increase in cost (due to taxation) of its plants. Indeed we think that the most likely situation would be that in which, in order to avoid more restrictive regulation, the dominant firm passes through much less than the increase in cost of the least polluting plants, i.e. $d\widehat{p}/d\tau < e_b$ (if $e_b < e_a$) and $d\widehat{p}/d\tau < e_a$ (if $e_b > e_a$).

Finally, another way of interpreting the price threshold is supposing that there is so much generation that price never is above the marginal cost of a peaker (technology c). In this case $d\widehat{p}/d\tau$ may be either higher or lower than the increase in cost of the operating plants (a and b), depending of the technological features of the peaker.

2.2. Equilibria. Given the regulatory framework described above, it is straightforward that price equilibria will depend on the power demand level. Since this latter continuously varies 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 periods in the year that price is equal to or higher than p.

As previously pointed out, we adopt a dominant firm facing a competitive fringe model. 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 capacity in the market operated by the dominant firm. Then the competitive fringe will operate a share $(1 - \delta)$ of the total capacity. and 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 capacity 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 same in the least efficient ones.

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

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

Finally, $\underline{S} = \left[\underline{\mu}^d\delta + \underline{\mu}^f(1-\delta)\right] S_T$ is the total capacity in most efficient plants.

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

Lemma 1. *There exists* $\widehat{D} \in \left]D_M; \underline{S}^f\right]$ *such that*

(i) if $D \geq \widehat{D}$*, in any equilibrium the system marginal price equals the price threshold,* $\widehat{p}$*;*

(ii) if $\underline{S}^f \leq D < \widehat{D}$*, in any equilibrium the system marginal price equals the marginal cost of the least efficient plants (*$\overline{MC}$*);*

(iii) if $D < \underline{S}^f$*, pure Bertrand equilibria (first marginal cost pricing) arise and prices equal the marginal cost of the most efficient plants (*$\underline{MC}$*), where*

$$\widehat{D} = \begin{cases} D_1\left(\delta, \underline{\mu}^d, \zeta\right) = \left[\underline{\mu}^d\delta\zeta + (1-\delta)\right] S_T & \text{for } \widehat{D} > \underline{S} \\ D_2\left(\delta, \underline{\mu}^f, \zeta\right) = (1-\delta)\left[\dfrac{(1-\underline{\mu}^f)}{(1-\zeta)} + \underline{\mu}^f\right] S_T & \text{for } \widehat{D} \leq \underline{S} \end{cases} \quad \text{with } \zeta = \frac{\left(\overline{MC} - \underline{MC}\right)}{\widehat{p} - \underline{MC}}$$

Proof. See Appendix. ■

We consider $\widehat{D}$ as the proxy of the degree of market power. In fact, $\widehat{H} = D^{-1}(\widehat{D})$ is the time (the number of hours) over which the dominant firm is able to set the price threshold[11].

Lermma 1 highlights that two price duration curves are possible depending on whether the discontinuity is at $H_1 = D^{-1}(D_1)$ or $H_2 = D^{-1}(D_2)$.

Finally, by differentiating D_1 and D_2 with respect to $\underline{\mu}^d$ and $\underline{\mu}^f$ we find that the degree of market power is an increasing function of $\underline{\mu}^f$, when $\widehat{D} < \underline{S}$, and a decreasing function of $\underline{\mu}^d$, when $\widehat{D} \geq \underline{S}$ (see Appendix).

[11] Indeed, the dominant firm exerts his market power not only when it bids the residual monopoly price but also when it is able to set prices just below the marginal cost of the least efficient units whereas under perfect competition prices would converge to the marginal cost of the most efficient ones. We ignore this "second effect" since it depends on $\underline{S}^f$ which does not depend on the tax rate.

3. The effect on market power

Lemma 1 highlights that the degree of market power depends on ζ. Since this latter depends on the tax rate, the environmental regulation is able to modify the degree of market power. The following lemma describes how this can occur.

Lemma 2. *(i)* $\partial\widehat{D}/\partial\tau \lesseqgtr 0$ *if* $\Gamma = (e_b - e_a)(\widehat{p}(0) - c_a) - (d\widehat{p}/d\tau - e_a)(c_b - c_a) \lesseqgtr 0$ *when* $\tau < \tau^*$. *(ii)* $\partial\widehat{D}/\partial\tau \lesseqgtr 0$ *if* $\Gamma \gtreqless 0$ *when* $\tau \geq \tau^*$.

Proof. For the formal proof, see 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. This occurs 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. ■

Table 1 shows the results corresponding to the possible combinations e_a, e_b, τ, $\widehat{p}$ and $\partial\widehat{p}/\partial\tau$. Note that, when $\tau \geq \tau^*$, then $\Gamma \ngtr 0$ and that the first derivative of $\widehat{D}$ with respect to τ is positive whatever $\partial\widehat{p}/\partial\tau$. However this does not mean that the introduction of the pollution tax (discrete variation of τ) is not able to increase market power. In fact, shifting from $\tau = 0$ to $\tau > \tau^*$ (discrete variation), the discrete change in market power ($\Delta\widehat{D}$) can be either positive or negative depending on the tax rate and on the share of most efficient plants operated by either the dominant firm or the competitive fringe. The following corollary describes how $\widehat{D}$ and $d\widehat{D}/d\tau$ depend on μ_a^d and μ_a^f.

Corollary 1. *(i) If* $e_b < e_a$ *and* $\tau < \tau^*$ *then both* $\widehat{D}$ *and* $d\widehat{D}/d\tau$ *are increasing (decreasing) in* μ_a^d (μ_a^f). *(ii) Vice versa if* $\tau \geq \tau^*$.

Proof. See Appendix. ■

By using this corollary it is possible to depict $\widehat{D}(\tau)$ for different values μ_a^d and μ_a^f. As can be noted (Fig. 1), when $\tau \geq \tau^*$ and if low μ_a^d combines with large μ_a^f then it is likely that $\Delta\widehat{D} > 0$ (shifting from $\tau = 0$ to $\tau > \tau^*$). Vice versa if large μ_a^d combines with low μ_a^f.

Table 1. Change in the degree of market power ($\widehat{D}$): in brackets discrete variation ($0 - \tau$)

	Change in market power			
	$\tau < \tau^*$		$\tau \geq \tau^*$	
	$\Gamma < 0$	$\Gamma > 0$	$\Gamma < 0$	$\Gamma > 0$
	I	II	III	IV
$A)\ e_b < e_a$				
$A1)\ \widehat{p} = \overline{p}\ (d\widehat{p}/d\tau = 0)$	$\partial\widehat{D}/\partial\tau < 0$ $(\Delta\widehat{D} < 0)$	$\partial\widehat{D}/\partial\tau > 0$ $(\Delta\widehat{D} > 0)$	$\partial\widehat{D}/\partial\tau > 0$ $(\Delta\widehat{D} \lesseqgtr 0)$	
$A2)\ \widehat{p} = \widehat{p}(\tau)$				
$A21)\ d\widehat{p}/d\tau < e_b$	$\partial\widehat{D}/\partial\tau < 0$ $(\Delta\widehat{D} < 0)$	$\partial\widehat{D}/\partial\tau > 0$ $(\Delta\widehat{D} > 0)$	$\partial\widehat{D}/\partial\tau > 0$ $(\Delta\widehat{D} \lesseqgtr 0)$	
$A22)\ e_b < d\widehat{p}/d\tau < e_a$	$\partial\widehat{D}/\partial\tau < 0$ $(\Delta\widehat{D} < 0)$		$\partial\widehat{D}/\partial\tau > 0$ $(\Delta\widehat{D} \lesseqgtr 0)$	
$A23)\ d\widehat{p}/d\tau > e_a$	$\partial\widehat{D}/\partial\tau < 0$ $(\Delta\widehat{D} < 0)$		$\partial\widehat{D}/\partial\tau > 0$ $(\Delta\widehat{D} \lesseqgtr 0)$	
$B)\ e_b > e_a$				
$B1)\ \widehat{p} = \overline{p}\ (d\widehat{p}/d\tau = 0)$		$\partial\widehat{D}/\partial\tau > 0$ $(\Delta\widehat{D} > 0)$		
$B2)\ \widehat{p} = \widehat{p}(\tau)$				
$B21)\ d\widehat{p}/d\tau < e_b$		$\partial\widehat{D}/\partial\tau > 0$ $(\Delta\widehat{D} > 0)$		
$B22)\ d\widehat{p}/d\tau > e_b$	$\partial\widehat{D}/\partial\tau < 0$ $(\Delta\widehat{D} < 0)$	$\partial\widehat{D}/\partial\tau > 0$ $(\Delta\widehat{D} > 0)$		

Lemma 2 rises the following issues. First, under imperfect competition taxation may lessen or amplify market distortions. Second (and most important), the change in market power due to taxation might significantly impact on pollution as long as it can modify the share of production by the different groups of plants (by increasing production by the most or by the least polluting plants). Thus the following question arises. Can taxation determine a rise (rather than a decrease) in pollution? In the next section we will try to answer this question.

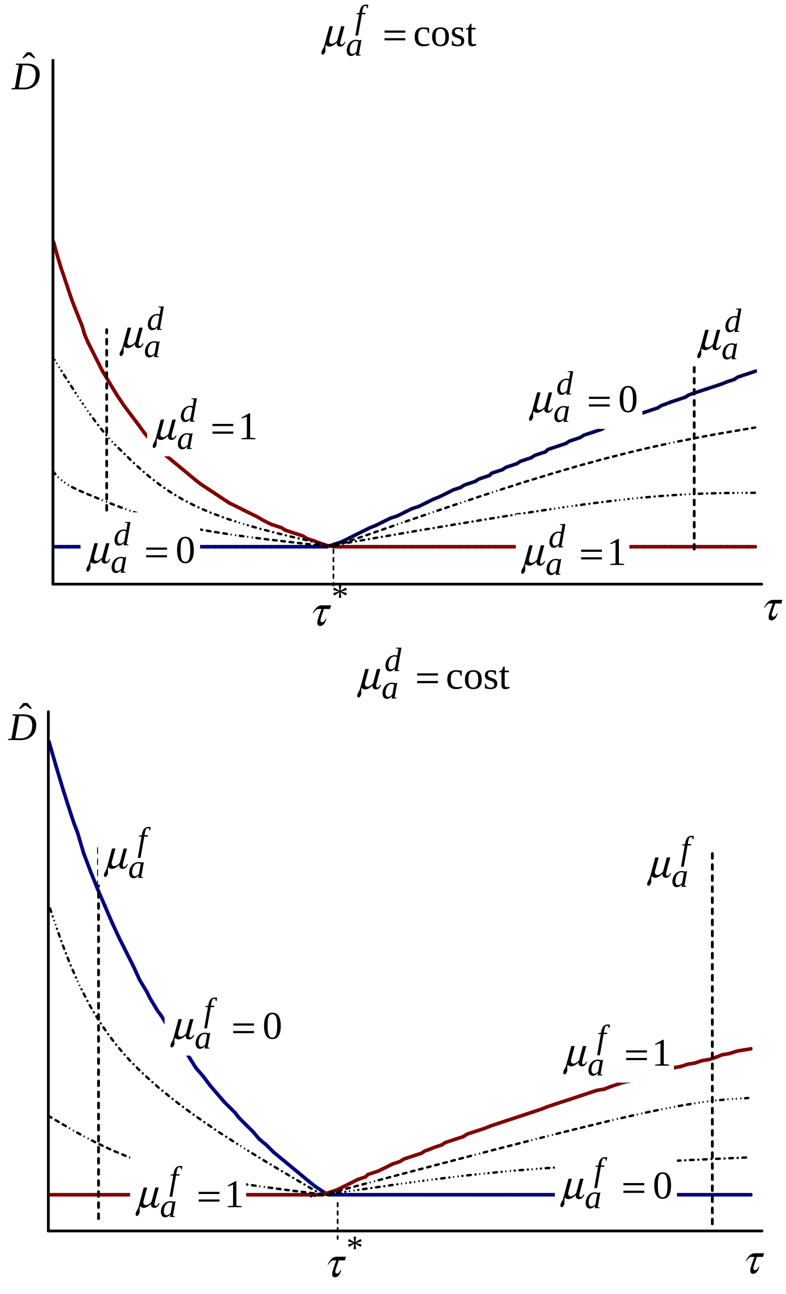

Figure 1: Change in market power due to taxation ($e_b < e_a$)

4. The effect on pollution

To undesrtand how the change in market power can impact on pollution, it is useful to compare the perfectly and imperfectly competitive outcomes.

Looking at the short run, in perfectly competitive markets taxation can modify the amount of pollutant emissions by means of two effects. On the one hand, it determines a decline in pollution as long as it causes an increases in prices and consequently a decrease in demand (and production). On the other hand, if $e_b < e_a$ and if the tax rate is above the "switching tax", it determines a switch of producers on the merit order. This switch reduces significantly the production by the most polluting plants.

In imperfectly competitive markets, apart from these two possible effects, we have to take into account an additional one that is the just mentioned impact of pollution taxes on the degree of market power. This additional effect includes two components: 1) the change in emissions caused by the corresponding change in the share of production by the different groups of technologies (ΔE_{ts}^{mp}) and 2) the change in emissions caused by the corresponding change in prices (ΔE_{D}^{mp}) during the time periods in which the dominant firm changes its strategy. Note that these periods are named as on-change periods whereas the reamining periods, in which the dominant firm's strategy remains unchanged, are named as off-change periods.

To understand how this additional effect may affect emissions, it is helpful to start by showing the simplified case in which the dominant firm operates only one group of units (a) and the fringe only the other one (b), that is $\mu_a^d = 1$ and $\mu_a^f = 0$.

Figures from 2 to 6 illustrate how the change in market power can modify the production by the two groups of units and consequently the aggregate emissions in a generic on-change period (one shot analysis). Remind that in all cases the pricing mechanism is an uniform first price auction. In each figure we report the expected sign of the two components described above.

In figures 2 and 3, $e_b < e_a$ and $\tau < \tau^*$ are assumed. Under these assumptions and from Lemma 1 there may be either an increase ($\Delta\widehat{D} < 0$) or a decrease ($\Delta\widehat{D} > 0$) in market power depending on the relative values of variable costs and emission rates (i.e. depending on Γ) and depending on the price threshold.

Figure 2 shows the former case ($\Delta\widehat{D} < 0$). Before taxation, the dominant firm prefers to maximize its production (units a) by bidding prices below the marginal cost of the

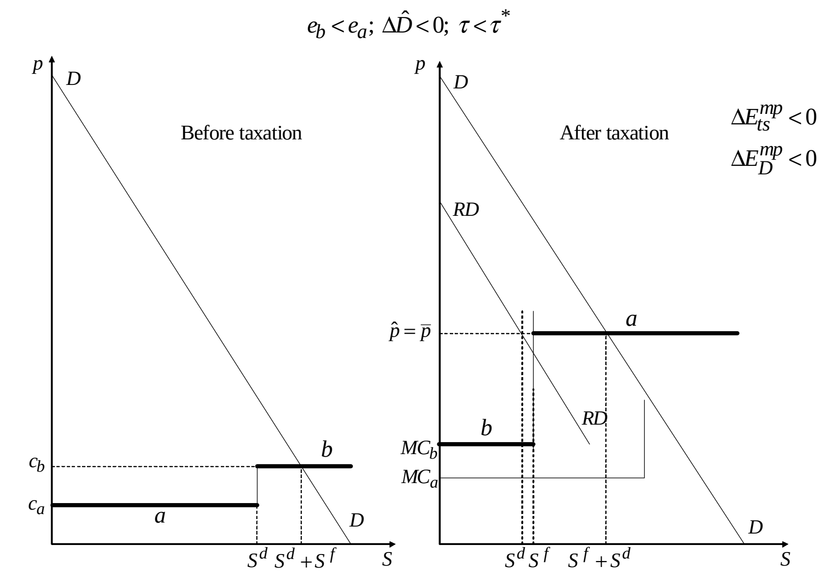

Figure 2: Change in emissions due to the change in market power ($e_b < e_a; \Delta\widehat{D} < 0; \tau < \tau^*; \mu_a^d = 1; \mu_a^f = 0$)

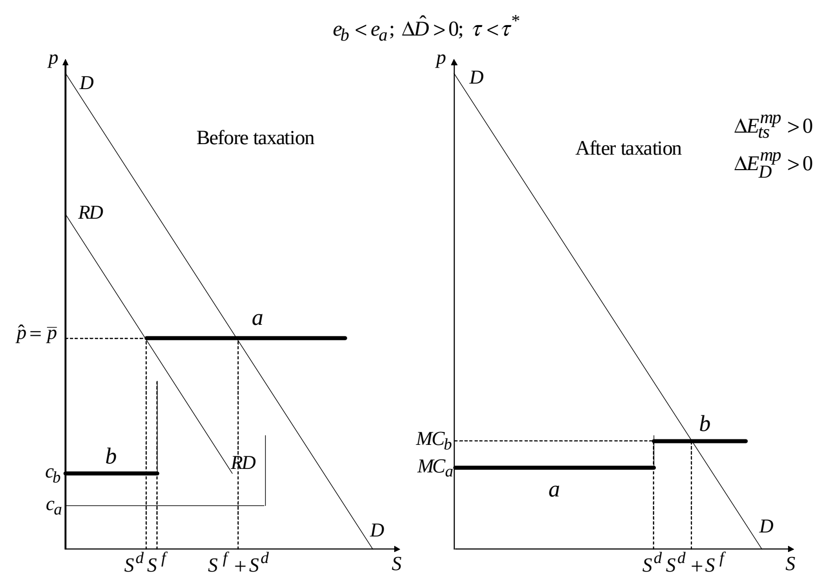

Figure 3: Change in emissions due to the change in market power ($e_b < e_a; \Delta\widehat{D} > 0; \tau < \tau^* \ \mu_a^d = 1; \mu_a^f = 0$)

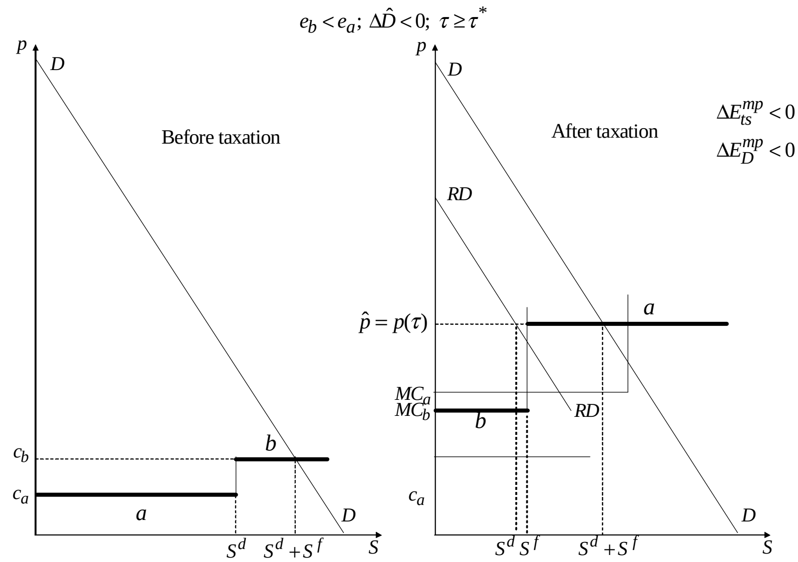

Figure 4: Change in emissions due to the change in market power ($e_b < e_a; \Delta\widehat{D} > 0$; $\tau \geq \tau^*$; $\widehat{p} = \overline{p}$; $\mu_a^d = 1$; $\mu_a^f = 0$)

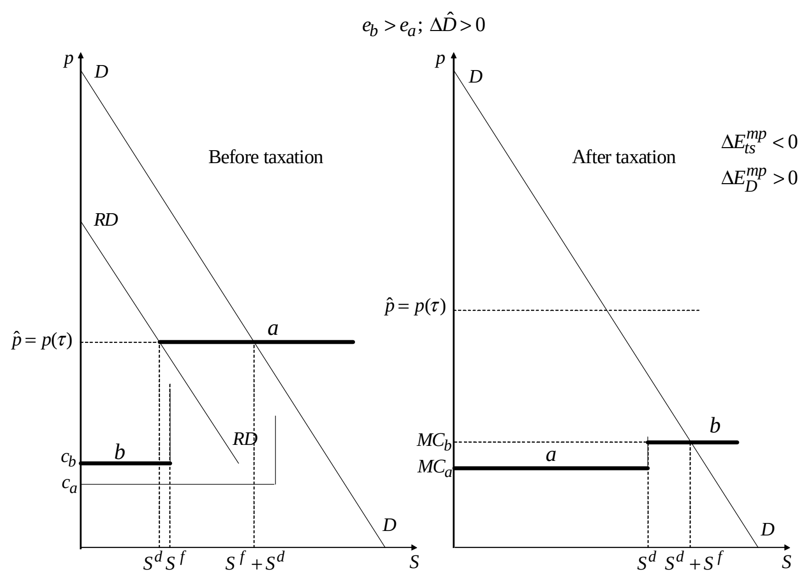

Figure 5: Change in emissions due to the change in market power ($e_b > e_a; \Delta\widehat{D} > 0; \mu_a^d = 1; \mu_a^f = 0$)

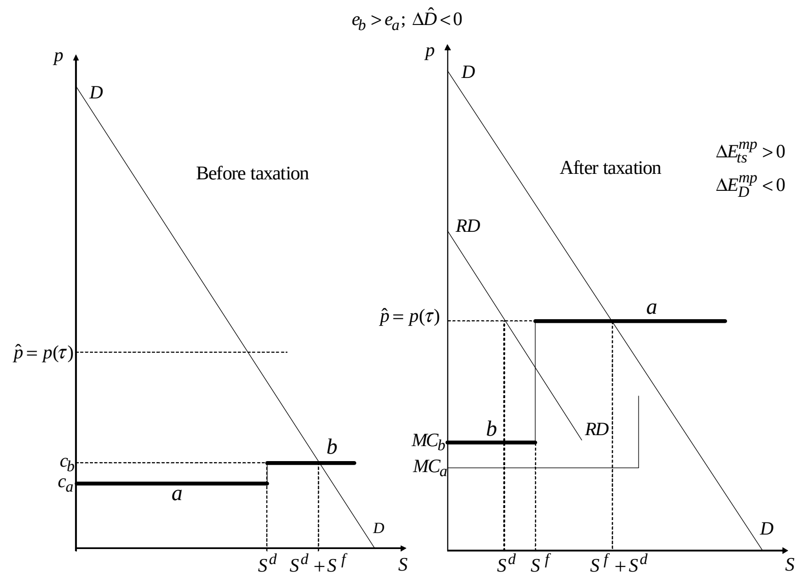

Figure 6: Change in emissions due to the change in market power ($e_b > e_a; \Delta\widehat{D} < 0; \mu_a^d = 1; \mu_a^f = 0$)

fringe's plants (units b). After taxation, the dominant firm accomodates maximum production by the fringe (units b) and bids the price threshold by restraining its production (units a). Therefore, the increase in market power determines a decrease in production by the most polluting plants a. Since units a are more polluting than units b, the change in market power determines a decrease in emissions ($\Delta E_{ts}^{mp} < 0$). In addition, the increase in price involves a decrease in demand and consequently a further reduction in production ($\Delta E_D^{mp} < 0$) during the on-change periods.

Figure 3 shows an example of what might happen when $\Delta\widehat{D} > 0$. This time, before taxation the leader bids the price threshold by restraining its production (units a) and accomodating the fringe's maximum production (units b). After taxation, the dominant firm prefers to maximize its production (units a) by bidding prices below the marginal cost of the fringe's plants (units b). Therefore, since units a are more polluting than units b, the change in market power determines an increase in emissions ($\Delta E_{ts}^{mp} > 0$) which is amplified ($\Delta E_D^{mp} > 0$) by the rise in production due to the demand effect (the drop in price) during the on-change periods.

When $e_b < e_a$ and $\tau \geq \tau^*$ only the case in which $\Delta\widehat{D} < 0$ is possible if $\mu_a^d = 1$ (see

Fig. 1). Before taxation, the dominant firm maximizes its production (units a) whereas after taxation it necessarily sets price equal to the threshold since the units a are now the least efficient ones. Therefore (Fig. 4), since $e_b < e_a$ then $\Delta\widehat{D} < 0$ implies a decrease in emissions ($\Delta E_{ts}^{mp} < 0$) amplified by the the drop in demand due to the rise in prices ($\Delta E_{D}^{mp} < 0$) during the on-change hours.

Finally, figures 5 and 6 describe what happens when $e_b > e_a$. In particular, if $\Delta\widehat{D} > 0$ (Fig. 5) taxation determines an increase in the production share of the least polluting plants (units a). Therefore on the one hand $\Delta E_{ts}^{mp} < 0$. On the other hand, the fall in market power determines a decrease in prices and consequently an increase in emissions ($\Delta E_{D}^{mp} > 0$) during the on-change periods. By contrast, if $\Delta\widehat{D} < 0$ (Fig. 6) the share of production by the most polluting plants (units b) rises ($\Delta E_{ts}^{mp} > 0$). Nevertheless, the increase in market power determines an increase in prices and consequently a drop in emissions ($\Delta E_{D}^{mp} < 0$) in the on-change hours.

The examples described above highlight that one or both market power components may be positive. This means that during the periods in which taxation can change the dominant firm's strategy (on-change hours) there may be an increase in pollution. Then the following question arises, looking at what may occur in the entire demand cycle (i.e. including the what occurs in the off-change hours). Can this increase completely offset the effectiveness of the environmental regulation that is can taxation determine a rise (rather than a decrease) in pollution? The following proposition and corollary try to answer this question.

Proposition 1. *Under imperfect competition,* $\Gamma > 0$ ($\Gamma < 0$) *is necessary condition for increased pollution if* $e_b < e_a$ ($e_b > e_a$).

Proof. For the formal proof see Appendix. By intuition and looking at figures from 2 to 6, increasing (decreasing) market power is necessary for increasing pollution if $e_b > e_a$ ($e_b < e_a$). As pointed out before (Lemma 2), market power rises (decreases) only when $e_b > e_a$ combines with $\Gamma < 0$ and only when $e_b < e_a$ and $\Gamma > 0$ (if $\tau < \tau^*$). ■

However, this does not suffice for increased pollution. Other conditions, described in the following corollary, are needed.

Corollary 2. *Under imperfect competition and for particular tax-rate intervals, taxation can increase pollution (i) if* $e_b < e_a$ *and* $\Gamma > 0$ *or (ii) if* $e_b > e_a$ *and* $\Gamma < 0$ *provided that* *sufficiently high asymmetry in cost functions combines with sufficiently low price elasticity of demand.*

Proof. See Appendix. By intuition, in both cases ((*i*) and (*ii*)) the main reason that emissions go up is that some technologies with high pollution rise their output whereas those with low pollution cut down on production. However, if the tax rate is set sufficiently high, so that each technology group's output goes down, then aggregate emissions also have to go down compared to the laissez-faire level (Requate, 2005). In the first case (case *(i)*), since the price threshold does not depend on (or is insensitive to) the tax rate, the demand effect in the off-change periods can not offset the market power effect, if the market power effect is enough high (this occurs when there is large asimmetry in emission rates between technologies). Then pollution rises regardless of the price elasticity and the other structural factors of power market. In the second case (case *(ii)*), the price threshold significantly depends on the tax rate. Consequently taxation causes a significant increase in prices which can offset by the market power effect if the price elesticity is not sufficiently low[12]. ■

Table 2 summarizes the results of Proposition 1 for all the possible situations. As can be noted, fourteen configurations are theoretically viable but in only three of them taxation might increase pollution, namely: i) when $e_b < e_a$ and under specific technological conditions ($\Gamma > 0$); *ii*) when $e_b > e_a$, the price threshold is sufficiently sensitive to the tax rate and if sufficiently low price elasticity combines with sufficiently large asymmetry in emissions rates.

However, this output must not lead to conclude that increasing pollution is not likely even if possible in principle. In fact, when we look at real examples (real configurations of power markets) it is possible to demonstrate that increasing pollution is likely to occur.

Consider the three only situations in which the necessary conditions for increased pollution are satisfied. By plotting the locus of points that $\Gamma = 0$ (the indifference lines) in the space (e_a, e_b), we can identify the areas including combinations of emission rates under which emissions may rise ($\Delta E > 0$): *i)* the area above the indifference line, if $e_b < e_a$ and *ii)* the area below that line if $e_b > e_a$. In figures 7, 8 and 9 the indifference

[12] It is interesting to note that, inversely to what the current literature suggests, extreme curvature of the inverse demand function is not necessary for increasing pollution (see Requate, 2005 and Levin, 1985). This is due to the fact that in our analysis prices are constrained below a threshold and can not achieve the residual monopoly price.

lines are depicted (each corresponding to plausible values of the ratio c_b/c_a[13]) and areas including plausible mix of power generating technologies. As can be noted, in the cases of both $e_b < e_a$ and $e_b > e_a$, the real technological solutions are located above (below) the indifference lines.

Since $e_b < e_a$ combined with a price threshold low sensitive to the tax rate is sufficient for increased pollution and since this is the most likely configuration of the most of power generating systems (including a mix of gas-fired and coal units), then it would be not unlikely that, under imperfect competition, taxation could increase rather than decrease aggregate emissions. The analysis highlights that the higher is the fuel price ration (c_b/c_a) the higher the probability of increasing pollution.

Table 2. Expected change in emissions

	Change in market power			
	$\tau < \tau^*$		$\tau \geq \tau^*$	
	$\Gamma < 0$	$\Gamma > 0$	$\Gamma < 0$	$\Gamma > 0$
	I	II	III	IV
$A)\ e_b < e_a$				
$A1)\ \widehat{p} = \overline{p}\ (d\widehat{p}/d\tau = 0)$	$\Delta E < 0$	$\boxed{\Delta E > 0}$	$\Delta E < 0$	
$A2)\ \widehat{p} = \widehat{p}(\tau)$				
$A21)\ d\widehat{p}/d\tau < e_b$	$\Delta E < 0$	$\boxed{\Delta E > 0}$	$\Delta E < 0$	
$A22)\ e_b < d\widehat{p}/d\tau < e_a$	$\Delta E < 0$		$\Delta E < 0$	
$A23)\ d\widehat{p}/d\tau > e_a$	$\Delta E < 0$		$\Delta E < 0$	
$B)\ e_b > e_a$				
$B1)\ \widehat{p} = \overline{p}\ (d\widehat{p}/d\tau = 0)$		$\Delta E < 0$		
$B2)\ \widehat{p} = \widehat{p}(\tau)$				
$B21)\ d\widehat{p}/d\tau < e_b$		$\Delta E < 0$		
$B22)\ d\widehat{p}/d\tau > e_b$	$\boxed{\Delta E > 0^{(*)}}$	$\Delta E < 0$		

$^{(*)}$ Under certain conditions

[13] These values have been calculated by looking at the historic monthly pattern (from 2004 to 2008) of natural gas and coal prices. Furthermore, the following electric efficiencies have been used: 52% for CCGT plants (Combined Cycle-Gas Turbine); 40% for coal plants and 42% for gas-SC plants (Gas fired-steam cycle)

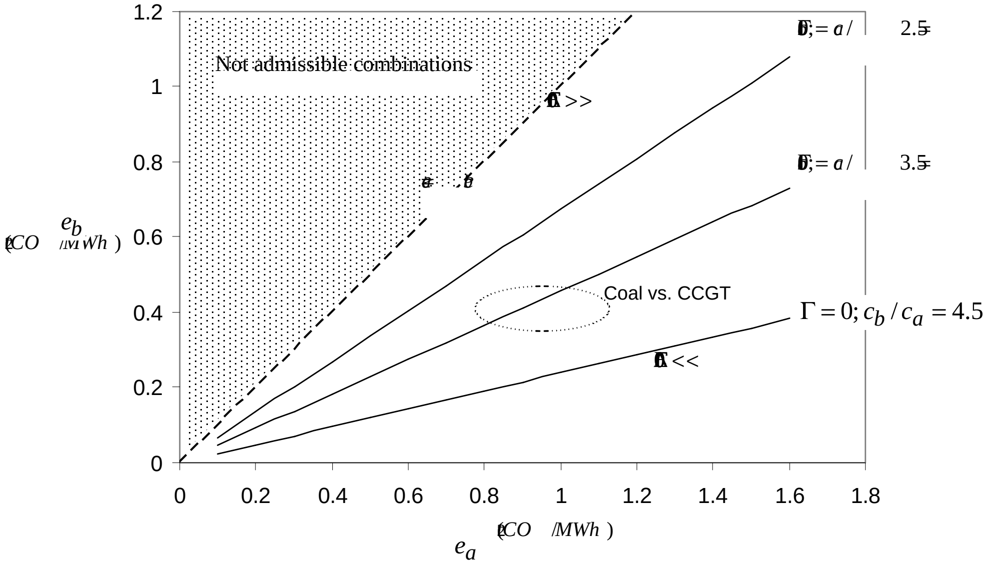

Figure 7: Examples of real technological configurations ($e_b < e_a$ and $d\widehat{p}/d\tau = 0$)

5. Conclusions

Under perfect competition taxation unambiguosly reduces aggregates emissions of the electricity industry by means of two effects. On the one hand, it determines a decline in pollution as long as it causes an increase in prices and consequently a decrease in demand (and production). On the other hand, if the tax rate is above the "switching tax", it determines a switch of producers on the merit order which reduces significantly the production by the most polluting plants. Obviously this latter effect depends on the technological compostion of the power generating system.

In imperfectly competitive markets we have to take into account an additional effect: the impact of taxation on the degree of market power that is on the time over which prices are above the competitive level. This effect may increase pollution as long as it changes the share of production by the different technologies favouring the most polluting ones and/or involves a decline in prices. According to the current literature on comparitive static effects, which is based on one-shot standard models of competition, this paper proves that this can occur even in the electricity market in which the pricing mechanism is a multi shot price auction, provided that certain conditions are satisfied. Rather this

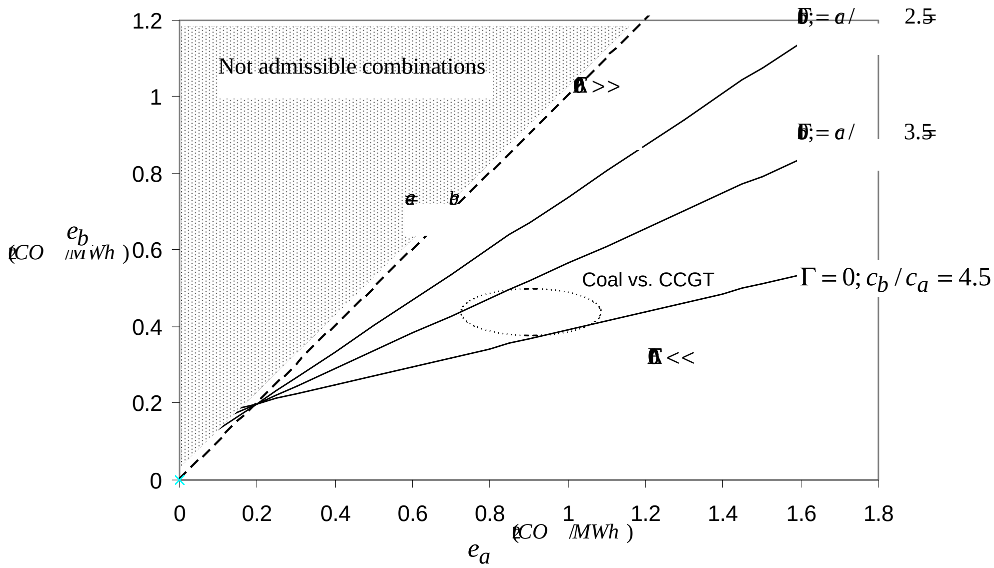

Figure 8: Examples of real technological configurations ($e_b < e_a$ and $d\widehat{p}/d\tau < e_b$)

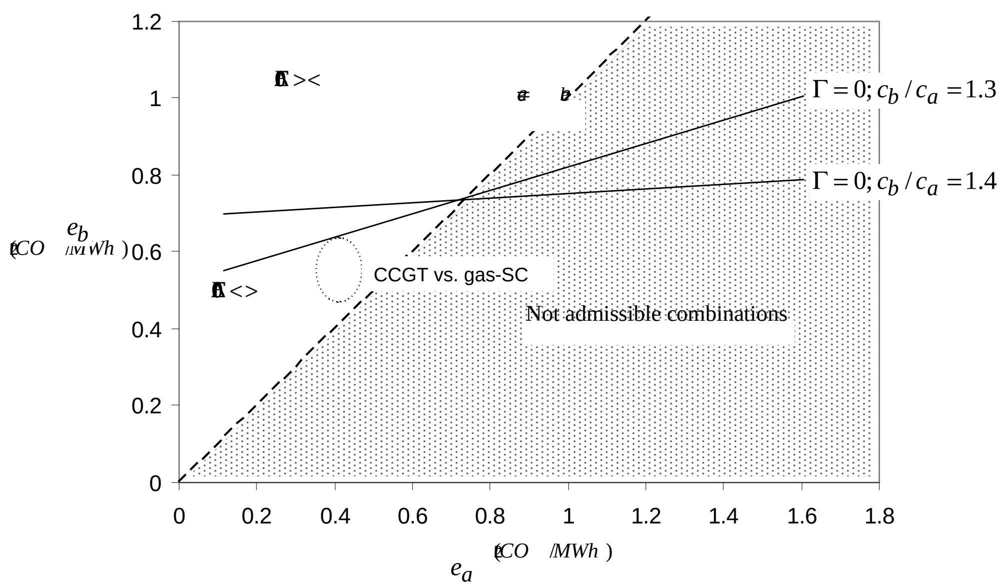

Figure 9: Examples of real technological configurations ($e_b > e_a$ and $d\widehat{p}/d\tau > e_b$)

article demonstates that increased pollution is not only possible theoretically. Looking at the real technological conditions of power sectors, it is even very likely if the natural gas/coal price ratio is sufficiently high.

6. APPENDIX

Proof of Lemma 1. Let $\overline{S} = D_M - \overline{S}^d$ be the peak demand minus the dominant firm's capacity in least efficient plants ($\overline{S}^d$). It is immediately intuitive that when $S \geq \overline{S}$ the system marginal price equals the price threshold, $\widehat{p}$. When $S < \underline{S}^f$, 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. 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 entering the market. In consequence prices will converge to the marginal cost of the most efficient plants.

It remains to identify the leader's optimal choice on $S \in \left]\overline{S}; \underline{S}^f\right]$[14]. Under the assumptions of the model, each firm in the competitive fringe has a unique dominant strategy whatever is the market demand: bidding according to its own marginal cost of production. By converse the best choice of the dominant firm might consist in *(i)* bidding the price threshold ($\widehat{p}$) or in *(ii)* bidding $\overline{MC}$[15].

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

$$\pi_A^d = (\widehat{p} - \underline{MC})\left[D(p,H) - S_T\,(1-\delta)\right] - \sum_{i=1}^{z} \sum_{j=a,b} s_j^i f_j^i \qquad \text{(A1)}$$

where f_j^i is the capital cost per unit of installed capacity of the unit i-th unit belonging to the group j of plants.

[14]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, 1998).

[15]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.

If the dominant firm chooses the second strategy, he earns

$$\pi_B^d = \left(\overline{MC} - \underline{MC}\right) \underline{\mu}^d \delta S_T - \sum\nolimits_{i=1}^{z} \sum\nolimits_{j=a,b} s_j^i f_j^i \tag{A2}$$

Therefore the leader's optimal strategy is bidding the residual monopoly price if and only if $\pi_A^d \geq \pi_B^d$, i.e. if and only if

$$D \geq \left[\underline{\mu}^d \delta\zeta + (1-\delta)\right] S_T = D_1(\delta, \underline{\mu}^d, \zeta) \tag{A3}$$

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

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

$$\pi_C^d = (\widehat{p} - \underline{MC}) \left[D(p,H) - S_T (1-\delta)\right] - \sum\nolimits_{i=1}^{z} \sum\nolimits_{j=a,b} s_j^i f_j^i \tag{A4}$$

and by choosing the second strategy, the profit is

$$\pi_D^d = \left(\overline{MC} - \underline{MC}\right) \left[D(p,H) - S_T \underline{\mu}^f (1-\delta)\right] - \sum\nolimits_{i=1}^{z} \sum\nolimits_{j=a,b} s_j^i f_j^i \tag{A5}$$

Thus the dominant firm will choose the first strategy (bidding $\widehat{p}$) if and only if $\pi_C^d \geq \pi_D^d$, i.e. if and only if

$$D \geq (1-\delta) \left[\frac{(1-\underline{\mu}^f)}{(1-\zeta)} + \underline{\mu}^f\right] S_T = D_2(\delta, \underline{\mu}^f, \zeta) \tag{A6}$$

Therefore the leader's best reply is a function of power market demand. We still have to demonstrate that the two critical values D_1 and D_2 never work together, i.e. if $D_1 \in \left]\overline{S}; \underline{S}\right[$ then $D_2 \notin \left]\underline{S}; \underline{S}^f\right[$ and vice versa.

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

$$D \geq D_1(\delta, \underline{\mu}^d, \zeta) = \zeta \underline{S}^d + S^f \tag{A7}$$

and equation (A6) as

$$D \geq D_2(\delta, \underline{\mu}^f, \zeta) = \frac{\overline{S}^f}{1-\zeta} + \underline{S}^f \tag{A8}$$

Assume for instance $D_1 > \underline{S}$. From (A7) $\dfrac{\overline{S}^f}{(1-\zeta)} > \underline{S}^d$ and from (A8) $D_2 > \underline{S}$. Thus, $D_2 \notin \left]\underline{S}; \underline{S}^f\right[$

Similarly suppose $D_2 < \underline{S}$. From (A8) $\underline{S}^d > \dfrac{\overline{S}^f}{1-\zeta}$ and from (A7) $D_1 < \underline{S}$. Thus, $D_1 \notin \left]\overline{S}; \underline{S}\right[$.

In addition, from (A7) and (A8), if $D_1 = \underline{S}$ then $D_2 = \underline{S}$ and vice versa.

Finally, note that $D_1 < \overline{S}$ and $D_2 > \underline{S}^f$.

Last some comparative statics,

$$\frac{\partial D_1}{\partial \underline{\mu}^d} = \delta\zeta S_T > 0; \; \frac{\partial D_2}{\partial \underline{\mu}^f} = -\frac{\zeta}{1-\zeta} S_T < 0$$

6.1. Proof of Lemma 2. The derivative of $\widehat{D}$ with respect to p^{tp} can be written as

$$\frac{\partial \widehat{D}}{\partial \tau} = \frac{\partial \widehat{D}}{\partial \zeta}\frac{\partial \zeta}{\partial \tau} \tag{A9}$$

Since (from (A3) and (A6))

$$\frac{\partial D_1}{\partial \zeta} = \underline{\mu}^d \delta S_T > 0 \text{ and } \frac{\partial D_2}{\partial \zeta} = \frac{(1-\delta)(1-\underline{\mu}^f)}{(1-\zeta)^2} S_T > 0 \tag{A10}$$

then, market power is a decreasing function of ζ.

By differentiating ζ with respect to τ we get

$$\frac{\partial \zeta}{\partial \tau} = \frac{(e_b - e_a)(\widehat{p}(0) - c_a) - (c_b - c_a)(\partial \widehat{p}/\partial \tau - e_a)}{(\widehat{p} - c_a - \tau e_a)^2} \text{ if } \tau < \tau^*$$

$$\frac{\partial \zeta}{\partial \tau} = \frac{(e_a - e_b)(\widehat{p}(0) - c_b) - (c_a - c_b)(\partial \widehat{p}/\partial \tau - e_b)}{(\widehat{p} - c_b - \tau e_b)^2} \text{ if } \tau \geq \tau^*$$

Consequently

(i) if $e_b < e_a$ and $\tau < \tau^* \Longrightarrow \dfrac{\partial \zeta}{\partial \tau} < 0$ and $\dfrac{\partial \widehat{D}}{\partial \tau} < 0$, $\forall c_j, e_j, \tau$ except for the case in which $\widehat{p} = \overline{p}$ and $(e_b - e_a)(\overline{p} - c_a) + e_a(c_b - c_a) > 0$;

(ii) if $e_b < e_a$ and $\tau \geq \tau^* \Longrightarrow \dfrac{\partial \zeta}{\partial \tau} > 0$ and $\dfrac{\partial \widehat{D}}{\partial \tau} > 0$, $\forall c_j, e_j, \tau$;

(iii) if $e_b > e_a \Longrightarrow \frac{\partial \zeta}{\partial \tau} < 0$ and $\frac{\partial \widehat{D}}{\partial \tau} < 0$ only when $\widehat{p} = p(\tau)$ and $(e_b - e_a)(\widehat{p}(0) - c_a) - (c_b - c_a)(\partial \widehat{p}/\partial \tau - e_a) < 0$.

Finally, it is possible to demonstrate that when $\widehat{p} = \overline{p}$ and $\tau \geq \tau^*$ then $\frac{\partial \widehat{D}}{\partial \tau} \nless 0$. In fact, in this case from (A9) and (A10), $\frac{\partial \widehat{D}}{\partial \tau} < 0$ only if $MC_a(\tau^*) > \overline{p}$ which is escluded by definition.

6.2. Proof of Corollary 1. By differentiating $\widehat{D}$ with respect to μ_a^d and μ_a^f, we get

$$\frac{\partial D_1}{\partial \mu_a^d} = \delta \zeta S_T > 0; \; \frac{\partial D_2}{\partial \mu_a^f} = -\frac{\zeta}{1-\zeta} S_T < 0$$

and by differentiating these expressions with respect to τ, it follows

(i) if $\tau < \tau^* \Longrightarrow \frac{\partial^2 D_1}{\partial \tau \partial \mu_a^d} = \delta \frac{\partial \zeta}{\partial \tau} S_T$ and $\frac{\partial^2 D_2}{\partial \tau \partial \mu_a^f} = -\frac{1}{(1-\zeta)^2} \frac{\partial \zeta}{\partial \tau} S_T$

(ii) if $\tau \geq \tau^* \Longrightarrow \frac{\partial^2 D_1}{\partial \tau \partial \mu_a^d} = -\delta \frac{\partial \zeta}{\partial \tau} S_T$ and $\frac{\partial^2 D_2}{\partial \tau \partial \mu_a^f} = \frac{1}{(1-\zeta)^2} \frac{\partial \zeta}{\partial \tau} S_T$

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

i) if $\tau < \tau^* \Longrightarrow \frac{\partial^2 D_1}{\partial \tau \partial \mu_a^d} < 0$ and $\frac{\partial^2 D_2}{\partial \tau \partial \mu_a^f} > 0$, $\forall c_j, e_j, \tau$ except for the case in which $\widehat{p} = \overline{p}$ and $(e_b - e_a)(\overline{p} - c_a) + e_a(c_b - c_a) > 0$;

ii) if $\tau \geq \tau^* \Longrightarrow \frac{\partial^2 D_1}{\partial \tau \partial \mu_a^d} < 0$ and $\frac{\partial^2 D_2}{\partial \tau \partial \mu_a^f} > 0$, $\forall c_j, e_j, \tau$.

6.3. Proof of Proposition 2. Assume for example the supply configuration described in Fig. 10 (case of $\widehat{D} > \underline{S}$ and $\tau < \tau^*$).

Given the price curve described by Proposition 1, the total amount of pollutant emissions, E, is

$$\text{(A11)} \; E = e_b \left[\int_0^{\overline{H}(p(\tau))} D(H, p(\tau)) dH - (S_a^d + S_a^f)\overline{H} \right] + e_a(S_a^d + S_a^f)\overline{H} +$$

$$+ e_a \left[\int_{\overline{H}(p(\tau))}^{H_1(p(\tau))} D(H, p(\tau)) dH - S_b^f (H_1 - \overline{H}) \right] + e_b S_b^f (H_1 - \overline{H}) +$$

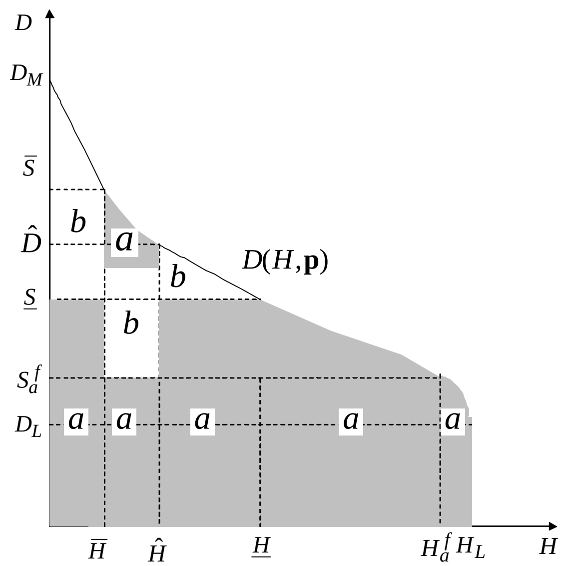

Figure 10: Supply configuration

$$+e_b\left[\int_{H_1(p(\tau))}^{\underline{H}(p(\tau))} D(H,p(\tau))dH-(S_a^d+S_a^f)(\underline{H}-H_1)\right]+e_a(S_a^d+S_a^f)(\underline{H}-H_1)+$$

$$+\ e_a\left[\int_{\underline{H}(p(\tau))}^{H_L} D(H,p(\tau))dH\right]$$

By differentiating (A11) with respect to τ and given that

$$\frac{\partial}{\partial\tau}\left[\int_{H_i(p(\tau))}^{H_j(p(\tau))} D(H,p(\tau))dH\right]=D(H_j,p(\tau))\frac{\partial H_j}{\partial\tau}-D(H_i,p(\tau))\frac{\partial H_i}{\partial\tau}+\int_{H_i(p(\tau))}^{H_j(p(\tau))}\frac{\partial D(H,p(\tau))}{\partial\tau}dH$$

we get

$$\text{(A12)}\ \frac{\partial E}{\partial\tau}=(e_b-e_a)(\overline{S}-D_1)\frac{\partial H_1}{\partial\tau}+e_b\left[\int_0^{\overline{H}(p(\tau))}\frac{\partial D(H,p(\tau))}{\partial\tau}dH\right]+e_a\left[\int_{\overline{H}(p(\tau))}^{H_1(p(\tau))}\frac{\partial D(H,p(\tau))}{\partial\tau}dH\right]+$$

$$+e_b\left[\int_{H_1(p(\tau))}^{\underline{H}(p(\tau))}\frac{\partial D(H,p(\tau))}{\partial\tau}dH\right]+e_a\left[\int_{\underline{H}(p(\tau))}^{H_L}\frac{\partial D(H,p(\tau))}{\partial\tau}dH\right]$$

Table A1 - Change in emissions

	$\tau < \tau^*$		$\tau \geq \tau^*$	
	$\Gamma < 0$	$\Gamma > 0$	$\Gamma < 0$	$\Gamma > 0$
	I	II	III	IV
$A)$ $e_b < e_a$				
$A1)$ $\widehat{p} = \overline{p}$ $(d\widehat{p}/d\tau = 0)$	$A < 0; B > 0$ $(\Delta E < 0)$	$A > 0; B < 0$ $(\Delta E > 0)$	$A < 0; B > 0$ $(\Delta E < 0)$	
$A2)$ $\widehat{p} = \widehat{p}(\tau)$				
$A21)$ $d\widehat{p}/d\tau < e_b$	$A < 0; B > 0$ $(\Delta E < 0)$	$A > 0; B < 0$ $(\Delta E > 0)$	$A < 0; B > 0$ $(\Delta E < 0)$	
$A22)$ $e_b < d\widehat{p}/d\tau < e_a$	$A < 0; B > 0$ $(\Delta E < 0)$		$A < 0; B > 0$ $(\Delta E < 0)$	
$A23)$ $d\widehat{p}/d\tau > e_a$	$A < 0; B > 0$ $(\Delta E < 0)$		$A < 0; B > 0$ $(\Delta E < 0)$	
$B)$ $e_b > e_a$				
$B1)$ $\widehat{p} = \overline{p}$ $(d\widehat{p}/d\tau = 0)$		$A < 0; B > 0$ $(\Delta E > 0)$		
$B2)$ $\widehat{p} = \widehat{p}(\tau)$				
$B21)$ $d\widehat{p}/d\tau < e_b$		$A < 0; B > 0$ $(\Delta E < 0)$		
$B22)$ $d\widehat{p}/d\tau > e_b$	$A > 0; B > 0^{(*)}$ $(\Delta E > 0^{(*)})$	$A < 0; B > 0$ $(\Delta E < 0)$		

The first element in (A12) is the change in emissions caused by the change in the production share by the different technology groups due to the change in market power. We name this component as A. Note that if $\tau \geq \tau^*$ then $A = (e_a - e_b)(\overline{S} - D_1)\dfrac{\partial H_1}{\partial \tau}$. Furthermore, by substituting the expression of $\dfrac{\partial H_1}{\partial \tau}$, $\overline{S}$ and D_1 in A we get

$$\text{(A13)}\quad A = (e_b - e_a)(\overline{S} - D_1)\frac{\partial H_1}{\partial \tau} =$$

$$= \frac{\partial H_1}{\partial D_1} S_T (e_b - e_a)(\mu_a^d \delta)^2 \left(\frac{\widehat{p} - MC_b}{\widehat{p} - MC_a}\right) \frac{1}{(\widehat{p} - MC_a)^2} \cdot \left[(e_b - e_a)(\widehat{p} - MC_a) - (\frac{\partial \widehat{p}}{\partial \tau} - e_a)(MC_b - MC_a)\right] =$$

$$= \frac{\partial H_1}{\partial D_1} S_T(e_b - e_a)(\mu_a^d \delta)^2 \frac{(\widehat{p} - c_b - \tau e_b)}{(\widehat{p} - c_a - \tau e_a)^3} [(\widehat{p} - c_a)e_b - (\widehat{p} - c_b)e_a]$$

The remaining elements in (A12) represent the demand effect due to the change in prices. This effect includes two components. The first one is the change in demand due to the change in prices during the periods in which the dominant firm modifies its strategy (on-change periods). The second one is the change in demand due to the change in prices during the periods in which the dominant firm's strategy remains unchanged (off-change periods).

We name the sum of these elements as B.

Provided that the change in emissions is given by

$$\text{(A14)}\ \Delta E = \int_0^\tau \frac{\partial E}{\partial \tau} d\tau = \int_0^\tau A d\tau - \int_0^\tau B d\tau$$

from (A12) and (A14) taxation may increase pollution ($\Delta E < 0$) only if $A > B$, $\forall \tau \in [0; \widehat{\tau}]$, where $\widehat{\tau}$ is the tax rate above which the demand effect is so high that aggregate emissions necessarly go down regardless of the market power effect.

Table A1 shows the cases in which increasing pollution is possible. By combining the different factors (tax-rates, emission rates and price threshold) we get fourteen configurations, each of them is commented below.

(i) Configurations A1I), A21I), A22I) and A23I). In these cases, since $\frac{\partial H_1}{\partial \tau} > 0$, $\forall \tau$ and $(e_b - e_a) < 0$ then $A < 0$, on the one hand. On the other hand the increase in market power determines an increase in price and consequently a decrease in emissons due to the decrease in demand (amplified by the rise in price threshold in A21I), A22I) and A23I). Therefore $B > 0$, $A < B$ and consequently $\Delta E < 0$ (from A12)).

(ii) Configuration A1II). In this case, $\frac{\partial H_1}{\partial \tau} < 0$, $\forall \tau$ and $(e_b - e_a) < 0$. Therefore $A > 0$, on the one hand. On the other hand the fall in market power determines a decrease in prices in the on-change hours and consequently an increase in emissons due to the rise in demand. Since the price threshold does not depend on the tax-rate, this rise is not offset by a decrease in demand during the off-change periods. Therfore $B < 0$, $A > B$ and consequently $\Delta E > 0$ (from A14)).

(iii) Configuration A21II). Even in this case, $\frac{\partial H_1}{\partial \tau} < 0$, $\forall \tau$ and $(e_b - e_a) < 0$. Again, $A > 0$, on the one hand, and, on the other hand, the decrease in market power determines an increase in emissons due to the rise in demand. This time, however, the price threshold depends on the tax-rate. Nevertheless, since the sensitiveness is very low it is possible that the rise in emissions during the on-change periods could not be offset by the decrease in emissios during the off-change periods. Thus it is possible that $B < 0$, $A > B$ and consequently $\Delta E > 0$ (from A14)).

(*iv*) Configuration A1III). On the one hand, since $\dfrac{\partial H_1}{\partial \tau} < 0$ and $(e_a - e_b) > 0$ then $A < 0$. Nevertheless $\Delta \widehat{D} \gtreqless 0$ and consequently $\Delta \widehat{H} \lesseqgtr 0$. If $\Delta \widehat{D} < 0$ prices increase and emissions decrease $(B > 0)$. Consequently $\Delta E < 0$. If $\Delta \widehat{D} > 0$ prices decrease and emissions increase $(B < 0)$. Consequently $\Delta E > 0$ only if $|A|$ is very low that is if $(e_a - e_b)$ is very low. But in this case even $\Delta \widehat{D}$ is very low so that the corresponding demand effect in the off-change periods is negligible. Thus $A < B$ and $\Delta E < 0$.

(*v*) Configurations A21III) and A22III) and A23III). Once again $\Delta \widehat{D} \gtreqless 0$ and consequently $\Delta \widehat{H} \lesseqgtr 0$. However $A < 0$ in both cases. If $\Delta \widehat{D} < 0$ prices increase and emissions decrease $(B > 0)$. Consequently $A < B$ and $\Delta E < 0$. If $\Delta \widehat{D} > 0$ prices decrease but this decrease (and its effect on emissions) is offset by the increase in the price threshold (and consequently by the corresponding fall in demand). Thus once again $B > 0$, $A < B$ and $\Delta E < 0$.

(*vi*) Configuration B1II). In this case, $\dfrac{\partial H_1}{\partial \tau} < 0 \; \forall \tau$ and $(e_b - e_a) > 0$. Therefore $A < 0$, on the one hand. On the other hand, the drop in market power determines a fall in prices and consequently an increase in emissons due to the increase in demand which, since the price threshold is insensitive to the tax-rate, would not be offset by the demnad effect in the off-change periods. Thus $B < 0$, and consequently $A > B$ and $\Delta E > 0$ only if $(e_b - e_a)$ is very low (i.e. $|A|$ very low). But in this case even $\Delta \widehat{D}$ would be very low so that the demand effect in the off-change periods would be negligible. Thus even $|B|$ would be very low and therefore $\Delta E < 0$.

(*vii*) Configuration B22I). This time, since $\dfrac{\partial H_1}{\partial \tau} > 0$ and $(e_b - e_a) > 0$ then $A > 0$. The increase in market power determines an increase in price and consequently a decrease in emissons due to the decrease in demand amplified by the decrease in emissions in the off-change periods (due to the increase in rpice threshold). Therefore $B > 0$. Consequently $\Delta E > 0$ is in principle possible but only if the price elasticity is sufficiently low and $(e_b - e_a)$, δ and μ_a^d are sufficiently high (i.e. $|A| > |B|$).

(*viii*) Configurations B21II) and B22II). In these cases $\dfrac{\partial H_1}{\partial \tau} < 0$ and $(e_b - e_a) > 0$.

Therefore, on the one hand $A < 0$. On the other hand, the decrease in market power determines a drop in prices and consequently a rise in emissions which is offset by the decrease in emissions due to the increase in the price threshold in the off-change periods. Therefore $B > 0$, $A < B$ and consequently $\Delta E < 0$.

Finally, it is possible to demonstrate that this result arises even for the case in which $\widehat{D} \leq \underline{S}$.

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