EUI Working Papers

RSCAS 2011/20
ROBERT SCHUMAN CENTRE FOR ADVANCED STUDIES
Loyola de Palacio Programme on Energy Policy

THE INTERACTION BETWEEN EMISSIONS TRADING AND ENERGY AND COMPETITION POLICIES

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EUI Working Paper **RSCAS** 2011/20

ISSN 1028-3625

Printed in Italy, March 2011
European University Institute
Badia Fiesolana
I – 50014 San Domenico di Fiesole (FI)
Italy
www.eui.eu/RSCAS/Publications/
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Abstract

Emissions trading is a “cap and trade” regulation aimed at reducing the cost of meeting environmental targets. This paper studies how this regulation interacts with energy and competition policies. Two vertically related and imperfectly competitive markets are investigated: 1) the electricity market (output market); 2) the market for natural gas (input market). The effect of energy policy is simulated by assuming that the supporting scheme is able to improve the competitiveness of the low carbon technologies which are able, at the same time, to increase security of supply. The effect of the competition policy is accounted for by assuming that firms try to meet a profit target rather than to maximize profits, because of the regulatory pressure exerted by the competition and sector-specific authorities. By using the dominant firm model (in both markets) and the auction approach (in the output market), the paper highlights a trade-off between these policies. Without regulatory pressure, the result is ambiguous. Together, environmental and energy policies can lead to an increase in market power and its effects, but this in turn not necessarily amplifies their performances. However the worst case, the absolute increase in pollution in the short-run, is excluded. With regulatory pressure, the environmental and energy policies may imply a decrease in market power and this in turn can lessen their performance. In addition, this time the absolute increase in pollution in the short-run is not only possible but even likely. However this unfavourable effect would happen only if the pollution price is sufficiently low, that is if the environmental policy is rather modest. From the policy implications point of view, the analysis suggests what follows. If the models used to estimate performances and costs of environmental and energy policies ignore the full role of imperfect competition (the impact on prices combined with the strategic use of power capacity), this may induce incorrect estimations of the cost of the public action or may lead to incorrect policy calibrations, depending on how the policy targets are set. Finally, although the results are based on a series of simple assumptions about the operation and the structure of energy markets, they seem to be enough robust. Nevertheless the paper suggests caution in extending to other market structures the outcome of the dominant firm model.

Keywords

Emissions trading, pollution, imperfect competition; energy policy

JEL code: Q4, Q5, L94

1. Introduction

Emissions trading is a "cap and trade" regulation aimed at reducing the cost of meeting environmental targets.

The models used to estimate its performance and/or to estimate its economic impact are generally based on specific hypotheses about the structure and operation of energy markets.

A fundamental assumption of these models is that energy markets are fully competitive or behave as such. In the former case, the fully competitive outcome is simulated. In the latter case, the models claim to internalize market power simply applying a mark-up to the competitive prices without taking into account how the strategic behaviour of firms can change their share of production and how this in turn can impact on prices. This essentially means that changes in prices, in production and in emissions are the same of the absolute fully competitive outcome, under the usual conditions of the demand function[1].

As this does not reflect the reality in most situations, simulations may provide a biased representation of the impact of emissions trading leading to underestimate or overestimate its performance. This suggests to check what can happen when the assumption of full competition is removed. In fact, imperfect competition, by means of its impact on prices combined with the strategic use of power capacity, may largely affect the performance of environmental policy as long as it has impact on costs, on prices and on the share of production of the different polluting technologies and, consequently, on emissions.

In addition emissions trading interacts with other policies for the energy sector, namely: 1) energy policies aimed at supporting the deployment of renewable technologies and/or at increasing security of supply; 2) competition and regulation policies aimed at lessening market power and its effects. Under full competition, these areas of public action are in principle supplementary, in the sense that energy policies can amplify the performance of emissions trading and vice versa while the pro-competitive regulation is not relevant by definition. Instead what could happen under imperfect competition is less clear.

The analysis carried out in this paper is finalized to check how imperfect competition is able to affect the interaction between emissions trading and the other policies.

Note that the focus is not on the comparison of the different market structures in absolute terms, i.e. the difference in emissions, prices or in the development of the low carbon technologies, at any one time. Here we are simply interested in change over time of these variables. As explained later, this is important in order to calibrate the public action and in order to estimate its economic effects.

Two vertical related markets are investigated, namely:

1. The electricity market which is one of the most important markets subjected to environmental regulation (e.g. power generation is the largest sector covered by the European Emissions Trading Scheme, the EU ETS);
2. The market for natural gas which is one of the basic inputs for power generation in several countries.

The analysis is a comparative static analysis useful to evaluate the combined performances of the different policies.

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1 With linear downward sloping demand (variable price elasticity) the outcome is the same but is different if iso-elastic demand is assumed.

The abatement process and/or the impact on investments are not accounted for. Consequently there are two possible interpretations and two possible utilizations of the results. First, if we look at the starting configuration (the beginning of the compliance period), the results may be interpreted as the expression of what can happen in the short-run. Note that this is not a limitation of the analysis. In fact, as pointed out before, the short-run impact is crucial for the long-run as far as what happens in the short-run can affect the cost and the ability to meet the long-run objectives. Second, if we look at the end of the compliance period, they may be interpreted as the combined inertial impact of the environmental and energy regulations on the “business as usual” scenario, i.e. on that situation in which, given the long-run evolution of markets, the public action has an inertial impact on demand and production but not on investments choices. In this sense the results may indicate the distance from targets and can help us to reflect on the policy implications of the analysis. In fact, they allow us to check how the simulation models based on full competition can affect the policy calibration and the estimates of the related economic impact.

As previously underlined, emissions trading is evaluated on the basis of its ability to reduce the cost of meeting the environmental target. We deduce this ability through the short-run or, which is equivalent, the inertial change in emissions. This change has an important implication. For example, if the short-run or inertial decrease in emissions under imperfect competition is lower than under full competition, or rather there is an absolute increase in pollution, this means that a greater effort of abatement is needed and that the models based on full competition overestimate the performance of the ETS. Consequently this may lead to accept more severe environmental targets or to underestimate the cost of meeting a specific target. Similarly if we look at the energy policy targets and at their effects.

The effectiveness of energy policy lies in its ability to support the deployment of low carbon technologies which are, at the same time, able to increase security of supply. The model assumes that the supporting scheme is based on the application of feed-in tariffs: generators receive a premium price plus the wholesale electricity price. Furthermore, another fundamental assumption is that the policy measures are at least able to make the low carbon (or carbon free) technologies closer to the competitiveness threshold up to make them the main alternative to the gas-fired existing power technologies.

Finally, the competition policy is evaluated on the basis of its ability (even implicit) to lessen the degree of market power and its effects on prices in the electricity market.

The situations before and after the simultaneous implementation of emissions trading and energy policies are compared. Then the effect of the competition policy is simulated by considering two scenarios. One in which there is no regulatory pressure and firms can maximize profits. The other in which, because of the regulatory pressure exerted by the competition and sector-specific authorities, firms pursue strategies besides the profit maximization[2], namely they try to pursue a short or long-term profit target.

Furthermore we do not try to measure the overall change in social welfare. This measurement may be misleading since it requires to estimate the economic value of the environmental damage which is largely uncertain. Instead, the main aim is to simply identify the mechanisms through which energy and competition policies can interact with the environmental regulation and vice versa.

In this regard, the main finding is that imperfect competition triggers a trade-off between emissions trading and the other policies. Under regulatory pressure, emissions trading combined with energy policies can lessen market power and its effect but this in turn can lessen their performances, provided that the pollution price is sufficiently low.

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[2] For an analysis of the carbon cost pass-through when firms maximize market shares or sales revenues, see Vivid Economics (2007) and Sijm et al. (2008a, 2008b).

Finally it is worth pointing out that we do not claim to provide the best simulation of energy markets. In fact, the analysis is based on a series of assumptions (about technologies, market structure, firms' behavior, etc.) that largely simplify the real conditions of operation in these markets. However these assumptions can make it easier to identify the mechanisms through which the public action interacts with the structure of energy markets. At the end of the paper, we discuss about them in order to check the robustness of the results.

The paper is organised as follows. Section 2 focuses on the structure of the model used to characterize equilibria under imperfect competition. Section 3 deals with the combined impact of environmental regulation and energy policy on gas prices and on marginal costs of power technologies. Section 4 investigates how environmental and energy policies can change the degree of market power in the electricity market, distinguishing the cases without and with regulatory pressure exerted by competition and sector-specific authorities. Section 5 focuses on how the change in costs is passed through to electricity prices and on the consequent impact on pollution. Section 6 discusses the robustness of the results. Finally, section 7 summarizes the main findings of the article.

2. The basic model: assumptions

This section describes the structure of the model by detailing the main assumptions on the environmental regulation and the main hypotheses on the regulation of the electricity and gas markets.

2.1. The environmental regulation

The assumptions about environmental regulation are quite simple. We assume that the environmental policy is based on emissions trading (ETS).

The ETS gives rise to a market for emissions allowances. This market is very large and involves a large number of polluting firms so that none of them is able to exercise market power on it.

Permits are auctioned and/or benchmarked. The benchmark is the emission rate, r_{bn}, of the best operating technology. This framework is consistent with the European carbon market created by the introduction of the EU ETS (European Union Emissions Trading Scheme).

Finally, emissions abatement in the electricity sector is impossible or, equivalently, the abatement cost is infinitely costly. Therefore the analysis proposed in this article is a short-run analysis.

2.2. The natural gas market

The natural gas demand function, $D_g(p_g)$, is continuous and for all gas prices, p_g, we assume that $-\infty < \partial D_g \big/ \partial p_g < 0$ and $\partial^2 D_g \big/ \partial p_g^2 < 0$.

To simulate market power we adopt a dominant firm with competitive fringe model. This model is well suited to simulate the structural features of several natural gas markets.

The dominant firm (d_g) and the fringe (f_g) supply the market with capacity given by $K_g^{d_g} > 0$ and $K_g^{f_g} > 0$, respectively, with $K_g^{d_g} > K_g^{f_g}$. We assume linear technologies whose cost per unit of gas delivered, $c_g \geq 0$, is constant. $c_g^{d_g}$ and $c_g^{f_g}$ are the leader's and fringe's costs, respectively, with $c_g^{d_g} < c_g^{f_g}$.

Firms are price-setting and all players are assumed to be risk neutral and to act in order to maximize their expected payoff (profit). Production costs as well as firms' installed capacity are common knowledge.

Natural gas firms serve several segments of consumption (industry, power generation, residential sector, etc.). So, even if large, firms operating in each segment (including power firms) are not able to exert significant market power on the natural gas market[3].

The natural gas trading is regulated by long term contracts. These contracts include rules for price indexation over time. Therefore they are consistent with the short-run horizon of the analysis.

The leader's production capacity is very large such that the dominant firm is able to serve the entire market by itself, i.e. $K_g^{d_g} \geq D_g(c_g^{d_g})$.

Furthermore, we assume that natural gas has perfect substitutes, the alternative fuels (*AF*), in each segment of consumption. Firms which deliver the same alternative fuel are homogenous and operate in a fully competitive context.

The alternative technologies change over time because of the implementation of energy policy. For the sake of simplicity, we assume that, before the energy policy, the alternative mix includes two technologies with different cost and more polluting than gas. We denominate as AF_1 the low-cost alternative technology within this mix. After the energy policy, this technology is replaced by a low carbon fuel or a carbon free technology (AF_2).

2.3. The power market

In the power sector the demand function can be represented by the load duration curve $D_e(p_e, H)$ where H is the number of hours in the reference time-period (e.g. the day or the year) that demand is equal to or higher than D_e, with $0 \leq H \leq H_L$, and p_e is the spot price. $D_{e_L}(p_e) = D(p_e, H_L)$ is the minimum demand and $D_{e_M}(p_e) = D(p_e, 0)$ is the maximum demand. Demand is deterministic and for each hour is a linear downward sloping demand, $D_e(p_e) = \gamma - \beta \cdot p_e$ with $\beta > 0$.

As with the gas, to simulate market power we use the dominant firm with competitive fringe model (this choice is discussed in sub-section 6.3.). This model is well suited to simulate the structural features of several electricity markets.

The dominant firm (d_e) and the fringe (f_e) supply the market with capacity given by $K^{d_e} > 0$ and $K^{f_e} > 0$ respectively. Once again, we assume (this assumption is discussed in sub-section 6.1.) linear technologies which are characterised by constant per-unit variable cost of production, $c_e \geq 0$, and by constant emission rate, $r \geq 0$ (emissions per unit of output, e.g. tCO2/MWh). The fringe and the dominant firm supply the quantities $q_e^{f_e} \in \left[0; K_e^{f_e}\right]$ and $q_e^{d_e} \in \left[0; K_e^{d_e}\right]$ respectively.

Without loss of generality, we restrict the analysis to two groups of power technologies, the group *a* and the group *g* (the gas-fired units). Each of them includes a large number n of homogeneous units[4] such that

3 This is a reasonable assumption. In addition it allows us to avoid the problem of price indeterminacy due to the existence of bilateral market power.

$K_{e_j} = \sum_{i=1,2,..n} k^i_{e_j}$, $j = a, g$ and $c^i_{e_j} = c_{e_j}$; $r^i_j = r_j$, $\forall i, j$

where $c^i_{e_j} = c_{e_j} \geq 0$, $r^i_j = r_j \geq 0$ and $k^i_{e_j} = k_{e_j} > 0$ are the variable cost, the emission rate and the capacity of the *i*-th unit belonging to the group *j*, respectively. Thus K_{e_a} and K_{e_g} are the installed capacity of groups *a* and *g*, respectively, with $K_{e_a} + K_{e_g} = K_{e_T} = D_{e_M}$, i.e. the units of kind *a* and *g* are sufficient to meet the maximum demand. $q_{e_a} \in \lfloor 0; K_{e_a} \rfloor$ and $q_{e_g} \in \lfloor 0; K_{e_g} \rfloor$ are the amounts of electricity produced by groups *a* and *g* respectively.

Furthermore, we assume trade-off between variable costs and emission rates, i.e. the technology with lower variable cost is the worse polluter ($c_{e_a} < c_{e_g}$ but $r_a > r_g$) and vice versa. This condition is well-suited to simulate a very common technological configuration namely the configuration that includes coal (group a) and CCGT (Combined Cycle Gas Turbine) plants (group g). Finally, we assume that, after the implementation of the energy policy, the main alternative to natural gas is a low carbon technology (see sub-section 2.2.) with $0 \leq r_{AF_2} \leq r_b$.

The marginal cost of the *i*-th unit belonging to the group *j* of units is given by the first derivative of the total cost and, given the assumptions described above, is

(1) $MC_{e_j} = c_{e_j} + r_j \cdot \tau$, with $j = a, g, AF$

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

Furthermore, there exists a pollution price, the "switching price", $\tau^s = (c_{e_g} - c_{e_a})/(r_a - r_g)$, such that the marginal cost of the units of the group a , MC_{e_a} , is equal to that of the units of the group g , MC_{e_g} . $\overline{MC}_e = \max\{MC_{e_a}; MC_{e_g}\}$ is the marginal cost of the least efficient units and $\underline{MC}_e = \min\{MC_{e_a}; MC_{e_g}\}$ 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 hour (short-lived auctions). 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 suppliers submit different bids, the lower-bidding supplier's capacity is despatched first. If this capacity is not sufficient to satisfy the total demand, the higher-bidding supplier's capacity is then despatched to serve the residual demand, i.e. total demand minus the capacity of the lower-bidding supplier Given the assumptions about electricity demand and about market structure there exists a unique price p^r_e which maximizes the dominant firm' profits from serving the residual demand, i.e. $p^r_e = \arg\max_{p_e} \{p_e [D_e(p_e) - K^{f_e}] - \underline{MC}_e\}$.
p^r_e will be referred to as the 'residual monopoly price' (Fabra at al., 2002).

(Contd.) ——————————

4 Assuming that each group includes the same number *n* of units implies that $k_{e_j} \geq 0$ depends on $K_{e_j} \geq 0$. This is an arbitrary assumption which does not undermine, however, the significance of the analysis.

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.

3. Change in gas prices and change in marginal costs of power generation

In the dominant firm model the gas leader faces two strategies: *(i)* to accommodate the fringe's maximum production by setting prices equal to the residual monopoly price; (ii) to set price equal to the marginal cost of the fringe so maximizing its production. If we consider what really happens in several gas markets, the former strategy is far more likely.

Nevertheless in our model the leader is not able to set the residual monopoly price because there is an alternative fuel able to create a sort of price cap in the input market. In fact under the assumptions reported in sub-section 2.2 and if the residual monopoly price is sufficiently high, the leader firm will set prices just below $\hat{p}_g$. This is the price which would make the end user indifferent when choosing between an installation using gas and the alternative technology.

This means that, in order to set $\hat{p}_g$, gas firms look at the long run marginal cost of the alternative fuel ($LRMC_{AF_j}$) which is the cost to deliver an additional unit of this output under the assumption that this requires investment in capacity expansion[5]. Then the price threshold, $\hat{p}_g$, will be equal to the long run marginal cost of the alternative fuel power installation minus the extra-fuel costs[6] of the gas fired installation. This difference is the net long run marginal cost ($NLRMC_{AF_j}$ *)*.

Note that this kind of pricing is also denominated as "market value principle". It is largely used for price indexation in the natural gas long term contracts for natural gas.

Given this framework, the following lemma characterizes price equilibria in the natural gas market with dominant firm and inter-fuel competition.

Lemma 1. *If the gas leader behaves as a residual monopolist and if the residual monopoly price is enough high, in any equilibrium the natural gas price equals the net long run marginal cost of the alternative fuel.*

Proof. See Figure 1. Given the natural gas demand, D_g, and the fringe's maximum production, K_g^{fg}, the residual demand will be RD_g. The residual demand curve has been constructed by using the efficient rationing rule. If the size of the fringe is enough low and the potential capacity of the low-cost alternative fuel enough high (higher than the dominant firm's residual demand at $\hat{p}_g$), the dominant firm will set the price threshold $\hat{p}_g$ if this is lower than the residual monopoly price. For a discussion about equilibria in duopolistic contexts see sub-section 6.3..

Proof. See the arguments illustrated above and figure 1.

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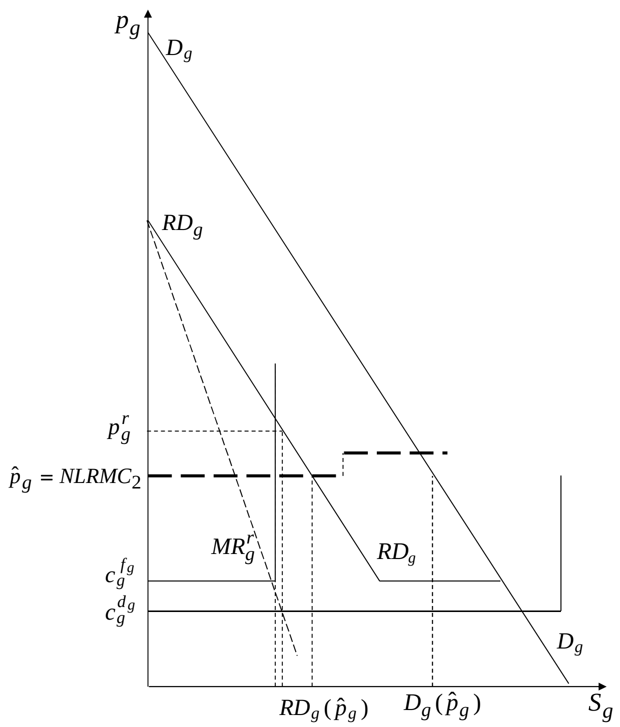
5 In particular, in the model carried out in this paper the long run marginal cost of the alternative technology is the average cost of the best alternative technology.

6 Extra-fuel costs include capital costs and operating and maintenance costs.

Figure 1. Equilibrium in the natural gas market with inter-fuel competition (leader behaving as a residual monopolist)



Lemma 1 suggests that, if we wish to know the impact of the environmental policy on the natural gas price, we should study how the environmental policy modifies $\hat{p}_g$.

Under emissions trading the outcome depends on the method and on the rules of allowances allocation. To understand why and how, we should consider the following.

First, the ETS gives rise to a market for the emissions allowances. Therefore, since the allowances have a value their use generates an opportunity cost equal to the allowance price multiplied by the emission rate, $r_j \tau$, hereafter the pollution cost.

Second, as in the case of taxation, the ETS determines an increase in the unit variable cost equal to the pollution cost.

Third, this cost arises even if the public authority allocates to the generator an amount of allowances free of charge. Nevertheless, the value of these allowances is a sort of "gift" for the generator. Consequently, if we want to calculate the net long run marginal cost (which includes the fixed components), the unit value of these allowances (the value per unit of electricity generated) should be deducted from the cost. Then from Lemma 1 and equation (1), the natural gas price will be given by

$$(2)\quad p_g = \hat{p}_g = NRLMC_{AF} = \eta_g \left[CT_{AF_2} - CT_{AF_1} - EXF_g + \tau(E_{AF_2} - \overline{E}_{AF_2}) - \tau(E_g - \overline{E}_g \right]$$

Where

CT_{AF_j} = total cost per unit of electricity generated by using the low-cost alternative fuel installation, $j = AF_1, AF_2$

EXF_g = extra-fuel cost per unit of electricity generated by using the gas-fired power station

η_g = electric efficiency of the gas-fired power installation

$E_j = r_j$ = actual emissions per unit of electricity generated, with $j = AF_2, g$

$\overline{E}_j = r_{bn} =$ "emissions allocated" free of charge per unit of electricity generated, with $j = AF_2, g$

With full auctioning, $\overline{E}_j = 0$. With benchmarking, $\overline{E}_j = r_{bn}$.

By differentiating equation (2) with respect to τ and provided that $p_g = \eta_g c_{e_g}$ we get

$$(3)\quad \left(\frac{dc_{e_g}}{d\tau}\right)_{ETS} = \frac{1}{\eta_g}\frac{dp_g}{d\tau} = r_{AF_2} - r_g$$

Equations (3) points out two interesting results. First, if $r_{AF_2} < r_g$ the environmental policy would determine a decrease in the gas price. Second, the change in the gas price does not depend on the type of allowances allocation (auctioning or benchmarking). These results are summarized in the following proposition and corollaries.

Proposition 1. *In presence of imperfect competition in the input (natural gas) market, the pollution price becomes a direct driver of the natural gas price.*

Proof. This proposition is a direct consequence of Lemma 1.

Corollary 1. *The change in the gas price due to the emissions trading equals the difference in pollution costs between alternative fuel and natural gas regardless of how allowances are allocated (auctioned or benchmarked).*

Proof. See equations (3) and the related comments above.

In conclusion, imperfect competition gives rise to a direct link between natural gas prices an pollution prices in the sense that the environmental policy directly impacts on the natural gas price through the cost of the alternative fuel. This impact (Table 1) depends on the type of the alternative fuel.

In particular, it is important to underline that the change in the natural gas value is negative if the emission rate of the alternative fuel is lower than that of the gas-fired power station. This means that if the alternative technology is a low carbon or carbon free technology (e.g. renewable technology or fossil fuels with Carbon Capture and Sequestration (CCS)) the environmental regulation determines a decrease in natural gas price. Otherwise there will be an increase.

From equation (1) this implies that the marginal cost of the gas-fired plants will be equal to the fuel cost plus the carbon cost of the alternative fuel rather than that of the gas-fired one. In fact, for a generic $\tau > 0$:

$$(4)\quad MC_{e_g} = c_{e_g}(\tau) + r_g \cdot \tau = c_{e_g}(0) + (r_{AF_2} - r_g) \cdot \tau + r_g \cdot \tau = c_{e_g}(0) + r_{AF_2} \cdot \tau$$

Corollary 2. *Under imperfect competition in the gas market, the change in marginal cost of the gas-fired power units equals the carbon cost of the alternative technology.*

Proof. See equation (4) and table 1.

Table 1. Impact of emissions trading on the input price

	Input market fully competitive	Input market imperfectly competitive
		ETS
		Auctioning or benchmarking
Gas price sensitivity	$\frac{dc_{e_g}}{d\tau}=0$	$\frac{dc_{e_g}}{d\tau}=r_{AF_2}-r_g$
Total change in marginal cost of gas fired technologies	$\Delta MC_{e_b}=r_g\cdot\tau$	$\Delta MC_{e_g}=r_{AF_2}\cdot\tau$

4. Change in market power in the electricity market

Given the assumptions on the power market described in sub-section 2.3, it is straightforward that power price equilibria will depend on the power demand level. As the latter continuously varies over time, an useful way of representing the price schedule is to carry out the so-called price curve $p_e(H)$ characterizing price equilibrium for every level of power demand in the load duration curve, i.e. for every value of H .

In order to derive the price schedule in the form of a price 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 leader. Then the 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 $\underline{\mu}^{d_e}\in[0;1]$ and $\underline{\mu}^{f_e}\in[0;1]$ representing the share of capacity the leader and the fringe get in most efficient plants, respectively. By complement, $\overline{\mu}^{d_e}=1-\underline{\mu}^{d_e}$ and $\overline{\mu}^{f_e}=1-\underline{\mu}^{f_e}$ are the same in the least efficient ones.

By facing the fringe, the dominant firm has two alternative strategies: (1) bidding the residual monopoly price (p_e^r) 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 $\underline{K}_e^{f_e}$ be the installed capacity in most efficient plants operated by the fringe. Thus $\underline{K}_e^{f_e}=\underline{\mu}^{f_e}(1-\delta)K_{e_T}$ and $\underline{H}^f=D^{-1}(\underline{K}^{f_e})$. Finally, $\underline{K}_e=\left[\underline{\mu}^{d_e}\delta+\underline{\mu}^{f_e}(1-\delta)\right]K_{e_T}$ is the total capacity in most efficient plants.

4.1. No regulatory pressure

The following Lemma describes the shape of the price curve when the dominant firm can set the residual monopoly price, p_e^r .

Lemma 2. (i) There exists $\hat{D}_e \in \left[D_{e_M}; \underline{K}_e^{f_e}\right]$ such that (i) $p_e = p_e^r$ if $D_e \geq \hat{D}_e$, (ii) $p_e = \overline{MC}_e$ if $\underline{K}_e^{f_e} \leq D_e < \hat{D}_e$ and (iii) $p_e = \underline{MC}_e$ if $D_e < \underline{K}_e^{f_e}$, where

$$\hat{D}_e = \begin{cases} (1-\delta)K_T + \left(\zeta \underline{\mu}^{d_e} \delta K_T\right)^{1/2} & \text{if } \hat{D}_e \geq \underline{K}_e \\ (1-\delta)K_{e_T} + \dfrac{\zeta}{2} + \dfrac{1}{2}\left[\zeta^2 + 4\zeta(1-\delta)K_{e_T}(1-\underline{\mu}^{f_e})\right]^{1/2} & \text{if } \hat{D}_e < \underline{K}_e \end{cases}$$

where $\zeta = \beta(\overline{MC}_e - \underline{MC}_e)$ and $\beta = -\dfrac{dD_e}{dp_e}$

Proof. See Appendix.

We consider $\hat{D}_e$ as the proxy of the degree of market power. In fact, $\hat{H} = D^{-1}(\hat{D}_e)$ is the time (the number of hours) over which the dominant firm is able to set the price threshold[7].

Lemma 2 highlights that two price curves are possible depending on whether the discontinuity is at $\hat{H}_1 = D^{-1}(\hat{D}_{e_1})$ or $\hat{H}_2 = D^{-1}(\hat{D}_{e_2})$.

Finally, by differentiating $\hat{D}_e$ with respect to $\underline{\mu}^{d_e}$ and $\underline{\mu}^{f_e}$ we find that the degree of market power is an increasing function of $\underline{\mu}^{f_e}$ and an decreasing function of $\underline{\mu}^{d_e}$ (see Appendix).

Lemma 2 also shows that the degree of market power depends on ζ. Since the latter depends on pollution price, the environmental regulation is able to modify the degree of market power. Increasing market power means that the number of hours in which the dominant firm prefers to offer the residual monopoly price goes up. Vice-versa with decreasing market power. The following Lemma explains when this can occur.

Lemma 3. *If the dominant firm can maximize profits, the environmental policy always determines an increase in the degree of market power,* $\Delta\hat{D}_e < 0$, *in the electricity market if* $\bar{\tau} < \tau^s$; *if* $\bar{\tau} \geq \tau^s$ *market power can either increase,* $\Delta\hat{D}_e < 0$, *or decrease,* $\Delta\hat{D}_e > 0$.

Proof. From Lemma 3

$$\frac{\partial \hat{D}_e}{\partial \tau} = \begin{cases} \dfrac{\beta}{2} \cdot \underline{\mu}^{d_e} \delta K_{e_T} \left[\zeta \underline{\mu}^{d_e} \delta K_{e_T}\right]^{-1/2} (\bar{r} - \underline{r}) & \text{if } \hat{D}_e \geq \underline{K}_e \\ \dfrac{\beta}{2}\left[1 + \dfrac{\zeta + 2(1-\delta)(1-\underline{\mu}^{f_e})K_{e_T}}{\left(\zeta^2 + 4\zeta(1-\delta)(1-\underline{\mu}^{f_e})K_{e_T}\right)^{1/2}}\right](\bar{r} - \underline{r}) & \text{if } \hat{D}_e < \underline{K}_e \end{cases}$$

Where $\bar{r} = r_{AF_2}$ and $\underline{r} = r_a$ if $\tau < \tau^s$ while $\bar{r} = r_a$ and $\underline{r} = r_{AF_2}$ if $\tau \geq \tau^s$.

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7 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 $\underline{K}_e^{f_e}$ which does not depend on the pollution price.

Therefore since $r_{AF_2} < r_a$ then $\left(\frac{\partial \hat{D}_e}{\partial \tau}\right)_{\tau<\tau^s} < 0$ and $\left(\frac{\partial \hat{D}_e}{\partial \tau}\right)_{\tau>\tau^s} > 0$ always. Then, since $\Delta\hat{D}_e$ can be expressed as $\Delta\hat{D}_e = \int_0^{\tau^s}\left(\frac{\partial \hat{D}_e}{\partial \tau}\right)_{\tau<\tau^s} d\tau + \int_{\tau^s}^{\overline{\tau}}\left(\frac{\partial \hat{D}_e}{\partial \tau}\right)_{\tau\geq\tau^s} d\tau$, for a given τ and a given τ^s, $\Delta\hat{D}_e > 0$ when $\left|\frac{\partial \hat{D}_e}{\partial \tau}\right|_{\overline{\tau}<\tau^s}$ is sufficiently low and/or $\left|\frac{\partial \hat{D}_e}{\partial \tau}\right|_{\overline{\tau}\geq\tau^s}$ is sufficiently high. This can occur when the dominant firm holds a large share of gas units (low $\underline{\mu}^{d_e} = \mu_a^{d_e}$ when $\tau < \tau^s$; high $\underline{\mu}^{d_e} = \mu_g^{d_e}$ when $\tau \geq \tau^s$). Finally, note that $\left|\frac{\partial \hat{D}_e}{\partial \tau}\right|$ is an increasing function of τ.

4.2. With regulatory pressure

The basic model makes the assumption that firms can maximize profits i.e. the dominant firm is able to set the residual monopoly price.

However firms may pursue strategies besides profit maximization. In particular, because of the regulatory pressure exerted by the competition and sector-specific authorities, their offer prices may be constrained to be below some threshold lower than the residual monopoly price. In other words firms may restrain themselves to bid above some threshold in order to avoid the risk of more restrictive regulation (implicit price cap).

In the presence of a price threshold, lemma 2 becomes

Lemma 2bis. (i) *There exists* $\hat{D}_e \in \left[D_{e_M}; \underline{K}_e^{f_e}\right]$ *such that (i)* $p_e = \hat{p}_e$ *if* $D_e \geq \hat{D}_e$, *(ii)* $p_e = \overline{MC}_e$ *if* $\underline{K}_e^{f_e} \leq D_e < \hat{D}_e$ *and (iii)* $p_e = \underline{MC}_e$ *if* $D_e < \underline{K}_e^{f_e}$, *where*

$$\text{(A7)}\ \hat{D}_e = \begin{cases} \hat{D}_{e_1} = \left[\underline{\mu}^{d_e}\delta\sigma + (1-\delta)\right]K_{e_T} \\ \hat{D}_{e_2} = (1-\delta)\left[\dfrac{1-\sigma\underline{\mu}^{f_e}}{1-\sigma}\right]K_{e_T} \end{cases}$$

where $\sigma = \dfrac{\overline{MC}_e - \underline{MC}_e}{\hat{p}_e - \underline{MC}_e} < 1$

Proof. See Appendix.

Given this lemma the conditions under which emissions trading can increase or decrease market power become:

Lemma 3bis. *(i) When* $\tau < \tau^s$ *then* $\partial\hat{D}_e/\partial\tau \leq 0$ *if* $\partial\hat{p}_e/\partial\tau \geq \hat{r} = r_a + \lambda(r_g - r_a + dc_{e_g}/d\tau)$ *and vice versa; (ii) When* $\tau \geq \tau^s$ *then* $\partial\hat{D}_e/\partial\tau \leq 0$ *if* $\partial\hat{p}_e/\partial\tau \leq \hat{r}$ *and vice versa, with* $\lambda = (\hat{p}_e(0) - c_{e_a})/(c_{e_g}(0) - c_{e_a}) > 1$

Proof. See Appendix.

Lemma 3bis underlines that, if the price threshold is sufficiently low sensitive to the pollution price, the environmental policy can decrease market power.

A typical case in which, because of the regulatory pressure, firms offer below the profit-maximizing price is when they try to meet a profit target. This latter may be a short-term (e.g. one-year) target or a long-term target (e.g. multi-years target). This latter consist of keeping constant the profit over time at the same time minimizing the price volatility. The following corollary describes the change in cost pass-through to prices under these different solutions.

Corollary 2. *(i) if the dominant firm pursues a short-term profit target the pass-through rate may be less than one only with benchmarking of emissions allowances; (ii) if the dominant firm pursues a long-term profit target the pass-through rate may be much less than one regardless of the kind of allowances allocation.*

Proof. See Appendix. Intuitively, if the profit target is a short-term target (e.g. one-year target), to keep constant the profit requires prices have to increase more than the increase in cost because the price threshold is lower than the residual monopoly price. If the profit target is a long-term profit target the dominant firm can choose to pass through less than the increase in cost, when the cost goes up, provided that the pass-through is sufficiently less than the decrease in cost, when the cost goes down. The loss of profit in the former case is offset by the additional profit in the latter case. Consequently the profit over time remains unchanged.

Looking at the long-term target, it remains the last question: which change in prices (pass-through) the dominant firm will choose when the price goes up? It presumably will choose a value enough low to minimize the regulatory risk but at the same enough high to reduce the effect of the uncertainty about the time evolution of pollution prices. In fact a too low bid is risky when you do not know in advance whether, when and how much the pollution price will decrease in the future. Given these constraints, the most likely pass-through is that expected by the regulator namely a value lower than the change in marginal cost of the marginal technology if the market was fully competitive. Note that (see Appendix), when costs go down, the price drop is lower than the price increase when costs go up, in absolute terms. This is a typical behavior we can observe in those markets with market power and regulatory pressure.

Table 2. Carbon cost pass-through with profit target

	Input market fully competitive	Input market imperfectly competitive	
		Auctioning	Benchmarking
Gas price sensitivity	$\frac{dc_{e_g}}{d\tau} = 0$	$\frac{dc_{e_g}}{d\tau} = r_{AF_2} - r_g$	
$\hat{r}$ ($\tau < \tau^s$)	$\hat{r} = r_a + \lambda(r_g - r_a)$	$\hat{r} = r_a + \lambda(r_{AF_2} - r_a)$	
Short-term Target		$\Delta\hat{p}_e > r_a\tau$	$\Delta\hat{p}_e > (r_a - r_{bn})\tau$
Long-term Target		$\Delta\hat{p}_e < r_{AF_2}\tau$	$\Delta\hat{p}_e < (r_{AF_2} - r_{bn})\tau$

The following corollary summarizes the above results.

Corollary 3. *If the dominant firm pursues a profit target, the environmental regulation may determine a decrease in market power especially if allowances are benchmarked.*

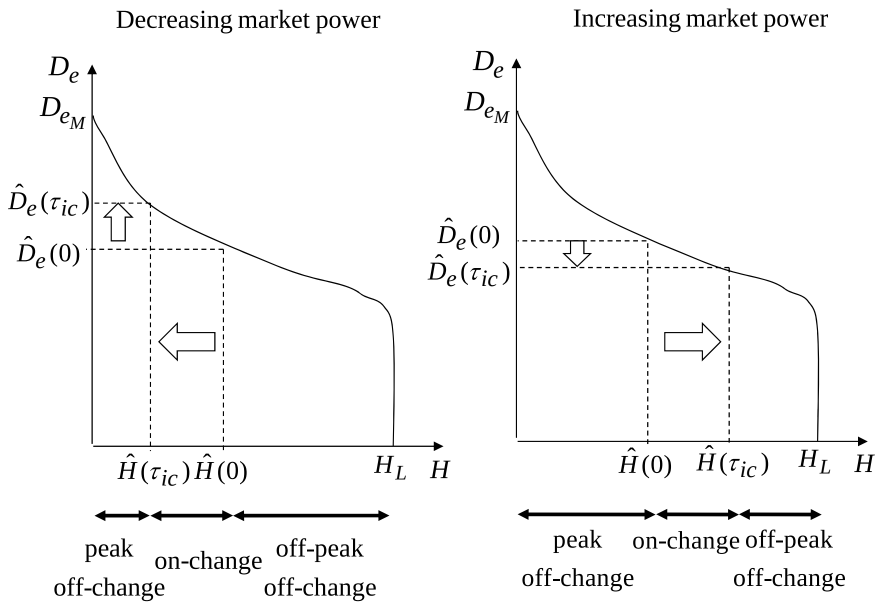
Proof. Looking at the case analysed here the change in price threshold will be lower than the change in marginal cost of the gas-fired plants (the marginal units under full competition). Under imperfect competition in the gas markets this is equal to the pollution cost of the alternative fuel. Therefore $\Delta\hat{p}_e < r_{AF_2}\tau$ with auctioning, and $\Delta\hat{p}_e < (r_{AF_2} - r_{bn})\tau$ with benchmarking[8] (Table 2). In this latter case it is therefore very likely that the environmental policy determines an increase rather than a decrease in prices. This time therefore, from Lemma 2bis, the condition for decreasing market power, $\frac{\partial\hat{p}_e}{\partial\tau} < \hat{r} = r_a + \lambda(r_{AF_2} - r_a)$, is always satisfied.

5. Change in prices and in pollution in the electricity market

Looking at the short run, in fully competitive markets the environmental policy 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 increase in prices and consequently a decrease in demand (and production). The increase in price, and consequently the drop in demand, is related to the marginal cost of the marginal technology that is to the emission rate of the gas fired plants and coal plants in our model. On the other hand, if $r_g < r_a$ and if the pollution price is above the "switching price", it determines a switch of power 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 should take into account an additional one that is the just mentioned impact on the degree of market power.

Figure 2. Changes in market power



This effect occurs in the hours in which the dominant firm modifies its strategy. These hours are denominated as the "on-change hours" while the remaining ones, in which the dominant firm's strategy remains unchanged, are denominated as "off-change hours" (Fig. 2). The off-change hours

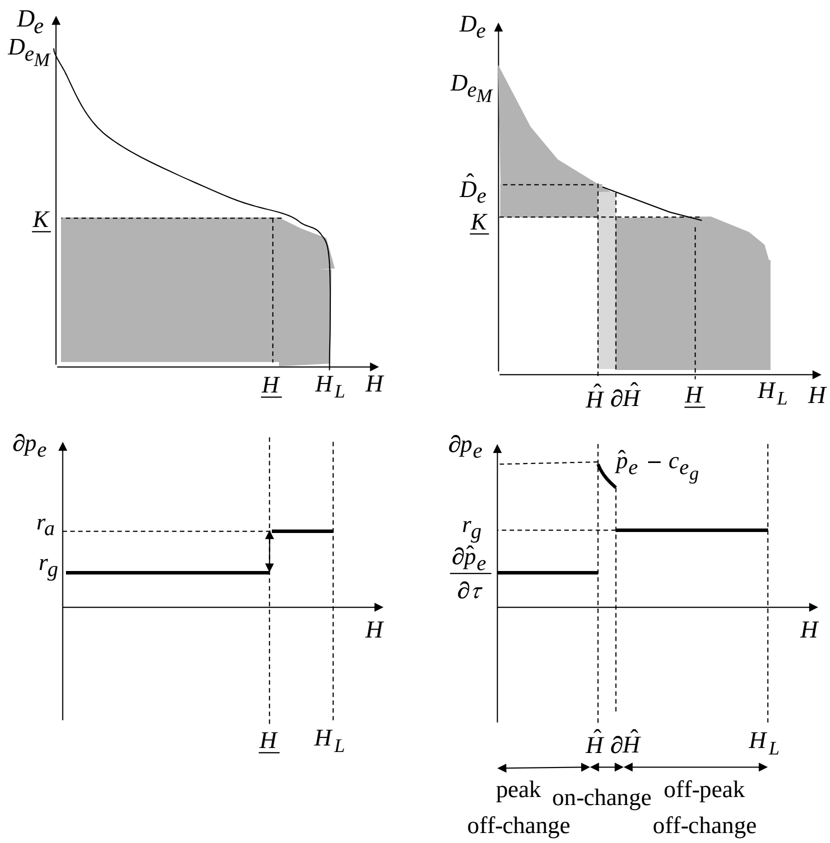
8 See also Chernyavs'ka and Gullì (2008a and 2008b).

include: *(i)* the peak off-change hours in which the dominant firm bids the price threshold before and after the environmental policy; *(ii)* the off-peak off-change hours in which the dominant firm bids the marginal cost of the fringe before and after the environmental policy.

Overall imperfect competition will lessen the performance of environmental policy when $\Delta E_{ic} = \Delta E^{on} + \Delta E^{off}_{peak} + \Delta E^{off}_{off-peak} < \Delta E_{fc}$, where ΔE_{ic} and ΔE_{fc} are the change in emissions under imperfect competition and full completion respectively.

To understand how the change in market power can impact on electricity prices and on pollution, it is helpful to analyze the two extreme technological configurations: 1) the case in which the leader holds only the more polluting units (group *a*) and the fringe only the less polluting ones (group *g*), that is $\mu_a^{d_e} = 1$ and $\mu_a^{f_e} = 0$; 2) the case in which the leader holds only the less polluting units (group *g*) and the fringe only the more polluting ones (group *a*), that is $\mu_a^{d_e} = 0$ and $\mu_a^{f_e} = 1$. These cases allow us to greatly simplify the graphical explanation without loss of generality. In fact the results of the other configurations (in which the dominant firm and the fringe operate both kinds of generating units) are intermediate between the extreme ones.

Figure 3. Load duration and marginal price curves ($\mu_a^{d_e} = 1$ and $\mu_a^{f_e} = 0$): production by units of group *a* (grey area); production by units of group *g* (white area)



For the sake of simplicity, we restrict the formal analysis only to the case in which $\mu_a^{d_e} = 1$ and $\mu_a^{f_e} = 0$ and $\tau < \tau^S$. The other cases are illustrated graphically.

From Proposition 1, when $\mu_a^{d_e} = 1$ and $\mu_a^{f_e} = 0$, at the margin the load duration and price curves of figure 3 arise. Note that when demand is less than the fringe's capacity (i.e. when the dominant firm and the fringe offer the same price, MC_g) only the dominant firm's plants (the most polluting and most efficient plants) are despatched. This implicitly assumes the efficient rationing. However, with the proportional rationing and multi-unit auctions the result would remain substantially unchanged[9]. At the same time, when demand is above the fringe's total capacity the rationing rule is not relevant since the dominant firm always bids below or above the marginal cost of the fringe.

The difference in marginal emissions between imperfect and full competition is (see Appendix)

(5)

$$\frac{\partial E_{ic}}{\partial \tau} - \frac{\partial E_{fc}}{\partial \tau} = \underbrace{\Bigg\{ \underbrace{r_a \left[-\beta \frac{\partial \hat{p}_e}{\partial \tau} \int_0^{\hat{H}} D_e dH \right]}_{\text{Imperfect competition}} - \underbrace{r_g \left[-\beta r_g \int_0^{\hat{H}} D_e dH \right]}_{\text{Full competition}} \Bigg\}}_{\text{peak off-change hours}} +$$

$$+ \underbrace{\Bigg\{ \underbrace{(r_g - r_a) K_{e_T} \frac{\partial \hat{H}}{\partial \tau} - \hat{D}_e \left[\frac{\partial H}{\partial D_e} \left(\mp \beta (\hat{p}_e - MC_{AF_2}) + \frac{\partial \hat{D}_e}{\partial \tau} \right) \right]}_{\text{Imperfect competition}} - \underbrace{\left[r_g (-\beta r_g) \left| \frac{\partial \hat{H}}{\partial \tau} \right| \right]}_{\text{Full competition}} \Bigg\}}_{\text{on-change hours}} +$$

$$+ \underbrace{\Bigg\{ \underbrace{r_g \left[-\beta r_{AF_2} \int_{\hat{H}}^{\overline{H}} D_e dH \right] + r_a \left[-\beta r_{AF_2} \int_{\underline{H}}^{H_L} D_e dH \right]}_{\text{Imperfect competition}} - \underbrace{r_g \left[-\beta r_g \int_{\hat{H}}^{\overline{H}} D_e dH \right] - r_a \left[-\beta r_a \int_{\underline{H}}^{H_L} D_e dH \right]}_{\text{Full competition}} \Bigg\}}_{\text{off-peak off-change hours}}$$

By integrating over τ we get the total difference in the change in pollution

$$\Delta E_{ic} - \Delta E_{fc} = \int_0^{\tau_{ic}} \frac{\partial E_{ic}}{\partial \tau} d\tau - \int_0^{\tau_{fc}} \frac{\partial E_{fc}}{\partial \tau} d\tau$$

Where: τ_{ic} and τ_{fc} are the change in pollution price under imperfect competition and full competition, respectively. Furthermore, the sign (+) (the sign (-)) in the on-change components refers to decreasing (increasing) market power.

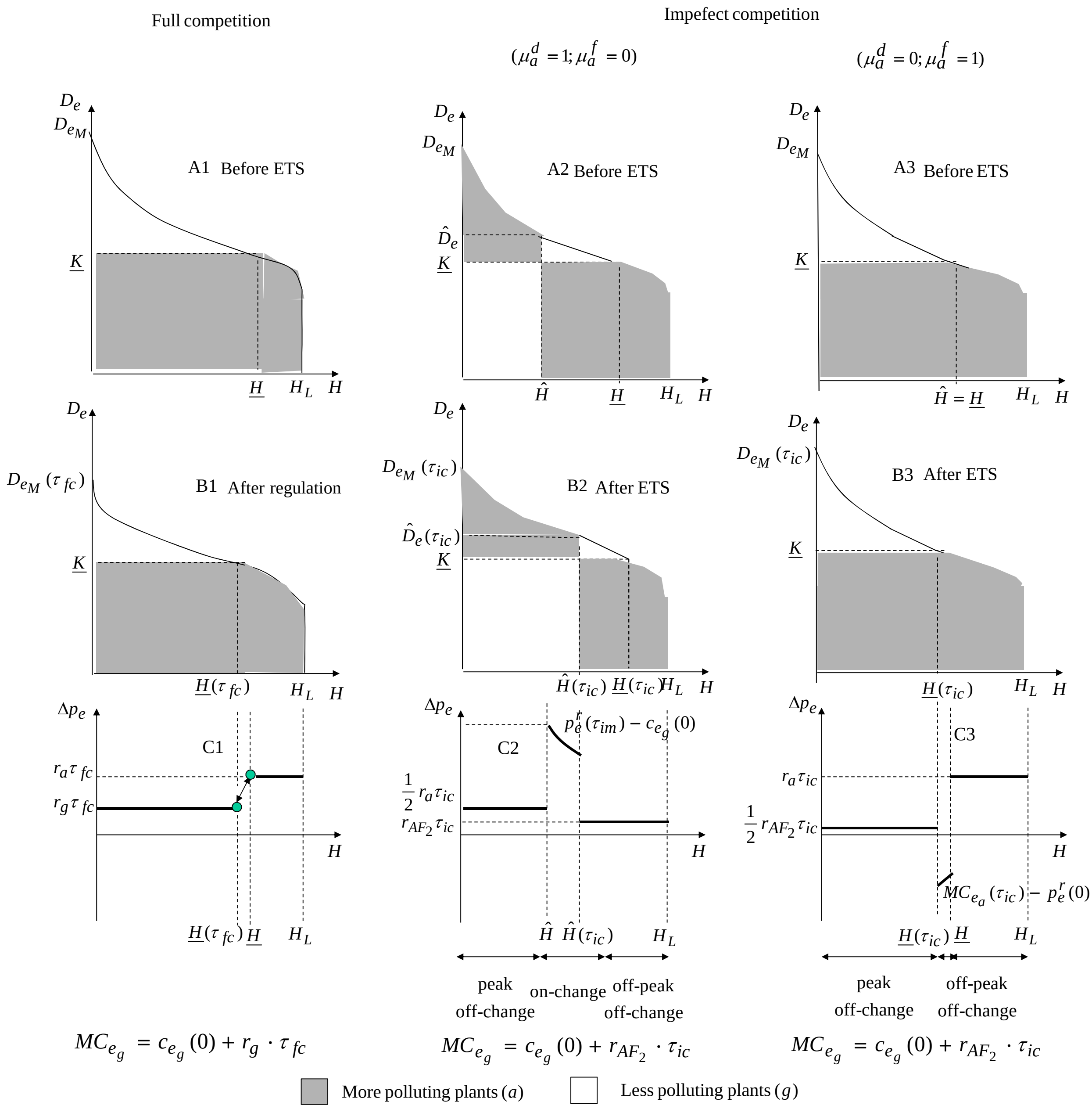
5.1. No regulatory pressure

In this case, when $\mu_a^{d_e} = 1$ and $\mu_a^{f_e} = 0$, from Lemma 3 $\partial \hat{H} / \partial \tau > 0$. Consequently the on-change component in equation (5) is negative. The marginal decrease in emissions under imperfect competition is higher than under full competition. By intuition, in the on-change hours the dominant

[9] With multi-unit auctions, strictly speaking, only offer prices of sets that may become marginal need equal the system marginal price. Thus proportional rationing has a negligible impact on pollution if the unit size is relatively small.

firm will bid the marginal cost of the gas plants and the price threshold before and after the environmental regulation respectively. Therefore prices will sharply increase. At the same time the change in the dominant firm's strategy has impact on how the different technologies are despatched (with their total capacity or not). After the implementation of the environmental policy, the fringe's units (the less polluting ones) will be despatched with their total capacity while the dominant firm will supply the residual demand. Together with the decrease in price, this will involve a strong decrease in pollution.

Figure 4. Changes in prices and in emissions ($\forall \tau < \tau_{ic}^{s}$)



In the off-peak off-change hours, the corresponding component in equation (5) is surely positive. Therefore the marginal decrease in emissions is lower under imperfect competition than under full competition.

In the peak off-change hours and with full competition, prices increase by r_g. Instead under imperfect competition and with linear demand, the price sensitivity to the pollution price is $\partial p_e^r / \partial \tau = 1/2 \cdot r_a$. Therefore under the likely condition that $r_a > r_b \sqrt{2}$ the rise in prices under imperfect competition (and consequently the marginal decrease in emissions) is certainly higher than under full competition.

Overall in the off-change hours, it is likely that marginally emissions decrease less when markets are imperfectly competitive.

It remains to evaluate the difference in the total change in emissions (equation 6). This requires to focus on the change in the pollution price. In this respect, we have to account for how the demand for allowances varies over time. In principle, higher marginal decrease in emissions leads to lower demand and consequently to lower pollution prices which can partially offset the increase in emissions and vice versa. Therefore there will be a trade-off between marginal emissions and the change in pollution price. However, it is unlikely that this trade-off could nullify the difference in emissions between imperfect and full competition, for the following reasons. The impact on pollution price of the change in demand by the power sector is relatively slight because total demand also depends on emissions in the other sectors covered by the ETS. This is even more true if we look at a specific power sector within a multi-country ETS (as in the case of the EU-ETS). Therefore the pollution price is almost exogenous and the effect of marginal emissions is prevalent on the effect of the absolute change in pollution price. So, if the dominant firm holds a sufficiently share of the more polluting units, emissions under imperfect competition will decrease more than under full competition, even in absolute terms.

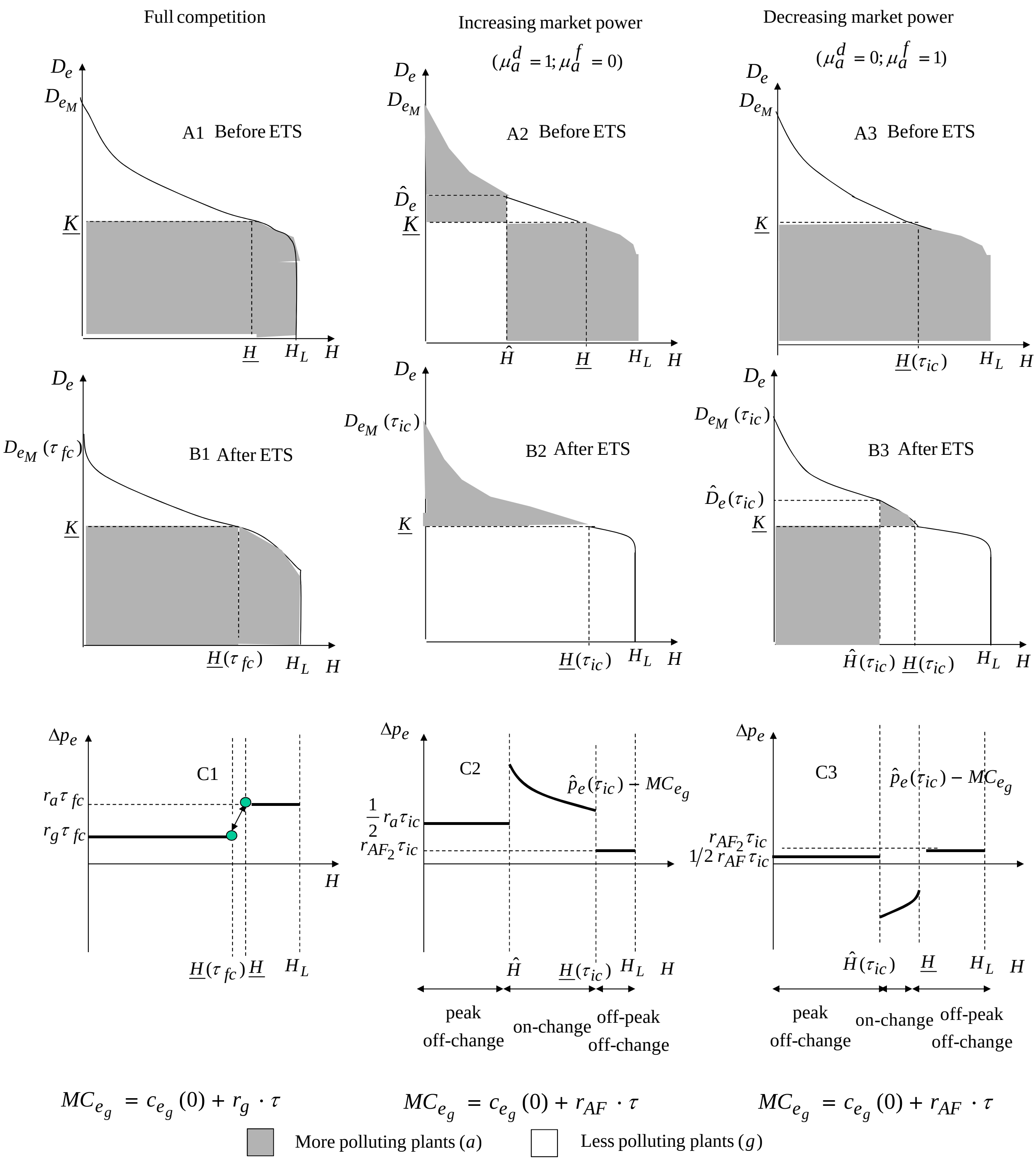
The overall results are described in Figure 4 (graphs A2, B2 and C2) which compares the cases of full competition and imperfect competition. Three series of graphs are illustrated. The first and second series highlight the share of production by the two kinds of plants before (graphs A) and after (graphs B) the ETS implementation. The third series (graphs C) depicts the corresponding price curves and consequently the change in prices[10]. As can be noted, it is very likely that emissions decrease more under imperfect than full competition.

In the same figure (graphs A3, B3 and C3), the case in which the dominant firm holds only the less polluting plants and the fringe only the more polluting one are illustrated. This time there is a positive probability that the decrease in emissions under imperfect competition could be lower than under full competition.

Summing up, emissions would slightly decrease in the off-peak hours but they sharply decrease in the on-change hours. However this latter effect tends to disappear to the extent to the share of the dominant firm’s gas units goes up. Consequently it is unlikely that imperfect competition could lessen the performance of the environmental policy unless the dominant firm holds a large share of gas units. The results is ambiguous but the absolute increase in emissions in the short-run can be excluded.

[10] Note that, since we assume constant marginal costs for each category of plants (namely one-stepped supply curve), the increase in price under full competition is always equal to the full carbon cost of the marginal technology (full pass-through) except in the case where the demand curve intercepts the step of the supply curve (before or/and after regulation). However the number of hours in which the pass-through rate is lower than one is almost negligible if the difference in marginal costs between technologies (the step) is relatively limited.

Figure 5. Changes in prices and in emissions ($\tau_{fc}^{s} < \tau < \tau_{ic}^{s}$)



However, we have also to consider that the carbon price can involve a switch of power producers on the merit order. Under imperfect competition in the input market the "switching price" is $\tau_{ic}^{s} = (c_{e_g} - c_{e_a})/(r_a - r_{AF_2})$. Since under full competition $\tau_{fc}^{s} = (c_{e_g} - c_{e_a})/(r_a - r_g)$ then $\tau_{ic}^{s} < \tau_{fc}^{s}$, if the alternative fuel is a very low carbon fuel $(r_{AF} < r_g)$. This means that the induced change in merit order becomes more likely under imperfect than under full competition. In this case, the decrease in emissions under imperfect competition is higher than under full competition even if the share of gas units operated by the dominant firm is large (Fig. 5).

These results are summarized in the following proposition.

Proposition 2. *When the dominant firm can maximize profits, imperfect competition in both markets may lessen the performance of environmental policy only if the dominant firm holds a large share of gas-fired units and provided that the pollution price is sufficiently low. An absolute increase in pollution is excluded.*

Proof. See discussion and graphical explanations above.

5.2. With regulatory pressure

Under regulatory pressure, when $\mu_a^{d_e} = 1$ and $\mu_a^{f_e} = 0$, from Lemma 3bis (see the related proof in Appendix) $\partial\hat{H}/\partial\tau < 0$. Consequently the on-change component in equation (5) is positive. This means that marginally emissions under imperfect competition decrease much less (or rather increase) than under full competition.

In other words, in these hours after the implementation of the environmental policy the dominant firm's units (the more polluting plants) will be despatched with their total capacity. Together with the decrease in price, this will involve a strong increase in pollution (see also graphs B2 and C2 of figure 4).

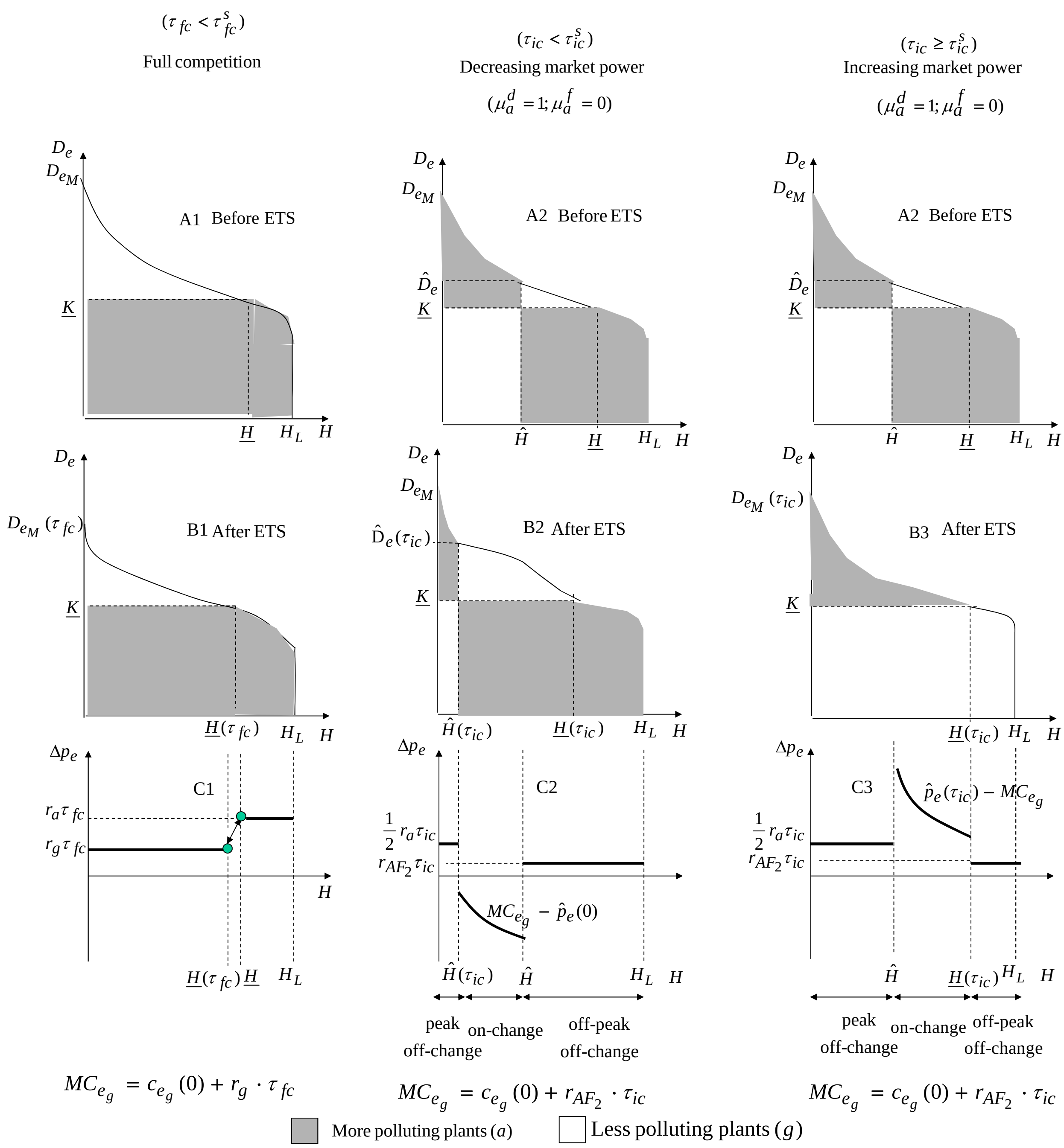
At the same time, either the off-peak off-change component or the peak off-change one are positive especially if allowances are benchmarked. Overall in the off-change hours the marginal decrease in emissions under imperfect competition will be much lower than under full competition.

Furthermore, since marginally emissions decrease less, the pollution price would be higher under imperfect competition (more demand for allowances). However this time there is no trade-off, for the following reason. If the pollution price goes up, also the degree of market power, and consequently the number of on-change hours in which emissions sharply increase, goes up (see proof of lemma 3bis in Appendix). If this effect is relevant (large asymmetry of firms), in equlibrium the change (decrease) in emissions will be much lower than under full competition.

Given all the findings before, under regulatory pressure it is very likely not only that the decrease in emissions under imperfect competition could be lower than under full competition but also that emissions trading could determine an absolute increase in pollution (perverse effect) at least in the short-run[11] (Fig. 6).

[11] On this issue, the economic literature provides a controversial framework. On the one hand, some authors find that the environmental policy increases pollution never. Among them, see Sugeta and Matsumoto (2007). Canton, Soubeyran and Stahn (2008). On the other hand, other authors (Levin, 1985; Requate, 2005) find that under imperfect competition the environmental policy can even increase emissions but only if specific conditions in terms of demand (extreme curvature) and supply (sufficiently asymmetric firms) are satisfied.

Figure 6. Changes in prices and in emissions: long-term profit target with auctioning



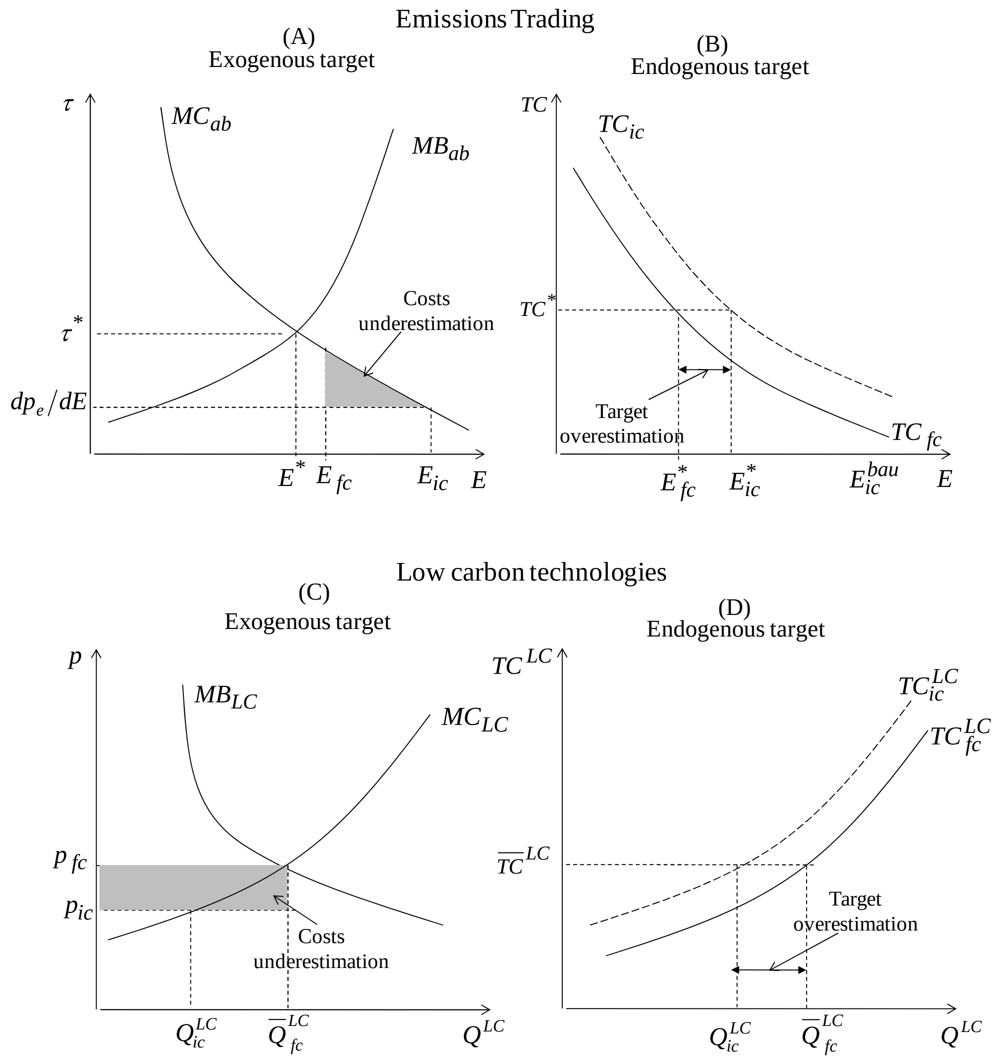
However it is important to note that this may happen if the pollution price is sufficiently low. Instead if $\tau_{ic}^{s} < \tau < \tau_{fc}^{s}$ the absolute increase in pollution is very unlikely (graphs 3 in figure 6). The perverse effect of the environmental policy, therefore, can arise only for particular pollution price intervals.

Then the following proposition arises.

Proposition 2bis. *Under imperfect competition in both vertical related markets and for particular pollution price intervals, the environmental policy can increase pollution if the dominant firm pursues strategies besides profit maximization and especially with free allocation of allowances.*

On the policy implications side, this proposition suggests to distinguish whether the quantitative targets (the emissions reduction and the expansion of the low carbon technologies) are completely exogenous or not.

Figure 7. Performances and cost efficacies of the ETS and the energy policy (qualitative terms): regulatory pressure with low pollution prices



Note: LC: Low Carbon technologies; MBab: marginal benefits of abatement; MCab: marginal costs of abatement; MCLC: long-run marginal cost of low carbon technologies; MBLC: marginal benefits of low carbon technologies; TC: total costs.

In the former case, policymakers choose the level of pollution simply comparing marginal benefits and marginal costs of abatement. This level is the optimal one and is exogenous in the sense that the total cost of achieving the target is the dependent variable. In principle, in setting the target, policymakers do not look at the total impact of their choice. Therefore, when imperfect competition implies lower decrease in emissions, ignoring its role can lead to underestimate the total cost of the ETS, i.e. can lead to overestimate its cost efficacy (graph A of figure 7). At the same time, since imperfectly competitive prices increase less (or rather go down), the amount of financial resources necessary to support the low carbon technologies would be underestimated (graph C of figure 7).

In the second case, the target is endogenous in the sense that policymakers choose the level of pollution by taking into account the total cost, which is now the independent variable. Given total cost, neglecting imperfect competition can lead to set or to accept too stringent targets as long as the simulation models based on full competition underestimate the costs of meeting the targets (graphs B and D of figure 7).

Vice versa if we consider the case in which, under imperfectly competitive markets, emissions decrease more than under full competition.

6. About the assumptions and the robustness of the results

The results described above depend on a series of simple assumptions about the structure and operation of energy markets, namely assumptions about technologies, competition models, firms' strategies and market structures. Before concluding it is important to discuss these hypotheses in order to check the robustness of the analysis.

6.1. Iso-elastic demand

In this paper we make two fundamental assumptions about the power demand function. There is no uncertainty (deterministic demand). The (inverse) demand curve is linear.

The first assumption is consistent with the fact that we consider firms make bids valid for short periods of time (they bids for each hour) when demand does not vary significantly during the period of time for which the bid is valid.

The second assumption has an important implication. With linear demand the residual monopoly price raises less than the marginal cost (pass-through less than one) whereas with iso-elastic demand the changes in (the residual monopoly) prices would be larger than the changes in marginal costs. Nevertheless this does not change the overall results of this analysis.

On the one hand, without regulatory pressure and when the dominant firm holds a large share of more polluting units, iso-elastic demand reinforces the result that imperfect competition decreases emissions more than full competition.

On the other hand, when the dominant firm holds a large share of less polluting units, the result remains substantially unchanged. In fact, in this case the change in the residual monopoly price is mainly related to the emission rate of the alternative fuel. Since this latter is very low, the increase in price will remain below the corresponding decrease under full competition which is related to the emission rate of the gas plants.

6.2. Variable marginal costs

As pointed out before, in our model we consider homogeneous plants within the same group of technologies. This assumption does not reflect the real conditions of operation for two reasons. First power generation costs include cycling costs which vary with the level of demand. Second, power stations may have different fuel costs even if they belong to the same group of technologies (using the same fuel).

The cycling cost is the additional cost of power generation when the generation unit is operating on margin that is when the generation unit meets varying demand and consequently has to adjust its output frequently, including frequent start-ups and shut-downs. The cost of cycling depends on the type of technology. Cycling involves increasing costs due to higher fuel costs and component degradation. The level of this additional cost depends on the type of technology. For example it is higher for coal plants than for gas plants. By using the analysis carried out by Denny and O'Malley

(2009), it is possible to estimate the cycling costs of a system including coal and gas units in the same proportion (50% coal and 50% gas). Within this system, the cycling cost is about 6 and 10 Euro/MWh when the gas plants and the coal plants operate on the margin, respectively. This component is important because it makes more expensive the strategic behavior. In fact, the dominant firm could not follow a strategy in which it actually reduced output once the level of demand became high enough to support a supposed equilibrium at the maximum price. It is expensive to adjust the level of output from power stations, particularly if the required pattern would involve reducing output at first and then increasing it as demand rises further.

Therefore, neglecting cycling cost and assuming homogeneous plants (within the same group of technologies) imply that the marginal cost curve in our model is “one-stepped”, and not a quasi-continuous increasing curve. As pointed out before, this assumption is not realistic but it does not undermine the significance of our analysis for the following reasons. First, looking at the case of imperfect competition, accounting for cycling costs and plants’ non-homogeneity modifies $\underline{MC}$ and $\overline{MC}$ and consequently the value of ζ so changing just the value of $\hat{D}_e$ (and consequently the impact on the degree of market power) but not its structure[12] (see Lemma 2). Second, looking at the case of full competition, the pass-through will be just lower than the marginal cost of the marginal technology provided that the price elasticity of demand in the short-run is relatively low, as assumed in this paper and consistently with the real situation of electricity markets.

6.3. Other market structures

The dominant firm model is generally used in the literature on the environmental policy under imperfect competition (see Conrad and Wang (1993), Chernyavs'ka and Gullì (2008) and Gullì (2008)). 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. In particular, this model allows us to overcome the problem of possible inexistent equilibria in pure strategy (see below). Moreover, investigating strategic bidding in electricity pools, Garcıa-Dıaz and Marın (2003) find that very strong asymmetries lead to a single equilibrium price with a dominant firm where small firms behave competitively.

However many natural gas and electricity markets have characteristics which can be better simulated by using oligopolistic models.

With regard to the gas market, in a duopolistic framework if both firms are capacity unconstrained the net long-run marginal cost of the alternative fuel is a pure-strategy equilibrium only with efficient rationing and if capacities are sufficiently small i.e. the price that clears all capacity is higher than the net long run marginal cost of the alternative fuel. Instead if the cost-leader is capacity unconstrained or both firms are capacity constrained and capacities are sufficiently high, i.e. such that the price that clears all capacity is lower than the net long-run marginal cost of the alternative fuel, the equilibrium is generally unique but in non-degenerate mixed strategies.

With regard to the electricity market, in their article on spot market competition in the UK electricity industry, using a typical duopolistic framework and the auction approach, von der Fehr and Harbord (1993) demonstrate the following:

1. If the demand is high, higher than the capacity of the largest generator, “prices always equal the highest admissible price”. However the low bidding generator may be either the high-cost or the low-cost generator so we cannot know which of them is dispatched with its total or part of its

[12] For instance, looking at the simplified case in which $\mu_a^{d_e} = 1$ and $\mu_a^{f_e} = 0$, $\overline{MC}$ will be the marginal cost (including cycling cost) of the marginal unit (the unit setting price), i.e. the last fringe’s unit despatched. $\underline{MC}$ will be the average marginal cost of the dominant firm’s most efficient units.

capacity. Instead under the dominant firm we know that, above (below) a certain level of demand, the high-cost generator is dispatched with its total (part of) capacity;

2. If the demand is low, lower than the capacity of the smallest generator, prices are always equal to the marginal cost of the less efficient generator. In this case only the low-cost generator will produce consistently with the outcome of the dominant firm model;
3. When demand is "intermediate", lower than the capacity of the largest generator but higher than that of the smallest one, there are equilibria only in mixed strategies in which prices are in between a lowest price and the maximum admissible price. The lowest price is strictly greater than the marginal cost of the least efficient generator. Furthermore it is increasing in demand and converges to the maximum price when demand converges to the capacity of the largest generator (case 1 above) and to the marginal cost of the low cost generator when demand converges to the capacity of the latter. Furthermore the lowest price is an increasing function of the marginal cost of the less efficient generator. This outcome is consistent with the results of the dominant firm model. In fact, on the one hand, when demand is relatively high we expect that the carbon cost pass-through will be affected by the price threshold sensitivity to the carbon price. On the other hand, when demand is relatively low, we expect that the pass-through will be more affected by the carbon cost of the less efficient generator. The only difference is that in the dominant firm model the price profile is discrete jumping from the marginal cost of the low cost generator to the price threshold. In the duopoly model this profile is continuous since prices moves gradually from the cost of the low cost generator to the price threshold. Instead once again, as suggested by von der Fehr and Harbord, we cannot know which generator will be the high-bidding generator. The high-cost generator will generally submit higher bids than the low-cost generator but there is a positive significant probability that the high-cost generator becomes the only operating generator.

Then, given this framework, we may conclude that the results of the dominant firm model can be only partially generalized to other market structures (namely duopolistic). The price profile seems to be very similar. In the periods of high demand prices equal the price threshold while in those of relatively low demand prices equal the marginal cost of the high-cost generator. In the intermediate periods prices are above and an increasing function of the the marginal cost of the less efficient generator converging to the price threshold as long as demand increases. Therefore the mechanism through which the pollution price is passed through to electricity prices are very similar. Instead the dispatching is ambiguous (which generator is the low or high-bidding generator). The results of the dominant firm model can be partially generalized only when, within the duopolistic model, the probability that the low-cost generator will be the high-bidding generator increases in demand[13].

7. Conclusions

This paper identifies the mechanisms through which emissions trading interacts with energy and competition policies, under imperfect competition in vertical related energy markets (electricity and natural gas markets). This interaction under imperfect competition is quite different than under full competition for several reasons: because of the difference (i) in the impact on the marginal costs of the power technologies and (ii) in how the change in cost is passed-through to prices; because under imperfect competition the change in cost structure between technologies determines a change in market power.

[13] In the variable demand periods, von der and Harbord (1993, 1998) demonstrates that the "high-cost generator profile stochastically dominates the strategy profile of the low-cost generator. Thus, the high-cost generator will generally (i.e. in expected terms) submit higher bids than the low-cost generator". However, looking at the strategy probability distributions of the two firms, the extent to which the strategy profile of the high-cost generator dominates that of the low-cost generator decreases in demand. Consequently we expect that the probability that the high-cost generator will be the high-bidding generator decreases in demand.

By using the dominant firm model (in both markets) and the auction approach (in the electricity market), the analysis shows that the pollution cost of the gas-fired plants does not depend on their own emission rate but depends on that of their main alternative.

Assuming that the measures of energy policy are at least able to make the low carbon (or carbon free) technologies (e.g. renewable or fossil fuels with Carbon Capture and Sequestration (CCS), etc.) closer to their competitiveness threshold (up to make them the main alternative to natural gas), the following results emerge.

If firms can maximize profits (no regulatory pressure exerted by the competition and sector-specific authorities), the result is ambiguous. Imperfect competition can either amplify or lessen the ability of environmental and energy policies to induce cost-effective decrease in pollution and/or to support the deployment of low carbon technologies. However, the worst case, the absolute short-run (or inertial) increase in pollution, is excluded.

Instead when the regulatory pressure induces the dominant firm to pursue a profit target (and especially a long-term profit target), emissions trading combined with energy regulation may determine a decrease in market power and this can lead to a short-run (or inertial) increase in pollution, especially if emissions allowances are benchmarked (allocated free of charge), so amplifying the distance from policy targets. At the same time the slight increase in prices (or rather the absolute decrease) penalizes the competitiveness of the low carbon technologies compared to what would occur under full competition. However the analysis also shows that this can happen only if the pollution price is sufficiently low, that is if the environmental policy is rather modest.

Therefore, the main finding is that imperfect competition triggers a trade-off between emissions trading and energy and competition policies. Under specific conditions, the effectiveness of emissions trading and energy policy can improve but at the expense of market efficiency (increasing degree of market power). Vice versa, it is very likely that the regulatory pressure can penalize the performance of the environmental and energy policies.

With regard to the policy implications, these results suggest what follows. First, if the simulation models ignore the full role of imperfect competition (including the strategic use of power capacity), this may induce incorrect estimations of the impact of the public action or incorrect policy calibrations, depending on how the targets are set.

Finally it is worth pointing out that the analysis of this paper is based on a series of simple assumptions about the operation and the structure of energy markets. Nevertheless the results seem to be enough robust although the analysis suggests caution in extending to other market structures the outcome of the dominant firm model.

Appendix

A.1. Proof of Lemma 2

Let $\overline{K}_e = D_{e_M} - \overline{K}_e^{d_e}$ be the peak demand minus the dominant firm's capacity in least efficient plants ($\overline{K}_e^{d_e}$) with $\overline{H} = D^{-1}(\overline{K}_e)$. It is immediately intuitive that when $D_e \geq \overline{K}_e$ the system marginal price equals the price threshold, $\hat{p}_e$. When $D_e \leq \underline{K}_e^{f_e}$, pure Bertrand equilibria (first marginal cost pricing) arise and prices equal the marginal cost of the most efficient plants ($\underline{MC}_e$). 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 residual monopoly price. 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 $D_e \in \left]\overline{K}_e; \underline{K}_e^{f_e}\right]$[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 ($\hat{p}_e$) or in *(ii)* bidding $\overline{MC}_e$[15].

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

$$\text{(A1)} \quad \pi_A^{d_e} = (\hat{p}_e - \underline{MC}_e)\left[D_e - (1-\delta)K_{e_T}\right] + \sum_{i=1}^{z} \sum_{j=a,b} \tau \cdot r_{bn} \cdot \overline{q}_j^i$$

Where

r_{bn} =emission rate of the technology chosen as the benchmark

$\overline{q}_j^i$ = reference production for the free allocation of allowances to the unit i-th unit belonging to the group j of plants. Obviously $\overline{q}_j^i = 0$ with full auctioning.

If the dominant firm chooses the second strategy, he earns

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[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 $\overline{MC}_e$ for units of kind b and $\hat{p}_e \leq \overline{MC}_e - \varepsilon$ (where $\varepsilon \cong 0^+$) for units of kind a.

(A2) $\pi_B^{d_e} = (\overline{MC}_e - \underline{MC}_e)\underline{K}_e^{d_e} + \sum_{i=1}^{z}\sum_{j=a,b} \tau \cdot r_{bn} \cdot \overline{q}_j^i$

If the dominant firm maximizes profits, $\hat{p}_e$ is the residual monopoly price with

$$\hat{p}_e = p_e^r = \arg\max_{p_e} \left\{ p_e \left[D_e(p_e) - K^{f_e} \right] \right\} = \frac{1}{\beta}\left[D_e - (1-\delta)K_{e_T} \right] + \underline{MC}_e$$

Consequently $\pi_A^{d_e} \geq \pi_B^{d_e}$ if and only if

(A3) $D_e \geq \hat{D}_{e_1} = (1-\delta)K_{e_T} + \left[\zeta \underline{\mu}^{d_e} \delta K_{e_T} \right]^{1/2}$

where $\zeta = \beta(\overline{MC}_e - \underline{MC}_e)$ and $\beta = -\frac{dD_e}{dp_e}$

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

(A4) $\pi_C^{d_e} = (p_e^r - \underline{MC}_e)\left[D_e - (1-\delta)K_{e_T} \right] + \sum_{i=1}^{z}\sum_{j=a,b} \tau \cdot r_{bn} \cdot \overline{q}_j^i$

and by choosing the second strategy the profit is

(A5) $\pi_D^{d_e} = (\overline{MC}_e - \underline{MC}_e)\left[D_e - \underline{\mu}^{f_e}(1-\delta)K_{e_T} \right] + \sum_{i=1}^{z}\sum_{j=a,b} \tau \cdot r_{bn} \cdot \overline{q}_j^i$

Thus the dominant firm will choose the first strategy if and only if $\pi_C^{d_e} \geq \pi_D^{d_e}$, i.e. if and only if

(A6) $D_e \geq \hat{D}_{e_2} = (1-\delta)K_{e_T} + \frac{\zeta}{2} + \frac{1}{2}\left[\zeta^2 + 4\zeta(1-\delta)K_{e_T}(1-\underline{\mu}^{f_e}) \right]^{1/2}$

Finally by differentiating $\hat{D}_e$ with respect to $\underline{\mu}^{d_e}$ and $\underline{\mu}^{f_e}$ we get

$$\frac{\partial D_{e_1}}{\partial \underline{\mu}^{d_e}} = \frac{\zeta \delta K_{e_T}}{2}\left[\zeta \underline{\mu}^{d_e} \delta K_{e_T} \right]^{-1/2} > 0; \quad \frac{\partial D_{e_2}}{\partial \underline{\mu}^{f_e}} = -\zeta(1-\delta)K_{e_T}\left[\zeta^2 + 4\zeta(1-\delta)K_{e_T}(1-\underline{\mu}^{f_e}) \right]^{-1/2} < 0$$

A.2. Proof of Lemma 2bis

Form equations (A1) and (A2)

(A7) $D_e \geq \hat{D}_{e_1} = \left[\underline{\mu}^{d_e} \delta\sigma + (1-\delta) \right] K_{e_T}$

and from (3) and (A4)

(A8) $D_e \geq \hat{D}_{e_2} = (1-\delta)\left[\frac{1-\sigma\underline{\mu}^{f_e}}{1-\sigma} \right] K_{e_T}$

where $\sigma = \dfrac{\overline{MC}_e - \underline{MC}_e}{\hat{p}_e - \underline{MC}_e} < 1$

A.3. Proof of Lemma 3bis

The derivative of $\hat{D}_e$ with respect to τ can be written as

$$\text{(A9)} \quad \frac{\partial \hat{D}_e}{\partial \tau} = \frac{\partial \hat{D}_e}{\partial \sigma}\frac{\partial \sigma}{\partial \tau}$$

Since (from (A7) and (A8))

$$\text{(A10)} \quad \frac{\partial \hat{D}_{e_1}}{\partial \sigma} = \underline{\mu}^{d_e} \cdot \delta \cdot K_{e_T} > 0 \text{ and} \frac{\partial \hat{D}_{e_2}}{\partial \sigma} = \frac{(1-\delta)(1-\underline{\mu}^{f_e})}{(1-\sigma)^2} K_{e_T} > 0$$

then the degree of market power is a decreasing function of σ.

By differentiating σ with respect to τ and given that $\hat{p}_e$ and that c_{e_g} depends on τ, we get

$$\text{(A11)} \quad \frac{\partial \zeta}{\partial \tau} = \frac{(r_g - r_a + dc_{e_g}/d\tau)\lfloor \hat{p}_e(0) - c_{e_a} \rfloor - (\partial \hat{p}_e/\partial \tau - r_g)(c_{e_g}(0) - c_{e_a})}{(\hat{p}_e - c_{e_a} - r_a \tau)^2} \text{ if } \tau < \tau^*$$

and

$$\text{(A12)} \quad \frac{\partial \zeta}{\partial \tau} = \frac{(r_a - r_g - dc_{e_b}/d\tau)\lfloor \hat{p}_e(0) - c_{e_g}(0) \rfloor - (\partial \hat{p}_e/\partial \tau - r_g - dc_{e_g}/d\tau)(c_{e_a} - c_{e_g}(0))}{(\hat{p}_e - c_{e_g} - r_g \tau)^2} \text{ if } \tau \geq \tau^*$$

From (A11)

$\dfrac{\partial \sigma}{\partial \tau} > 0$ and consequently $\dfrac{\partial \hat{D}_e}{\partial \tau} > 0$ if $\partial \hat{p}_e/\partial \tau < \hat{r} = r_a + \lambda(r_g - r_a + dc_{e_g}/d\tau)$ with $\lambda = (\hat{p}_e(0) - c_{e_a})/(c_{e_g}(0) - c_{e_a})$. Vice versa, if $\partial \hat{p}_e/\partial \tau > \hat{r}$ then $\dfrac{\partial \hat{D}_e}{\partial \tau} < 0$.

From (A12)

$\dfrac{\partial \sigma}{\partial \tau} > 0$ and consequently $\dfrac{\partial \hat{D}_e}{\partial \tau} > 0$ if $\partial \hat{p}_e/\partial \tau > \hat{r} = r_a + \lambda(r_g - r_a + dc_{e_g}/d\tau)$ with $\lambda = (\hat{p}_e(0) - c_{e_a})/(c_{e_g}(0) - c_{e_a})$. Vice versa, if $\partial \hat{p}_e/\partial \tau < \hat{r}$ then $\dfrac{\partial \hat{D}_e}{\partial \tau} < 0$.

Proof of equation (5)

Given the load duration curves in figure 3, the total amount of pollutant emissions, E, under imperfect competition is

$$E_{ic} = r_g\left[\int_0^{\hat{H}} D_e(H,\hat{p}_e)dH\right] + r_g\left[\int_{\hat{H}}^{\underline{H}} D_e(H,\hat{p}_e)dH\right] + (r_g - r_a)(K_{e_T}\hat{H} - K^{d_e}\underline{H}) +$$
$$+ r_a\left[\int_{\underline{H}(\tau)}^{H_L(\tau)} D_e(H,\hat{p}_e)dH\right]$$

And under full competition

$$E_{fc} = r_g\int_0^{\underline{H}} D_e dH + r_a\left[\int_{\underline{H}}^{H_L} D_e dH\right]$$

By differentiating E_{ic} and E_{fc} with respect to τ and given that

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

and that $\beta = -\frac{\partial D_e}{\partial p_e} = -\frac{\partial D_e}{\partial\tau}\bigg/\frac{\partial p_e}{\partial\tau}$ we get

(A13)
$$\frac{\partial E_{ic}}{\partial\tau} = r_a\left[-\beta\frac{\partial\hat{p}_e}{\partial\tau}\int_0^{\hat{H}} D_e dH\right] + (r_g - r_a)\left[(K_{e_T} - \hat{D}_e)\frac{\partial\hat{H}}{\partial\tau}\right] +$$
$$+ r_g\left[-\beta r_{AF}\int_{\hat{H}}^{\underline{H}} D_e dH\right] + r_a\left[-\beta r_{AF}\int_{\underline{H}}^{H_L} D_e dH\right]$$

and

(A14)
$$\frac{\partial E_{fc}}{\partial\tau} = r_g\left[-\beta r_g\int_0^{\underline{H}} D_e dH\right] + r_a\left[-\beta r_a\int_{\underline{H}}^{H_L} D_e dH\right]$$

Where $\frac{\partial\hat{H}}{\partial\tau}$ includes two components: $\frac{\partial H}{\partial D}\frac{\partial\hat{D}}{\partial\tau}$ which is the change in $\hat{H}$ due to the change in $\hat{D}_e$ (see Lemma 3 and Lemma 3bis); $\frac{\partial H}{\partial D}\frac{\partial D}{\partial p_e}\frac{\partial p_e}{\partial\tau} = -\beta\frac{\partial H}{\partial D}\frac{\partial p_e}{\partial\tau}$ which is the change in $\hat{H}$ to the change in demand.

By replacing these components in equation (A13) and by subtracting $\frac{\partial E_{fc}}{\partial\tau}$ from $\frac{\partial E_{ic}}{\partial\tau}$ we get the difference in marginal emissions between imperfect and full competition (equation (5) in sub-section (5)).

Proof of Corollary 2

When $D_e \in \left]\overline{K}_e ; \underline{K}_e^{f_e}\right]$ the profit that the dominant firm earns by setting the price threshold before the implementation of the ETS is

(A15) $\hat{\pi}_e(0) = (\hat{p}_e(0) - c_{e_a})RD_e(\hat{p}_e(0))$

With $RD_e = D_e - K^{f_e}$

After the ETS the profit is

(A16) $\hat{\pi}_{e_1}(\tau) = (\hat{p}_{e_1}(\tau) - MC_{e_a})RD_e(\hat{p}_{e_1}(\tau)) + \tau \cdot r_{bn} \cdot \overline{q}^{d_e}$

Then, $\hat{\pi}_{e_1}(\tau) = \hat{\pi}_e(0)$ implies that

(A17) $(\hat{p}_{e_1}(\tau) - c_{e_a}) = (\hat{p}_{e_1}(0) - c_{e_a})\dfrac{RD_e(\hat{p}_e(0))}{RD_e(\hat{p}_{e_1}(\tau))} - \tau \cdot r_{bn} \cdot \dfrac{\overline{q}^{d_e}}{RD_e(\hat{p}_{e_1}(\tau)} + \tau \cdot r_a$

Under full auctioning ($\overline{q}^{d_e} = 0$), equation (A17) implies that $(\hat{p}_e(\tau) - \hat{p}_e(0)) > r_a \cdot \tau$. Under benchmarking ($0 < \overline{q}^{d_e} \le RD_e(\hat{p}_e(0))$), then $(\hat{p}_{e_1}(\tau) - \hat{p}_e(0)) < r_a \cdot \tau$ if r_{bn} is sufficiently high.

Finally it remains to analyze the case in which the dominant firm pursues a long-term profit target (e.g. multi-year target) with the limit to ensure some stability in prices. Consider two periods and assume that the pollution price increases by τ (from $\overline{\tau}$ to $\overline{\tau} + \tau$) in the first period (period 1) and decreases by τ (from $\overline{\tau}$ to $\overline{\tau} - \tau$) in the second period (period 2).

If, in the first period, the dominant firm sets a price lower than the price corresponding to the profit invariance, $\hat{p}^*_{e_1} < \hat{p}_{e_1}$, the profit loss will be

$$\Delta\hat{\pi}_{e_1}(\tau) = \left[\hat{p}^*_{e_1} - (c_{e_a} + r_a(\overline{\tau} + \tau))\right]RD_e(\hat{p}^*_{e_1}) - \left[\hat{p}_e(\overline{\tau}) - (c_{e_a} + r_a\overline{\tau})\right]RD_e(\hat{p}_e(\overline{\tau})) < 0$$

In order to keep constant the two-periods profit, in the second period the dominant firm will choose a price, $\hat{p}^*_{e_2}$, such that

(A18) $$\left[\hat{p}^*_{e_2} - (c_{e_a} + r_a(\overline{\tau} - \tau))\right]RD_e(\hat{p}^*_{e_2}) + \left[\hat{p}^*_{e_1}(\tau) - ((c_{e_a} + r_a(\overline{\tau} + \tau))\right]RD_e(\hat{p}^*_{e_1}) = \\ = 2\left[\hat{p}_e(\overline{\tau}) - (c_{e_a} + r_a\overline{\tau})\right]RD_e(\hat{p}_e(\overline{\tau}))$$

From (A18), $\forall \hat{p}^*_{e_1} \in \left[p_e(\overline{\tau}), p_e(\overline{\tau}) + r_a\tau\right]$ there exists $\hat{p}^*_{e_2} \in \left[p_e(\overline{\tau}), \hat{p}^*_{e_1}\right[$ such that equation (A18) is satisfied. Consequently $\left(\dfrac{\partial \hat{p}^*_e}{\partial \tau}\right)_{t=2} \ge -\left(\dfrac{\partial \hat{p}^*_e}{\partial \tau}\right)_{t=1} > -r_a$. If $\left(\dfrac{\partial \hat{p}^*_e}{\partial \tau}\right)_{t=1} = r_g$ then $\left(\dfrac{\partial \hat{p}^*_e}{\partial \tau}\right)_{t=2} > -r_g$.

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