Environmental policy under imperfect competition in vertical related energy markets

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Abstract

Can imperfect competition lessen the ability of environmental policy to reduce pollution thus making it more difficult and expensive to meet environmental targets? May environmental policy increase rather than decrease pollution? In order to answer these questions we simulate the impact of environmental regulation (pollution taxes or emissions trading) on two vertical related markets: 1) the output market, namely the power market, and 2) the input market, namely the natural gas market. The emphasis is on the reduction of carbon emissions which is currently the most important objective of environmental policy. The basic idea underlying this analysis is that imperfect competition triggers a direct mutual relationship between energy and pollution prices. This may lead to increase the cost of the environmental policy and may even undermine its ability to reduce pollution at least in the short and medium run. We aim at verifying whether and under which conditions this can occur. The paper not only confirms, according to the current literature, that imperfect competition in the output market may involve increasing pollution but it reinforces this conclusion. In addition it highlights that market power also in the input market greatly amplifies the probability of increasing emissions. This would happen less or more likely depending on the type of environmental policy (pollution taxes or emissions trading) and regulation (e.g. methods and rules of allowances allocation). Finally the analysis shows that imperfect competition may increase the volatility of both natural gas and pollution prices thus contributing to undermine the effectiveness of the environmental policy even in the long run. Overall imperfectly competitive markets would make it more difficult and therefore more costly to meet the environmental targets. Even, under certain conditions, the environmental policy may increase rather than decrease pollution. This also means that under certain circumstances the laissez faire might be better than the public action. Looking at what really happens in energy markets, this paper suggests that these circumstances are not at all unlikely.

Keywords: environmental policy, emissions trading, imperfect competition

1. Introduction

The degree of reliability of the estimates of the cost of meeting the environmental targets is one of the most controversial aspects of the debate on the impact of the environmental policy. These estimates are made using simulation models based on specific hypothesis about the economic systems and, in particular, about the structure of energy markets.

A fundamental assumption of these models is that energy markets are fully competitive. As this does not reflect the reality in most cases, the above mentioned debate appears superfluous and misleading without a serious analysis of what can happens when the assumption of full competition is removed. In fact, imperfect competition may largely affect the performance of the environmental policy as long as it has impact on prices, on the share of production of the different polluting technologies and, consequently, on aggregate emissions.

In this paper we aim at examining the conditions under which imperfect competition can partially or totally undermine the effectiveness of the environmental policy thus making it more difficult and expensive to meet the environmental targets.

For this purpose we simulate the impact of the environmental regulation (pollution taxes or emissions trading) on two vertical related markets, namely:

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

The basic idea of the analysis is that, by triggering a direct mutual relationship between energy and pollution prices, imperfect competition may undermine the ability of the environmental policy to reduce emissions. This increases the cost of meeting the environmental targets and, under certain conditions, could even lead to increased (rather than to decreased) pollution[1].

The paper is organised as follows. Section 2 focuses on the structure and assumptions of the model used to characterize equilibria under imperfect competition. Section 3 deals with price equilibria in the input (natural gas) and output markets (power). Section 4 investigates how the environmental policy can change the degree of market power in the output market. Section 5 focuses on how the environmental policy impacts on pollution when markets are imperfectly competitive and in particular it explores the probability that the environmental policy could increase rather than decrease aggregate emissions. By looking at the real configurations of energy markets, section 6 tries to estimate this probability. Finally, section 7 summarizes the main results of the article.

2. The basic model: assumptions

This section describes the structure of the model detailing the main assumptions on the environmental regulation and the main hypotheses on the regulation of the output (electricity) and input (natural gas) markets.

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[1] Only few papers in the economic literature on environmental policy deal with this topic (among them see Levin, 1985 and Requate, 2005). These papers rely on one-shot standard models of competition which are poorly suited to describe the reality of energy markets in which the pricing mechanism may be a first price uniform or discriminatory auction (e.g. electricity market).

2.1. The environmental regulation

The hypotheses about the environmental regulation are quite simple. We assume that the environmental policy is based on emissions trading or on pollution taxes.

In the former case, an emissions trading scheme (ETS) is implemented. The ETS gives rise to a market for emissions allowances. This market is very large involving a large number of polluting firms so that none of them is able to exercise market power on it. Consequently firms are price takers and the pollution price (namely the price of the emissions allowances, τ) is given exogenously. This framework is consistent with the European carbon market created by the introduction of the EU ETS (European Union Emissions Trading Scheme).

In the second case, i.e. pollution taxes, we assume that taxation is proportional to emissions. The pollution price, τ , is equal to the tax rate which is the charge per unit of pollutant emitted. Therefore the pollution price is exogenous by definition.

Finally, emission abatement is supposed to be impossible or, equivalently, the abatement cost is infinitely costly. Therefore the analysis proposed in this article is a short-run analysis, i.e. we do not investigate how the environmental policy can affect firms' investment decisions.

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 $-\infty < \partial D_g / \partial p_g < 0$ and $\partial^2 D_g / \partial p_g^2 < 0$.

To simulate market power we use a dominant firm facing a competitive fringe model rather than the usual duopolistic-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 extremes of perfect competition and pure monopoly, at the same time escaping the difficulties of characterizing an oligopolistic equilibrium[2]. It is often used in the literature concerning environmental policy under imperfect competition[3]. On the practical side, it is well suited to simulate the structural features of several natural gas markets.

[2] 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 equilibrium in pure strategy. Instead, there exist a unique mixed-strategy Nash equilibrium.

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

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[4].

Natural gas trading is regulated by long term contracts including rules for price indexation over time.

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

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

Finally we assume that in each segment of consumption there is another input, the alternative fuel (AF), which is a perfect substitute for natural gas. Firms delivering the alternative fuel are homogenous and able to serve the entire market segment.

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 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_e, with $0 \leq H \leq H_L$. $D_{e_L}(p_e) = D(p_e, H_L)$ is the minimum demand and $D_{e_M}(p_e) = D(p_e, 0)$ is the maximum demand. Furthermore, for all (p_e, H), $-\infty < \partial D_e / \partial p_e < 0$, $\partial^2 D_e / \partial {p_e}^2 < 0$ and $\partial D / \partial H < 0$.

As with the gas, to simulate market power we use a dominant firm facing a competitive fringe model rather than the usual duopolistic-oligopolistic framework. This model is useful to characterize the structure of several electricity markets.

The leader (d_e) and the competitive fringe (f_e) supply the market with capacity given by $S^{d_e} > 0$ and $S^{f_e} > 0$, respectively. Again, we assume linear technologies which are characterised by the variable cost of production, $c_e \geq 0$, and by the emission rate, $r \geq 0$ (emissions per unit of output).

[4] 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.

Without loss of generality, we restrict the analysis to two groups of power technologies, a and b. Each of them includes a large number n of homogeneous units[5] such that

$$S_{e_j} = \sum_{i=1,2,\ldots n} s_{e_j}^i \text{, } j = a,b \text{ and } c_{e_j}^i = c_{e_j}\text{; } r_j^i = r_j\text{, } \forall i, j$$

where $c_{e_j}^i = c_{e_j} \geq 0$, $r_j^i = r_j \geq 0$ and $s_{e_j}^i = s_{e_j} > 0$ are the variable cost, the emission rate and the capacity of the *i*-th unit belonging to the group *j*, respectively. Thus S_{e_a} and S_{e_b} are the installed capacity of groups a and b, respectively, with $S_{e_a} + S_{e_b} = S_{e_T} = D_{e_M}$, i.e. the units of kind a and b are sufficient to meet the maximum demand. Furthermore, we assume trade-off between variable costs and emission rates, i.e. the technology with lower variable cost is the worse polluter ($c_{e_a} < c_{e_b}$ but $r_a > r_b$) and vice versa. This condition is well suited to simulate a very common technological configuration of power systems namely that including coal and CCGT (Combined Cycle Gas Turbine) plants.
Given these assumptions, the marginal cost of the *i*-th unit belonging to the group *j* of plants is given by

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

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.

Furthermore, there exists a pollution price, the "switching price", $\tau^* = (c_{e_b} - c_{e_a})/(r_a - r_b)$, such that the marginal cost of the plants of the group a, MC_{e_a}, is equal to that of the plants of the group b, MC_{e_b}. Then the tax rate is defined as low if $\tau < \tau^*$ and as high if $\tau \geq \tau^*$. Finally, $\overline{MC}_e = \max\{MC_{e_a}; MC_{e_b}\}$ is the marginal cost of the least efficient plants and $\underline{MC}_e = \min\{MC_{e_a}; MC_{e_b}\}$ 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

[5] Assuming that each group includes the same number n of units implies that $s_j \geq 0$ depends on $S_j \geq 0$. This is an arbitrary assumption which does not undermine, however, the significance of the analysis.

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 make the hypothesis that firm's offer prices are constrained below some threshold level, $\hat{p}_e$, which can be interpreted in two ways.

Firstly, it may be a (regulated) maximum price as officially introduced by the regulator. In this case, it is appropriate to assume that the threshold is insensitive to the pollution price. In fact, the price cap is so high[6] that the regulator does not see the need to change in order to account for the effect of the environmental regulation.

Secondly, we can suppose that the threshold 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. More likely, firms may believe that the regulator will introduce or modify regulation when the difference between the price and the marginal cost of the marginal unit[7] rises above a certain value.

For instance, if this marginal unit is a CCGT plant (group *b* of generating units) the perceived threshold will be given by its marginal cost plus a mark-up, i.e. $\hat{p}_e = c_{eb}(1+\gamma)$ where $\gamma > 0$ is the mark-up coefficient. If we adopt this interpretation we should expect that $\hat{p}_e$ is sensitive to the pollution price that is we should expect that, in consequence of the introduction of the environmental regulation, power firms will try to pass-through the pollution price into the price threshold.

Then the question is the following. How much is $\hat{p}_e$ sensitive to the pollution price? The empirical literature (Chernyavs'ka and Gullì, 2008a)[8] highlights that the pass-through is an inverse function of the degree of market power. Under high market power firms pass through much less (low sensitivity) than the pollution price and vice versa (high sensitivity) under low market power. But what does low or high sensitivity mean quantitatively?

In order to answer this question it is helpful to consider the analysis carried out by Chernyavs'ka and Gullì (2008a) This analysis focuses on the impact of the EU ETS on the different sub-markets of the Italian spot market and is based on the estimation of the marginal CO_2 cost pass-through rate (MPTR) that is the change in price due the ETS divided by the pollution cost (the emission rate multiplied by the pollution price) of the marginal unit (the unit setting price). The authors calculate the MPTR in the peak hours that is in those hours in which

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[6] Generally price caps in electricity spot markets are one order of magnitude higher than the average wholesale price.
[7] The marginal unit is the power generating plant with the highest probability to become the marginal unit.

[8] Other interesting empirical analyses have been carried out by Sijm et al. (2008), Bunn and Fezzi (2008) and Honkatukia et al. (2008).

it is very likely that the strategic firms bid the price threshold. They find that the MPTR is equal or higher than 1 (full pass-through) where there is low market power (the North sub-market) and lower or much lower than 1 where there is high market power[9] (the South sub-market).

Given the definition of the MPTR, this means that the pass-through (the change in price) is lower (higher) than the pollution cost of the marginal unit under high (low) market power. Consequently, the sensitivity of the power price threshold to the pollution price is lower (higher) than the emission rate of marginal unit under high (low) market power. Provided that in our model the gas plants (mainly CCGT with emissions rate around 0.4 tCO_2/MWh) are those having the highest probability to become the marginal units in most hours, we can use the emission rate of this technology, r_b, in order to discriminate between low, medium and high degree of market power and sensitivity.

Then we propose the following classification (Table 1). Levels of sensitivity less than the emission rate of the gas-fired units should be considered as low/medium and correlated to high/medium degree of market power. Levels of sensitivity more than the emissions rates of the gas-fired units should be considered as medium/high and correlated to medium/low degree of market power.

Thus, looking at the cases involving high/medium degree of market power (the relevant case for our analysis), the most likely outcome would be that in which the sensitivity of the power price threshold to the pollution price is less than the emission rate of the least polluting plants, i.e. $0 \le \partial p_e / \partial \tau < r_b$.

Finally, in our model we assume that $\hat{p}_e$ depends linearly on τ, that is $\hat{p}_e = c_{eb}(1+\gamma) + \beta\tau$ with $\beta = \partial \hat{p}_e / \partial \tau$.

Table 1. Correlation between the sensitivity of the power price threshold and degree of market power (DMP)

	Sensitivity to τ	Degree of market power	DMP
A1) $0 \le \partial \hat{p}_e / \partial \tau < r_b$	Low/medium	High/medium	H/M
A2) $\partial \hat{p}_e / \partial \tau \ge r_b$	Medium/high	Medium/low	M/L

[9] See Chernyavs'ka and Gullì (2008a and 2008b).

3. Equilibria

3.1. Input market

3.1.1. The dominant firm model with inter-fuel competition

In this model of competition the dominant firm faces two strategies: *(i)* to accommodate the maximum fringe's production and to set 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 dominant firm can not set the residual monopoly price as the presence of an alternative input creates 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 dominant firm will set prices just below that value, $\hat{p}_g$, which would make the end user indifferent when choosing between an installation using gas and that using the alternative fuel.

This means that, in order to set $\hat{p}_g$, gas firms look at the long run marginal cost of the alternative fuel ($LRMC_{AF}$) which refers to the cost of delivering an additional unit of this output under the assumption that this requires investment in capacity expansion[10]. Then the natural gas price threshold, $\hat{p}_g$, will be equal to the long run marginal cost of the alternative fuel minus the natural gas extra-fuel costs[11]. We denominate this difference as the net long run marginal cost ($NLRMC_{AF}$) which is the long run marginal cost of the best alternative technology net of the extra-fuel costs of the gas-fired installations.

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.

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 dominant firm 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.*

[10] 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.

[11] Extra-fuel costs include capital costs and operating and maintenance costs.

Proof. See Figure 1. Given the natural gas demand, D_g, and the fringe's maximum production, S^{f_g}, the residual demand will be RD_g. The dominant firm will maximize its profit by bidding the price threshold $\hat{p}_g$ if this is lower than the residual monopoly price.

Proof. See the arguments illustrated above.

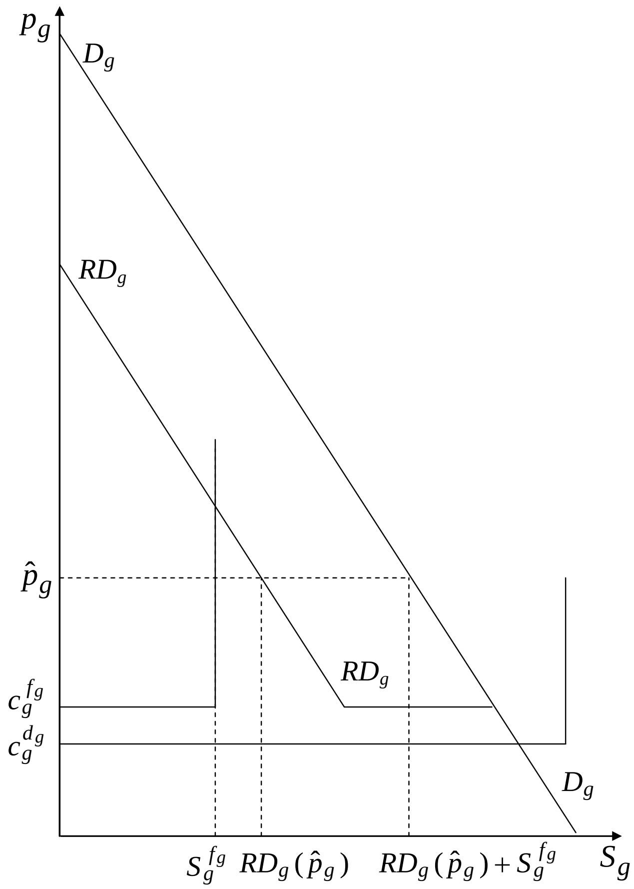

Figure 1. Equilibrium in the natural gas market with dominant firm and inter-fuel competition (leader behaving as a residual monopolist)

3.1.2. The impact of the environmental regulation on the input price

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 impacts on $\hat{p}_g$. For this purpose we should distinguish between pollution taxes and ETS (Emissions Trading Scheme).

Under taxation the outcome is immediate. From Lemma 1 and equation (1), the natural gas price threshold will be given by

(2) $p_g = \hat{p}_g = NLRMC_{AF} = \eta_b \left[c_{AF} + EXF_{AF} - EXF_b + \tau (r_{AF} - r_b) \right]$

where

c_{AF} = fuel cost per unit of electricity generated by using the alternative fuel installation

EXF_j = extra-fuel cost per unit of electricity generated, with $j = AF,\ b$

η_b = electric efficiency of the gas-fired power installation (CCGT)

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

(3) $\left(\frac{dc_{e_b}}{d\tau} \right)_{tax} = \frac{1}{\eta_b} \frac{dp_g}{d\tau} = (r_{AF} - r_b)$

This difference is positive as long as the emission rate of the alternative fuel installations is higher than that of the gas installations, $r_{AF} > r_g$. This assumption is not arbitrary. In fact the emission rates of the most likely alternative fuels to natural gas in power generation (coal and fuel oil) are much higher than that of natural gas.

Under emissions trading the outcome becomes slightly more complicated as it 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, $r_j \tau$, that is 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 a certain amount of allowance free of charge. Nevertheless, the value of these allowances is a sort of “gift” for the generator. Consequently, if we should calculate the long run marginal cost (including fixed components), the unit value of these allowances (the value per unit of electricity generated) should be deducted from the variable cost. Then formally

(4) $p_g = \hat{p}_g = NRLMC_{AF} = \eta_b \left[c_{AF} + EXF_{AF} - EXF_b + \tau (E_{AF} - \overline{E}_{AF}) - \tau (E_b - \overline{E}_b \right]$

where

E_j = actual emissions per unit of electricity generated, with $j = AF,\ b$

$\overline{E}_j$ = “emissions allocated” free of charge per unit of electricity generated, with $j = AF,\ b$

By differentiating equation (4) and taking into account that $p_g = \eta_b c_{e_b}$, we get

$$(5)\quad \left(\frac{dc_{e_b}}{d\tau}\right)_{ETS} = \frac{1}{\eta_b}\frac{dp_g}{d\tau} = \left[(E_{AF} - \overline{E}_{AF}) - (E_b - \overline{E}_b)\right]$$

Provided that $E_j = r_j$ with $j = AF,\ b$, equation (5) can be rewritten as

$$(6)\quad \left(\frac{dc_{e_b}}{d\tau}\right)_{ETS} = \left[r_{AF}(1-\alpha_{AF}) - r_b(1-\alpha_b)\right]$$

where

$\alpha_j = \overline{E}_j / E_j$ is the ratio of allocation for the fuel j

Equation (6) highlights that the change in the gas value due to the introduction of the ETS will be equal just to the difference between the pollution costs, $(r_{AF} - r_b)\tau$, only under two circumstances: 1) if no allowance is allocated free of charge ($\alpha_{AF} = \alpha_b = 0$) that is under full auctioning; 2) if the same amount (in absolute terms) of allowances is allocated to the natural gas installations and to the alternative fuel installations ($\alpha_b = \alpha_{AF}\, r_{AF}/r_b$) that is under a typical full benchmarking.

Instead, if allowances are allocated free of charge and the amount allocated depends on the type of technology, the change in the gas value will be less or more than the difference in pollution costs depending on the ratios of allocation, $\alpha_j = \overline{E}_j / E_j$. The impact on the natural gas value, therefore, will depend on the proportion of allowances allocated free of charge to the alternative fuel and to the gas installations. In particular, we assume that there is relative over-allocation (relative under-allocation) to the gas-fired unit when $\alpha_b > \alpha_{AF}\, r_{AF}/r_b$ (when $\alpha_b < \alpha_{AF}\, r_{AF}/r_b$).

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 environmental policy equals the difference in pollution costs between alternative fuel and natural gas under pollution taxes and under emissions trading with auctioning and/or benchmarking.*

Proof. See equations (5) and (6) and the corresponding comments above.

Corollary 2. *Under emissions trading, the change in the gas price is lower (higher) than the difference in pollution costs if there is relative under-allocation of allowances (relative over-allocation) to the gas-fired units.*

Proof. See equations (5) and (6) and the corresponding comments above.

In conclusion, the analysis described above highlights that imperfect competition gives rise to a direct link between the natural gas prices and the 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 2) depends on the type of the environmental policy and on the type of environmental regulation (methods and rules of allocation in the case of emissions trading). In particular, it is important to underline that the change in the natural gas value is lower than the difference in pollution costs only if there is relative under-allocation of allowances to the gas-fired units. In this case, the natural gas price might even decrease.

Table. 2. Impact of the environmental policy on the input price

	Input market fully competitive	Imperfect competition in the input market				
		Taxes	ETS			
			Auctioning $\alpha_{AF} = \alpha_g = 0$	Free allocation		
				$\overline{\alpha}_b = \alpha_{AF}\, r_{AF} / r_b$		
				$\alpha_b = \overline{\alpha}_b$ (benchmarking)	$\alpha_b < \overline{\alpha}_b$ (relative under-allocation)	$\alpha_b > \overline{\alpha}_b$ (relative over-allocation)
Gas price sensitivity	$\frac{dc_{eb}}{d\tau} = 0$	$\frac{dc_{e_b}}{d\tau} = (r_{AF} - r_b)$			$\frac{dc_{e_b}}{d\tau} < (r_{AF} - r_b)$	$\frac{dc_{e_b}}{d\tau} > (r_{AF} - r_b)$

3.2. Output market

Given the assumptions on the power market described in section 2, 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 carrying out the so-called price duration curve $p_e(H)$ where H is the number of periods in the year that price is equal to or higher than p_e.

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 $\underline{\mu}^{d_e} \in [0;1]$ and $\underline{\mu}^{f_e} \in [0;1]$ representing the share of capacity the strategic operator and the competitive fringe get in most efficient plants, respectively. By complement, $\overline{\mu}^{d_e} = 1 - \underline{\mu}^{d_e}$ and $\overline{\mu}^{f_e} = 1 - \underline{\mu}^{f_e}$ are the same in the least efficient ones.

By facing the competitive fringe, the dominant firm has two alternative strategies: (1) bidding the price threshold ($\hat{p}_e$) 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 $\underline{S}_e^{f_e}$ be the installed capacity in most efficient plants operated by the competitive fringe. Thus $\underline{S}_e^{f_e} = \underline{\mu}^{f_e}(1 - \delta)S_{e_T}$ and $\underline{H}^f = D^{-1}(\underline{S}^{f_e})$.

Finally, $\underline{S}_e = \left[\underline{\mu}^{d_e}\delta + \underline{\mu}^{f_e}(1 - \delta)\right]S_{e_T}$ is the total capacity in most efficient plants.

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

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

$$\hat{D}_e = \begin{cases} D_{e1} = \left[\underline{\mu}^{de}\delta\zeta + (1-\delta)\right]S_{eT} & \text{if } \hat{D}_e \geq \underline{S}_e \\ D_{e2} = (1-\delta)\left[\dfrac{1-\underline{\mu}^{fe}\zeta}{1-\zeta}\right]S_{eT} & \text{if } \hat{D}_e < \underline{S}_e \end{cases}$$

with $\zeta = \dfrac{\overline{MC}_e - \underline{MC}_e}{\hat{p}_e - \underline{MC}_e}$ and $\hat{p}_e = c_{eb}(1+\gamma) + \beta\tau$

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[12]. Lemma 2 highlights that two price duration 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 $\underline{\mu}^{de}$ and $\underline{\mu}^{fe}$ we find that the degree of market power is an increasing function of $\underline{\mu}^{fe}$ and a decreasing function of $\underline{\mu}^{de}$ (see Appendix).

4. The impact on the degree of market power in the output market

Lemma 2 shows that the degree of market power depends on ζ. Since the latter depends on the pollution price, the environmental regulation is able to modify the degree of market power. The following Lemma explains when this can occur.

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[12] 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 $\underline{S}_e^{fe}$ which does not depend on the pollution price.

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

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 it 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. Vice versa when the environmental regulations causes a decrease in market power.

Table 3. Environmental regulation and probability of decreasing or increasing degree market power (DMP) in power markets

	Input market fully competitive	Imperfect competition in the input market				
		Taxes	ETS			
			Auctioning $\alpha_{AF} = 0$ $\alpha_b = 0$	Free allocation		
				$\overline{\alpha}_b = \alpha_{AF}\, r_{AF}/r_b$		
				$\alpha_b = \overline{\alpha}_b$ (benchmar.)	$\alpha_b < \overline{\alpha}_b$ (relative under-allocation)	$\alpha_b > \overline{\alpha}_b$ (relative over-allocation)
Gas price sen-sitivity	$\frac{dc_{eb}}{d\tau} = 0$	$\frac{dc_{e_b}}{d\tau} = (r_{AF} - r_b)$			$\frac{dc_{e_b}}{d\tau} < (r_{AF} - r_b)$	$\frac{dc_{e_b}}{d\tau} > (r_{AF} - r_b)$
$\hat{r}$ ($\tau < \tau^*$)	$\hat{r} = (1+\lambda)r_b - \lambda r_a$	$\hat{r} = (1+\lambda)r_{AF} - \lambda r_a$			$\hat{r} < (1+\lambda)r_{AF} - \lambda r_a$	$\hat{r} > (1+\lambda)r_{AF} - \lambda r_a$
DMP in power market		Lower (higher) probability of increasing (decreasing) DMP			Higher (lower) probability of increasing (decreasing) DMP	Lower (higher) probability of increasing (decreasing) DMP

Lemma 3 shows another interesting result. It highlights that the higher $\hat{r}$ the higher the probability of decreasing market power. Since $\hat{r}$ depends on (increases in) $\frac{dc_{e_b}}{d\tau}$, this probability will depend of how the environmental regulation impacts on the natural gas price.

Then, from Proposition 1 and Lemma 3 (see also Table 2), we get the results illustrated in Table 3.

As can be noted, the probability that the environmental policy could decrease or increase market power depends on the kind of environmental policy and, in the case of the ETS, on the methods and rules of allocation. In particular, two results arise.

First, the degree of market power is more likely to decrease (increase) with (without) imperfect competition in the input market unless, under the ETS, there is a large under-allocation of allowances to the gas-fired units.

Second the probability of increasing (decreasing) market power is lower (higher) under taxation or ETS with auctioning or benchmarking or with over-allocation of free allowances.

5. The effect on pollution

Lemma 3 raises the following issues. First, under imperfect competition the environmental policy may lessen or amplify market distortions. Second (and most important), the change in market power due to the environmental policy might significantly impact on pollution as long as it can modify the share of production by the different groups of plants (by favouring or penalizing production by the most or by the least polluting plants). Thus the following question arises.

Can the environmental regulation determine a rise (rather than a decrease) in pollution?

To understand 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 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). On the other hand, if $r_b < r_a$ 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.

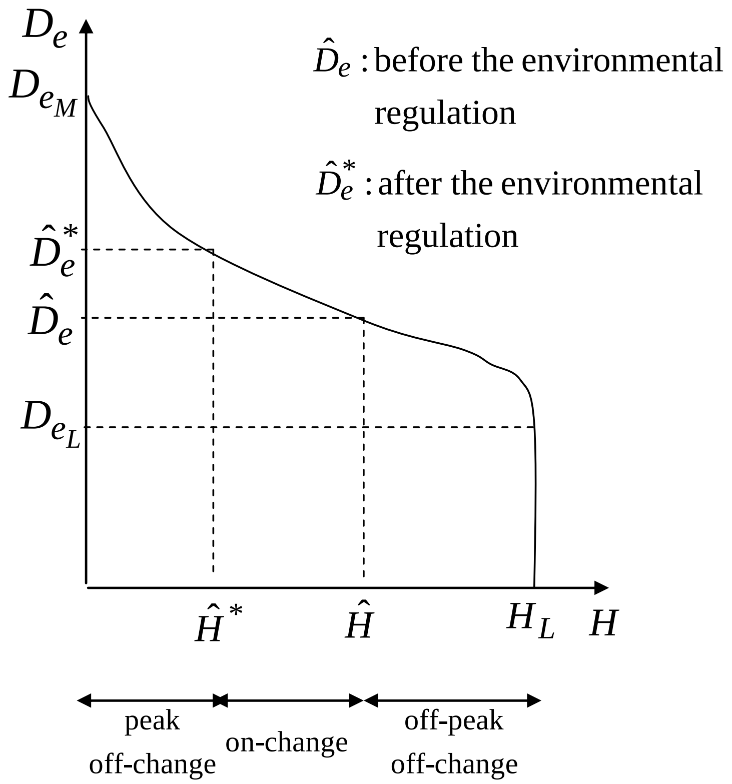

Figure 2. On-change and off-change hours in the load duration curve

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, the "change in market power effect". This effect occurs in the hours in which the dominant firm modifies its strategy. We denominate these hours as "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 "change in market power effect" includes two components: 1) the change in emissions (ΔE_{ts}^{on}) caused by the corresponding change in the share of production by the different groups of technologies and 2) the change in emissions ($\Delta E_{D_e}^{on}$) caused by the corresponding change in prices and in demand during the on-change hours.

Instead the change in emissions during the off-change hours, ΔE^{off}, is due simply to the impact of the environmental policy on power demand. Note that ΔE^{off} can be divided into two components (Fig. 2). The first one is the change in emissions during the peak off-change hours, ΔE_{peak}^{off}. In these hours the dominant firm bids the price threshold before and after the environmental policy. The other one is the change in emissions during the off-peak off-change hours, $\Delta E_{off-peak}^{off}$. In these hours the dominant firm bids the marginal cost of the least efficient plants before and after the environmental policy.

Then the environmental policy will increase pollution if $\Delta E_{ts}^{on} + \Delta E_{D_e}^{on} + \Delta E_{peak}^{off} + \Delta E_{off-peak}^{off} > 0$. The following Lemma describes when this can occur.

Lemma 4. *Under imperfect competition and for particular pollution price intervals, increasing pollution is possible and very likely only if* $0 \le \partial\hat{p}_e/\partial\tau < r_b$, $\partial\hat{p}_e/\partial\tau < \hat{r}$ *and* $\tau < \tau^*$.

Proof. For the formal proof see Appendix. Below a graphical explanation of this Lemma.

To understand how the change in market power may affect emissions, it is helpful to show a simplified case in which: *(i)* $\tau < \tau^*$; *(ii)* $0 \le \partial\hat{p}_e/\partial\tau < r_b$ and *(iii)* the dominant firm operates only one group of units (group a) and the fringe only the other one (group b), that is $\mu_a^{d_e} = 1$ and $\mu_a^{f_e} = 0$.

Figures 3 to 5 illustrate how the environmental policy can modify aggregate emissions in the on-change and in the off-change hours. Note that this example refers to the case in which the environmental policy determines a decrease in market power and remind that in all cases the pricing mechanism is an uniform first price auction.

In each figure we report the expected sign of the components described above.

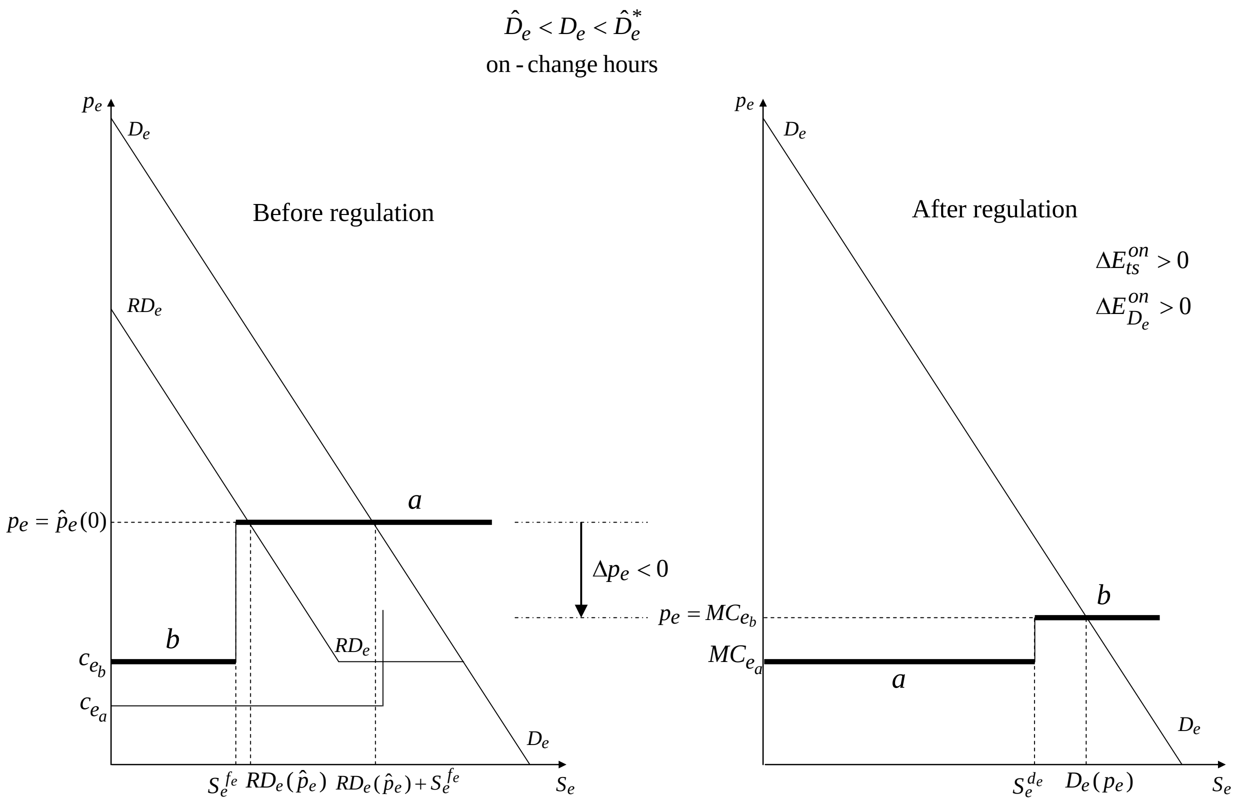

Figure 3. Change in emissions in the on-change hours (decreasing market power)

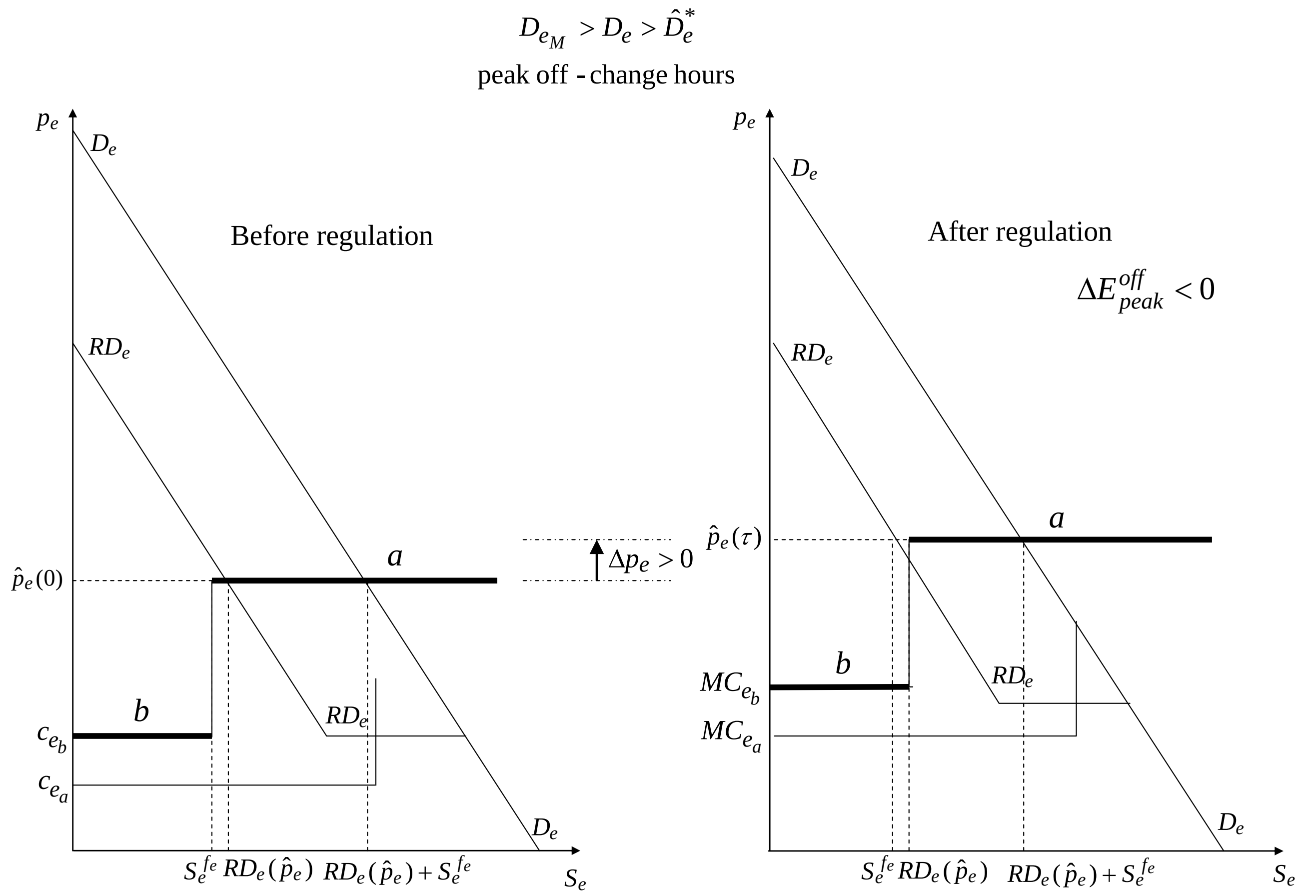

Figure 4. Change in emissions in the peak off-change hours

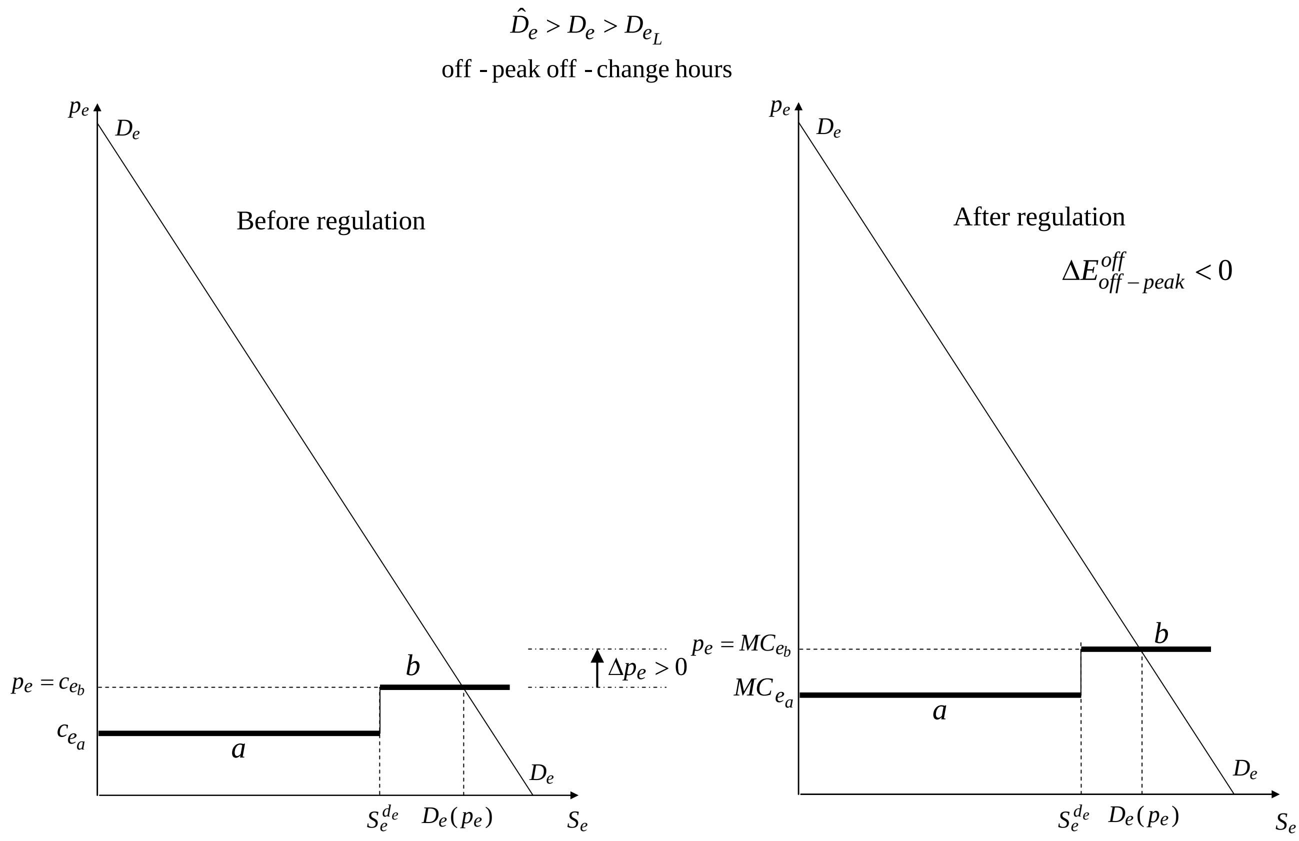

Figure 5. Change in emissions in the off-peak off-change hours

Figure 3 shows what may occur in the on-change hours, $\hat{H}^* > H \geq \hat{H}$. In this case, after the introduction of the environmental regulation, the dominant firm prefers to maximize its production whereas before the introduction of the regulation it prefers to behave as a residual monopolist. Therefore, the environmental regulation determines an increase in the share of production by the most polluting plants on the one hand and, on the other hand, an absolute increase in production (and consequently in emissions) due to the decrease in prices. Overall, we will have a significant rise in emissions in the on-change hours due to the drop in the degree of market power.

Figure 4 illustrates what may occur in the peak off-change hours, $H \leq \hat{H}^*$. In this case the environmental regulation determines an increase in prices which implies a decrease in demand and in production by the most polluting plants. However, since the price threshold is low sensitive to the pollution price (i.e. $0 \leq \partial\hat{p}_e / \partial\tau < r_b$), the decrease in emissions is very slight.

Figure 5 shows what may occur in the off-peak off-change hours, $H > \hat{H}$. In this case the environmental regulation determines an increase in prices which involves a decrease in demand and consequently in production by the least polluting plants. Again, since the emissions rate of the least polluting plants is low, the decrease in emissions is almost negligible.

Finally, given this framework, it is very likely that $\Delta E_{ts}^{on} + \Delta E_{D_e}^{on} + \Delta E_{peak}^{off} + \Delta E_{off-peak}^{off} > 0$ especially if the price elasticity of demand is relatively low as in the case of the electricity sector[13]. In all the other situations, increasing pollution is impossible or very unlikely (see Appendix).

In addition, Lemma 4 underlines that increasing pollution is possible only for particular pollution price intervals. In fact 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 pollution price 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).

[13] 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.

6. What is the real probability of increasing pollution?

Lemma 4 highlights that the environmental policy may increase emissions only under specific conditions. However, this should not lead to conclude that the probability that emissions go up is very low. In fact, it is possible to demonstrate that increasing pollution is very likely to occur if we look at what really happens in energy markets (real configurations of power markets).

For this purpose it is necessary to return to Lemma 4 stating that $0 \leq \partial\hat{p}_e / \partial\tau < r_b$, $\partial\hat{p}_e / \partial\tau < \hat{r}$ *and* $\tau < \tau^*$ are almost sufficient conditions for increasing emissions. With regard to these condition, we already know (see sub-section 2.3 and Table 1) that $0 \leq \partial\hat{p}_e / \partial\tau < r_b$ is the most likely outcome when we face medium/large market power (the relevant case in our analysis). Therefore, in order to check the probability of increasing emissions, we just have to see how $\partial\hat{p}_e / \partial\tau < \hat{r}$ is likely that is we should estimate the probability of decreasing market power (see Lemma 3).

We attempt to estimate this probability by adopting plausible values of emission rates and fuel costs. With regard to the emission rates we use $r_b = 0.4$ tCO_2/MWh for CCGT plants, $r_a = 0.8$ tCO_2/MWh for coal plants and $r_{AF} = 0.7$ tCO_2/MWh for the alternative fuel installations (e.g. fuel oil). With regard to the fuel costs, c_{e_a} and c_{e_b}, the historical monthly patterns of coal and natural gas prices are used [14] .

The results are reported in Figures 5 and 6 where the density distributions of $\hat{r}$ are reported. As can be noted, if only the output market is imperfectly competitive (Fig. 5) there is a significant positive probability of increasing pollution ($\partial\hat{p}_e / \partial\tau < \hat{r}$) only if the sensitivity of the power price threshold is very low (lower than 0.2). Instead, if both markets (input and output) are imperfectly competitive (Fig. 6) this probability is much higher (practically 100%).

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[14] These values have been calculated by looking at the historic monthly pattern (from 2004 to 2008) of natural gas and coal prices. For the coal price we used the MCIS steam coal marker price (cif NEW). For the gas price we used the gas price at European borders. Furthermore, the following technical parameters have been adopted. With regard to electric efficiencies, 52% for CCGT plants (Combined Cycle-Gas Turbine); 40% for coal plants.

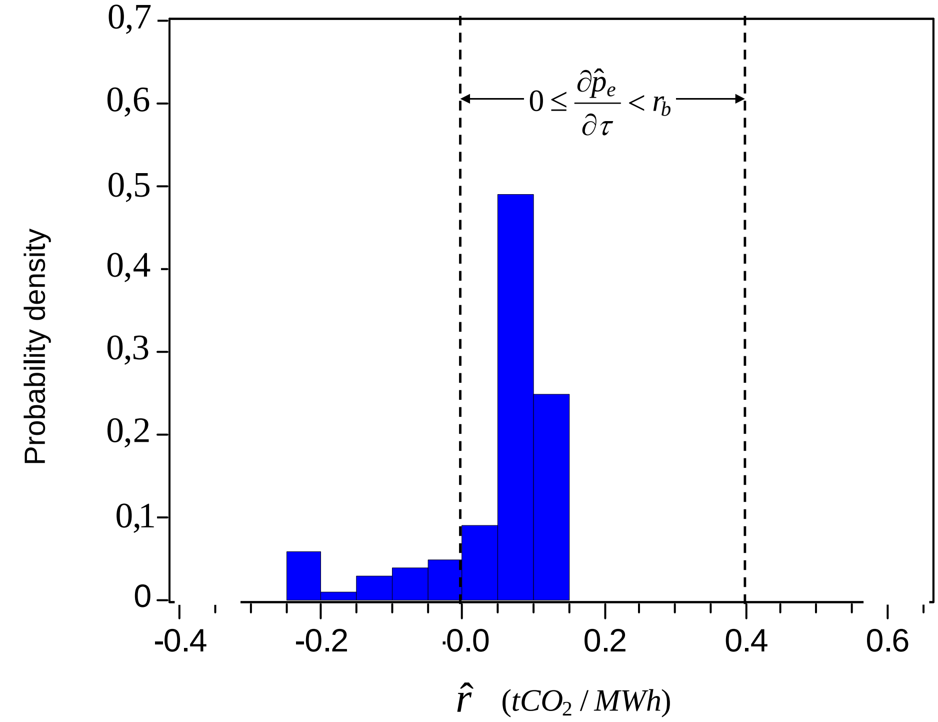

Figure 5. Probability distribution of $\hat{r}$ obtained by using historical data of natural gas and coal prices (without imperfect competition in the input market)

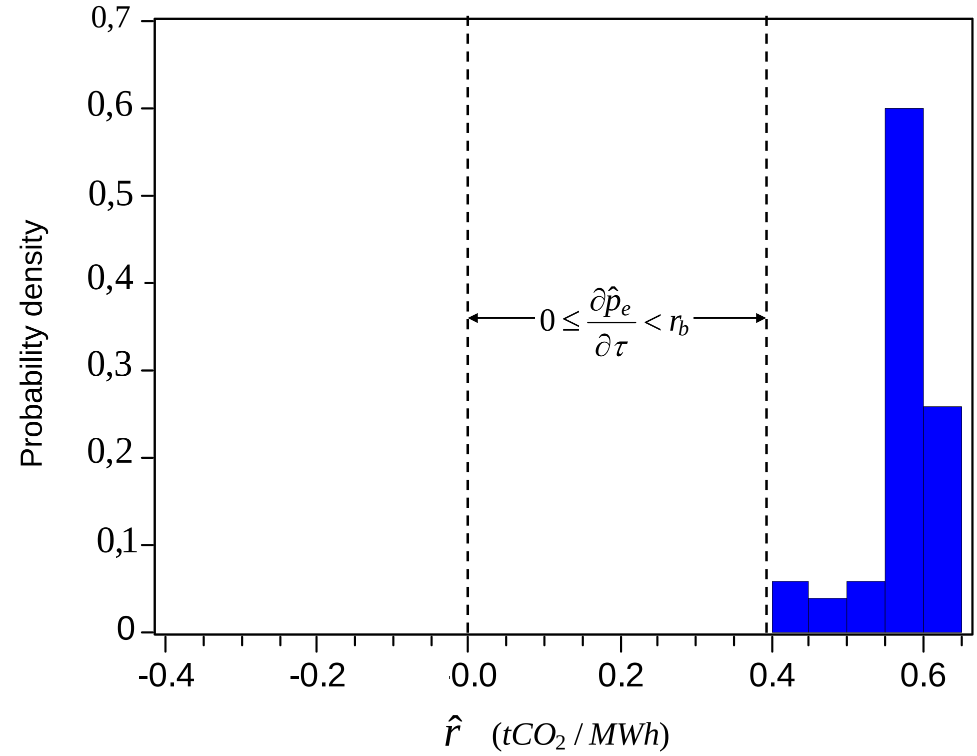

Figure 6. Probability distribution of $\hat{r}$ obtained by using historical data of natural gas and coal prices (with imperfect competition in both input and output markets)

Therefore, if imperfect competition in the output market combines with imperfect competition also in the input market there is a high probability that the environmental policy could increase pollution.

This result arises another issue. How does the probability of increasing emissions depend on the type of environmental regulation? To answer this question, in the space (α_b, α_{AF}) we have plotted (Fig. 7) the locus of points that $\hat{r}$ is equal to zero and 0.4 (the extremes of the range corresponding to medium/high market power) and we have identified the combinations of ratios of allocation (α_b and α_{AF}) associated to the different types of regulation using Proposition 1 and Lemma 3 (see also Table 3). The fill point (point A), in which $\alpha_b = \alpha_{AF} = 0$, corresponds to the outcome under pollution taxes and under the ETS with full auctioning. The line outgoing from this point is the locus of points that $\alpha_b = \alpha_{AF}\, r_{AF} / r_b$, that is the case in which allowances are benchmarked. Finally, the area below (above) this "benchmarking line" includes combinations of ratios of allocation corresponding to relative over-allocation (relative under-allocation) of allowances to the gas-fired plants, i.e. $\alpha_b > \alpha_{AF}\, r_{AF} / r_b$ ($\alpha_b < \alpha_{AF}\, r_{AF} / r_b$).

Figure 7 highlights two interesting issues. First, taxation and the ETS with auctioning or benchmarking are perfectly equivalent (same high probability of increasing pollution). Second, paradoxically one way to reduce the probability of increasing emissions is penalizing the least polluting plants (the gas-fired ones) by significantly under-allocating emissions allowances to them (with respect to the alternative fuel), if the environmental policy is based on the ETS. By converse relative over-allocation to the gas-fired units would rise the probability of increasing pollution.

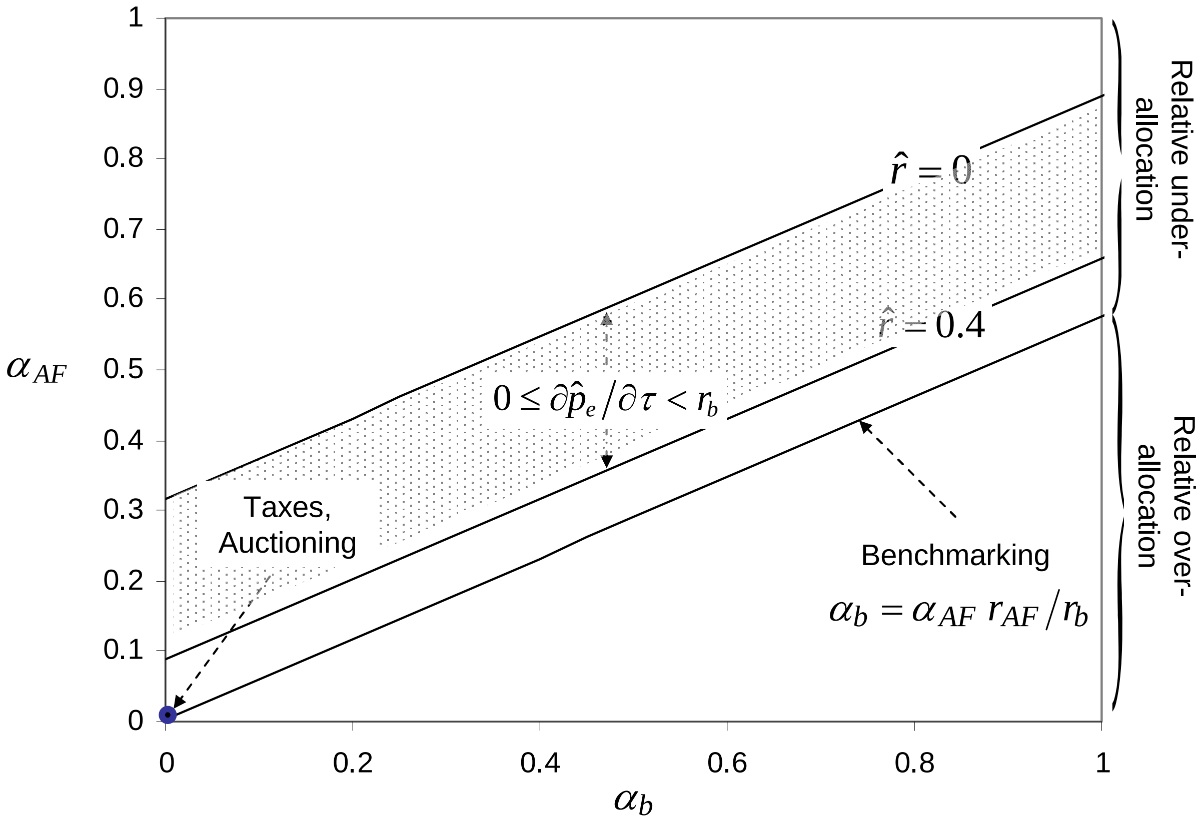

Figure 7. Probability of increasing emissions under different kinds of environmental regulation

Finally, note that emissions trading may significantly increase the volatility of both natural gas and pollution prices. Imperfect competition, in fact, might give rise to a loop between pollution and natural gas prices.

The logic pathway would be the following. An increase in the pollution price determines an increase in the alternative fuel cost especially under pollution taxes and under the ETS if allowances are auctioned or benchmarked or over-allocated to the gas-fired plants. Consequently this increase implies an increase in the natural gas price which involves a rise in the pollution price[15] and so on. In addition, the rise in the gas price determines a rise in the probability of increasing pollution. This increases the demand for emissions allowances involving further increase in pollution price. Vice versa, if we have a drop in the pollution price. Therefore imperfect competition contributes to increase volatility of both pollution and natural gas prices. This may contribute to lessen the effectiveness of the environmental policy even in the long run.

The following Proposition and the corresponding Corollary summarize these results.

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[15] All empirical studies highlight that the natural gas price is one of the main determinants of the carbon price. Among others, see Paolella and Taschini (2007), Alberola et al. (2007) and Bunn and Fezzi (2008).

Proposition 2. (*i) Under imperfect competition in the output (electricity) market it is likely that the environmental policy could increase pollution; (ii) imperfect competition also in the input (natural gas) market may greatly amplify the probability of increasing pollution.*

Corollary 4. *Imperfect competition increases volatility of both pollution and natural gas prices mainly under emissions trading and especially if allowances are auctioned or benchmarked or they are over-allocated to the gas-fired plants.*

6. Conclusions

This paper not only confirms, according to the current literature, that imperfect competition in the output market may lead to increased pollution but, looking at what can really happen in the energy markets, it reinforces this conclusion. In addition it highlights that market power also in the input market greatly amplifies the probability of increasing emissions. This occurs especially 1) under pollution taxes, 2) under emissions trading (ETS) if allowances are auctioned of benchmarked or, paradoxically, if the least polluting plants (the gas-fired ones) are favoured by significantly over-allocating (compared to the alternative fuel) emissions allowances to them.

These results have been obtained by simulating the impact of the environmental regulation on two vertical related markets: 1) the power market (output market) which is one of the most important environmentally regulated market; 2) the natural gas market (input market) which is one of the most important input for power generation in several countries.

The basic idea of the analysis is that, by triggering a direct mutual relationship between energy and pollution prices, imperfect competition may lessen the ability of the environmental policy to reduce emissions. This increases the cost of meeting the environmental targets and, under certain conditions, could even lead to increased (rather than to decreased) pollution

Furthermore the paper shows that imperfect competition may increase the volatility of both natural gas and pollution prices contributing to undermine the effectiveness of the environmental policy even in the long run.

Summing up, this analysis suggests that the cost of meeting environmental targets may be much higher than that expected under conditions of full competition. Therefore, in order to estimate the real economic impact of the environmental policy and its real effectiveness, simulation models should take accurately into account the effect of imperfect competition in energy markets. In fact, as demonstrated in this paper, imperfect competition can largely affect the performance of the environmental policy as long as it has impact on product prices, on the share of production by the different polluting technologies and, consequently, on aggregate emissions. We have found that the environmental policy may determine an increase rather than a decrease in pollution in the short-run thus making it more difficult to meet the environmental targets. This also means that under certain circumstances the laissez faire might be better than the public action. This paper also suggests that that these circumstances are not at all unlikely.

Appendix

Proof of Lemma 2

Let $\overline{S}_e = D_{e_M} - \overline{S}_e^{d_e}$ be the peak demand minus the dominant firm's capacity in least efficient plants ($\overline{S}_e^{d_e}$) with $\overline{H} = D^{-1}(\overline{S}_e)$. It is immediately intuitive that when $S \geq \overline{S}_e$ the system marginal price equals the price threshold, $\hat{p}_e$. When $D_e \leq \underline{S}_e^{f_e}$, 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 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 $D_e \in \left]\overline{S}_e; \underline{S}_e^{fe}\right]$[16]. 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 $\overline{MC}_e$[17].

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. $D_e \geq \underline{S}_e$), the profit the dominant firm earns by choosing the first strategy (i.e. $\forall H \in \left]\overline{H}; \underline{H}\right]$) is

[16] 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).

[17] 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.

(A1) $\pi_A^{d_e} = (\hat{p}_e - \underline{MC}_e)\left[D_e - (1-\delta)S_{e_T}\right] - \sum_{i=1}^{z}\sum_{j=a,b}\left(s_{e_j}^{i} f_{e_j}^{i} - \tau\overline{ET}_j^{i}\right)$

where $f_{e_j}^{i}$ is the capital cost per unit of installed capacity of the unit *i-th* unit belonging to the group *j* of plants.

If the dominant firm chooses the second strategy, he earns

(A2) $\pi_B^{d_e} = (\overline{MC}_e - \underline{MC}_e)\underline{S}_e^{d_e} - \sum_{i=1}^{z}\sum_{j=a,b}\left(s_{e_j}^{i} f_{e_j}^{i} - \tau\overline{ET}_j^{i}\right)$

where $\overline{ET}_j^{i}$ is the total amount of allowances allocated free of charge to the unit *i-th* unit belonging to the group *j* of plants. Obviously $\overline{ET}_j^{i} = 0$ if the environmental policy is based on pollution taxes.

Therefore the leader's optimal strategy is bidding the price threshold if and only if $\pi_A^{d_e} \geq \pi_B^{d_e}$, i.e. if and only if

(A3) $D_e \geq D_{e1}(\delta, \underline{\mu}^{d_e}, \zeta) = \left[\underline{\mu}^{d_e}\delta\zeta + (1-\delta)\right]S_{eT}$

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

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

(A4) $\pi_C^{d_e} = (\hat{p}_e - \underline{MC}_e)\left[D_e - (1-\delta)S_{e_T}\right] - \sum_{i=1}^{z}\sum_{j=a,b}\left(s_{e_j}^{i} f_{e_j}^{i} - \tau\overline{ET}_j^{i}\right)$

and by choosing the second strategy the profit is

(A5) $\pi_D^{d_e} = (\overline{MC}_e - \underline{MC}_e)\left[D_e - \underline{\mu}^{f_e}(1-\delta)S_{e_T}\right] - \sum_{i=1}^{z}\sum_{j=a,b}\left(s_{e_j}^{i} f_{e_j}^{i} - \tau\overline{ET}_j^{i}\right)$

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) $D_e \geq \hat{D}_{e_2} = (1-\delta)\left[\dfrac{1-\zeta \underline{\mu}^{f_e}}{1-\zeta}\right] S_{e_T}$

Summarizing, the dominant firm will behave as a residual monopolist when

$$D_e \geq \hat{D}_e = \begin{cases} D_{e1} = \left[\underline{\mu}^{d_e}\delta\zeta + (1-\delta)\right] S_{eT} & \text{if } \hat{D}_e \geq \underline{S}_e \\ D_{e2} = (1-\delta)\left[\dfrac{1-\underline{\mu}^{f_e}\zeta}{1-\zeta}\right] S_{eT} & \text{if } \hat{D}_e < \underline{S}_e \end{cases}$$

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

$$\frac{\partial D_{e_1}}{\partial \underline{\mu}^{d_e}} = S_{e_T}\,\delta\zeta > 0; \quad \frac{\partial D_{e_2}}{\partial \underline{\mu}^{f_e}} = -S_{e_T}\,(1-\delta)\frac{\zeta}{1-\zeta} < 0$$

Proof of Lemma 3

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

(A7) $\dfrac{\partial \hat{D}_e}{\partial \tau} = \dfrac{\partial \hat{D}_e}{\partial \zeta}\dfrac{\partial \zeta}{\partial \tau}$

Since (from (A3) and (A6))

(A8) $\dfrac{\partial \hat{D}_{e_1}}{\partial \zeta} = \underline{\mu}^{d_e}\delta S_{e_T} > 0$ e $\dfrac{\partial \hat{D}_{e2}}{\partial \zeta} = \dfrac{(1-\delta)(1-\underline{\mu}^{f_e})}{(1-\zeta)^2} S_{e_T} > 0$

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

By differentiating ζ with respect to τ and given that $\hat{p}_e(\tau) = c_{e_b}(0)(1+\gamma) + \beta\tau$ and that c_{e_b} depends linearly on τ (see equations (2) and (4) in sub-section 3.1.2.), we get

(A9) $\dfrac{\partial \zeta}{\partial \tau} = \dfrac{(r_b - r_a + dc_{eb}/d\tau)\left[c_{eb}(0)(1+\gamma) - c_{ea}\right] - (\partial \hat{p}_e/\partial \tau - r_a)(c_{eb}(0) - c_{ea})}{(\hat{p}_e - c_{ea} - r_a \tau)^2}$ if $\tau < \tau^*$

and

(A10) $\dfrac{\partial \zeta}{\partial \tau} = \dfrac{(r_a - r_b - dc_{eb}/d\tau)\left[c_{eb}(0)(1+\gamma) - c_{eb}(0)\right] - (\partial \hat{p}_e/\partial \tau - r_b - dc_{eb}/d\tau)(c_{ea} - c_{eb}(0))}{(\hat{p}_e - c_{eb} - r_b \tau)^2}$ if $\tau \geq \tau^*$

From (A9)

$\dfrac{\partial \zeta}{\partial \tau} > 0$ and consequently $\dfrac{\partial \hat{D}_e}{\partial \tau} > 0$ if $\partial \hat{p}_e/\partial \tau < \hat{r} = (1+\lambda)(r_b + dc_{eb}/d\tau) - \lambda r_a$ with $\lambda = \gamma\, c_{eb}(0)/(c_{eb}(0) - c_a)$. Vice versa, if $\partial \hat{p}_e/\partial \tau > \hat{r}$ then $\dfrac{\partial \hat{D}_e}{\partial \tau} < 0$.

From (A10)

$\dfrac{\partial \zeta}{\partial \tau} > 0$ and consequently $\dfrac{\partial \hat{D}_e}{\partial \tau} > 0$ if $\partial \hat{p}_e/\partial \tau > \hat{r} = (1+\lambda)(r_b + dc_{eb}/d\tau) - \lambda r_a$ with $\lambda = \gamma\, c_{eb}(0)/(c_{eb}(0) - c_a)$. Vice versa, if $\partial \hat{p}_e/\partial \tau < \hat{r}$ then $\dfrac{\partial \hat{D}_e}{\partial \tau} < 0$.

Finally, note that when $\tau \geq \tau^*$ we should look at the discrete variation of $\hat{D}_e$ ($\Delta \hat{D}_e$) that is to the variation from zero to $\tau \geq \tau^*$. In this case $\Delta \hat{D}_e$ may be either positive or negative regardless of the first derivative $\partial \hat{D}_e/\partial \tau$.
In fact, from (A3) we get

$\hat{D}_e(\tau = 0) > \hat{D}_e(\tau > \tau^*)$ if

(A11) $\mu_a^d > \mu_b^d \dfrac{\hat{p}_e - c_{ea}}{(\hat{p}_e - c_{eb} - r_b \tau)(c_{eb} - c_{ea})}\left[c_{ea} - c_{eb} + \tau(r_a - r_b)\right]$

This means that $\Delta \hat{D}_e$ may be either positive or negative depending on μ_a^d, μ_b^d and τ. The higher μ_a^d and the lower μ_b^d and τ the more likely that $\Delta \hat{D}_e > 0$. Vice versa for $\Delta \hat{D}_e < 0$.

The same result is obtained by using equation (A6).

Proof of Lemma 4

Assume for example the supply configuration described in Figure A1 (case of $\hat{D}_e \geq \underline{S}_e$ and $\tau < \tau^*$).

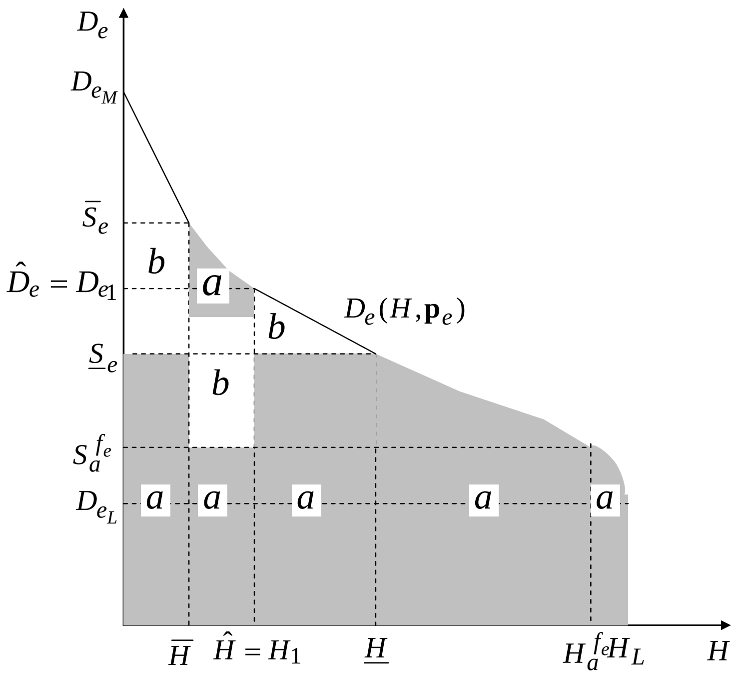

Figure A1. Example of supply configuration: production by units of group *a* (grey area); production by units of group *b* (white area)

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

(A12)

$$E = r_b\left[\int_0^{\bar{H}(p_e(\tau))} D_e(H, p_e(\tau))dH - (S_{e_a}^{d_e} + S_{e_a}^{f_e})\bar{H}\right] + r_a(S_{e_a}^{d_e} + S_{e_a}^{f_e})\bar{H} +$$

$$+r_a\left[\int_{\bar{H}(p_e(\tau))}^{\hat{H}(p_e(\tau))} D_e(H, p(\tau))dH - S_{e_b}^{f_e}(\hat{H} - \bar{H})\right] + r_b S_{e_b}^{f_e}(\hat{H} - \bar{H}) +$$

$$+r_b\left[\int_{\hat{H}(p_e(\tau))}^{\underline{H}(p_e(\tau))} D_e(H, p(\tau))dH - (S_{e_a}^{d_e} + S_{e_a}^{f_e})(\underline{H} - \hat{H})\right] + r_a(S_{e_a}^{d_e} + S_{e_a}^{f_e})(\underline{H} - \hat{H}) +$$

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

By differentiating (A12) with respect to τ and given that

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

we get

(A13)

$$\frac{\partial E}{\partial \tau} = (r_b - r_a)(\bar{S}_e - \hat{D}_e)\frac{\partial \hat{H}}{\partial \tau} + r_b\left[\int_0^{\bar{H}(p_e(\tau))} \frac{\partial D_e(H, p_e(\tau))}{\partial \tau}dH\right] + r_a\left[\int_{\bar{H}(p_e(\tau))}^{\hat{H}(p_e(\tau))} \frac{\partial D_e(H, p_e(\tau))}{\partial \tau}dH\right] +$$

$$+r_b\left[\int_{\hat{H}(p_e(\tau))}^{\underline{H}(p_e(\tau))} \frac{\partial D_e(H, p(\tau))}{\partial \tau}dH\right] + r_a\left[\int_{\underline{H}(p_e(\tau))}^{H_L} \frac{\partial D_e(H, p(\tau))}{\partial \tau}dH\right]$$

The first element in (A13) is the change in emissions in the on-change hours caused by the change in market power (excluded the effect due to the change in demand). This effect is due to the modification in the share of production by the different technology groups. We denominate this component as

$$A = (r_b - r_a)(\bar{S}_e - \hat{D}_e)\frac{\partial \hat{H}}{\partial \tau}$$

Therefore, since $r_b < r_a$ and $\bar{S}_e \geq \hat{D}_e$, if $\frac{\partial \hat{H}}{\partial \tau} < 0$ then $A > 0$ and if $\frac{\partial \hat{H}}{\partial \tau} > 0$ then $A < 0$.

The remaining elements in (A13), the integrals, represent the change in emissions due to demand effect caused by the change in prices. We denominate the sum of these four elements as B.

Provided that the discrete change in emissions due to the introduction of the pollution price τ is given by

(A14) $$\Delta E = \int_0^\tau \frac{\partial E}{\partial \tau} d\tau = \int_0^\tau A d\tau + \int_0^\tau B d\tau \ , \ \forall \tau \in [0;\hat{\tau}]$$

the environmental policy will increase pollution ($\Delta E > 0$) only if

(A15) $$C = \int_0^\tau A d\tau > F = -\int_0^\tau B d\tau \ , \ \forall \tau \in [0;\hat{\tau}]$$

where $\hat{\tau}$ is the pollution price above which the demand effect (the decrease in demand) is so high that aggregate emissions necessarily go down regardless of the market power effect.

Table A1. Change in emissions

	Change in market power				DMP
	$\tau < \tau^*$		$\tau \geq \tau^*$		
	$\partial \hat{p}_e / \partial \tau < \hat{r}$	$\partial \hat{p}_e / \partial \tau > \hat{r}$	$\partial \hat{p}_e / \partial \tau < \hat{r}$	$\partial \hat{p}_e / \partial \tau > \hat{r}$	
	I	II	III	IV	
A1) $0 \leq \partial \hat{p}_e / \partial \tau < r_b$	$C > 0, F < 0$ $C > F$ $(\Delta E > 0)$	$C < 0, F > 0$ $C < F$ $(\Delta E < 0)$	$C < 0, F > 0$ $C < F$ $(\Delta E < 0)$	$C < 0, F > 0$ $C < F$ $(\Delta E < 0)$	HM
A2) $\partial \hat{p}_e / \partial \tau \geq r_b$	$C > 0, F \gg 0$ $C < F$ $(\Delta E < 0)$	$C < 0, F > 0$ $C < F$ $(\Delta E < 0)$	$C < 0, F > 0$ $C < F$ $(\Delta E < 0)$	$C < 0, F > 0$ $C < F$ $(\Delta E < 0)$	ML

Then we may have the following situations corresponding to the possible combinations (Table A1) of pollution price (τ), sensitivity of the power price threshold ($\partial \hat{p}_e / \partial \tau$) and change in market power ($\partial \hat{p}_e / \partial \tau - \hat{r}$):

(i) $\tau < \tau^*$, $\partial \hat{p}_e / \partial \tau < \hat{r}$ and $0 \leq \partial \hat{p}_e / \partial \tau < r_b$ (configuration A1I). In this case, $\frac{\partial \hat{H}}{\partial \tau} < 0$, $\forall \tau$ (see Lemma 3). Therefore $A > 0$ and $C > 0$, on the one hand. On the other hand the fall in market power determines a strong decrease in prices during the on-change hours and consequently an increase in emissions due to the rise in demand (and production). Instead, the environmental policy determines an increase in prices and consequently a decrease in demand during the off-change hours (both peak and off-peak). Since the price threshold is low sensitive to the pollution price and r_b is relatively low, this decrease is very slight in both peak and off-peak off-change hours. Thus it is unlikely that it could offset the increase in emissions during the on-change hours. Therefore it is very likely that $C > F$ and consequently $\Delta E > 0$ (from A14 and A15)).

(ii) $\tau < \tau^*$, $\partial \hat{p}_e / \partial \tau < \hat{r}$ and $\partial \hat{p}_e / \partial \tau \geq r_b$ (configuration A2I). In this case, we get $\frac{\partial \hat{H}}{\partial \tau} < 0$, $\forall \tau$, again. Therefore, on the one hand, $A > 0$ and $C > 0$. Nevertheless A is low as the sensitivity of the price threshold to the pollution price is medium/high. In fact, from (A9) the higher $\partial \hat{p}_e / \partial \tau$ the lower $\partial \zeta / \partial \tau$ and consequently the lower $\partial \hat{D}_e / \partial \tau$ (and thus $\partial \hat{H} / \partial \tau$). On the other hand, the fall in market power determines a decrease in prices during the on-change hours and consequently an increase in emissions due to the rise in demand (and production). Again, since $\partial \hat{H} / \partial \tau$ is low this rise in emissions occurs during a very short period (few hours) and consequently it is likely to be largely offset by the strong decrease in demand during the off-change periods (especially during the peak off-change periods). Therefore it is very likely that $F \gg 0$ and consequently that $C < F$ and $\Delta E < 0$ (from A14 and A15)).

(iii) $\tau < \tau^*$, $\partial \hat{p}_e / \partial \tau > \hat{r}$, $\forall \partial \hat{p}_e / \partial \tau \geq 0$ (configurations A1II and A2II). In these cases, since $\frac{\partial \hat{H}}{\partial \tau} > 0$, $\forall \tau$, then $A < 0$ and $C < 0$, on the one hand. On the other hand, the increase in market power determines an increase in price and consequently a decrease in emissions during the on-change hours amplified by that during the off-change hours especially in A2II. Therefore certainly $F > 0$ and consequently $\Delta E < 0$ (from A14 and A15)).

(iv) $\tau \geq \tau^*$, $\partial \hat{p}_e / \partial \tau < \hat{r}$ or $\partial \hat{p}_e / \partial \tau > \hat{r}$, $\forall \partial \hat{p}_e / \partial \tau \geq 0$ (configurations A1III, A2III, A1IV and A2IV). In this case, as pointed out before (Proof of Lemma 3), we have to look at the discrete variation of $\hat{D}_e$ ($\Delta \hat{D}_e$) which may be either positive or negative.

Consequently $\Delta\hat{H}$ may be either negative or positive, respectively. However, it is possible to demonstrate that $A<0$ and $C<0$ in both cases. In order to escape computational complexity, we try to do this graphically. Figure A2 shows the case in which $\Delta\hat{D}_e<0$. As can be noted the increase in market power implies the increase in the share of production by the least polluting plants, then $A<0$. In addition, prices increase and emissions decrease everywhere, then $B<0$ and $F>0$. Consequently $C<F$ and $\Delta E<0$. Figure A3 shows the case in which $\Delta\hat{D}_e>0$. Again, the decrease in market power determines the increase in the share of production by the least polluting plants, then $A<0$ and $C<0$ again. Furthermore, prices decrease during the on-change hours but this decrease (and its effect on emissions) is totally or partially offset by the increase in prices (and consequently by the corresponding fall in demand and production) during the off-change hours. Thus once again it is very likely that $C<F$ and consequently that $\Delta E<0$ (from A14 and A15).

Given this framework, combination A1I ($\partial\hat{p}_e/\partial\tau<\hat{r}$ and $0\leq\partial\hat{p}_e/\partial\tau<r_b$ combined with $\tau<\tau^*$) is the only situation in which increasing pollution is not only possible but also very likely.

Finally, it is possible to demonstrate that these results arise even for the case in which $\hat{D}_e\leq\underline{S}_e$.

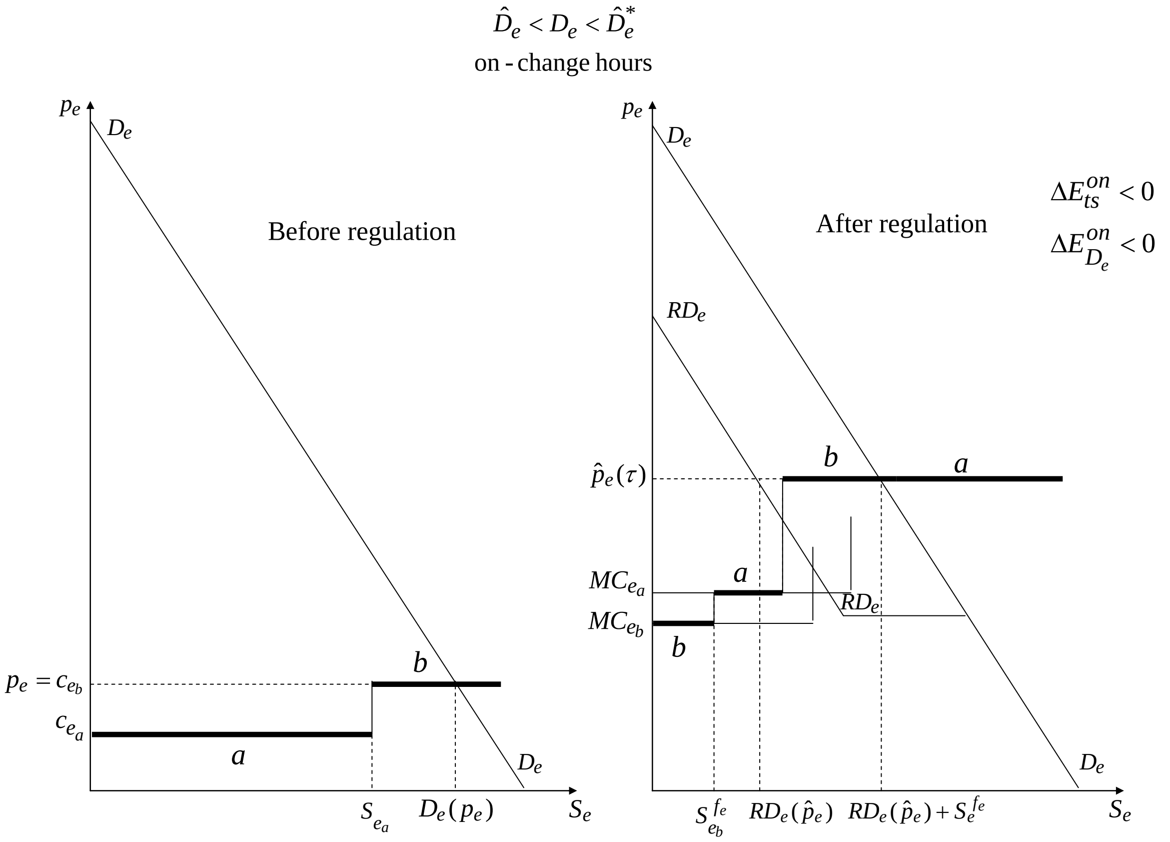

Figure A2. Change in emissions in the on-change hours ($\Delta\hat{D}_e < 0$ and $\tau \geq \tau^*$)

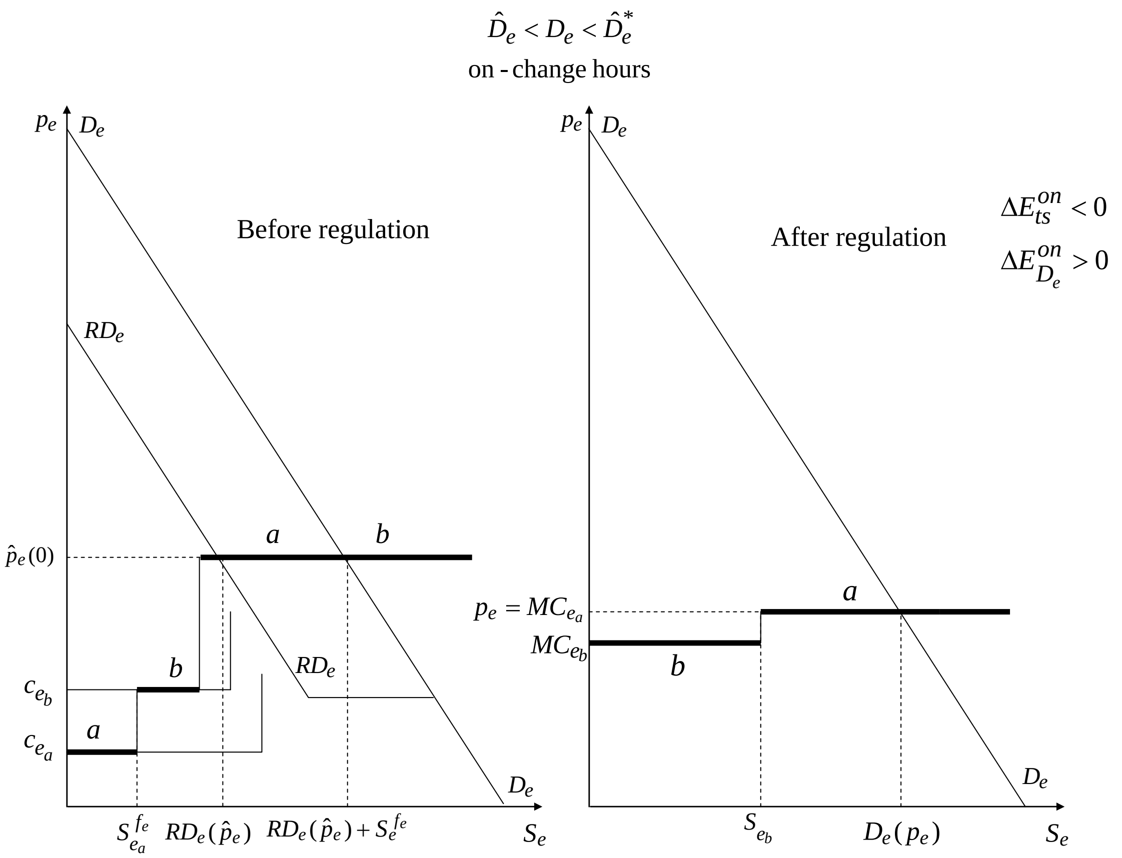

Figure A3. Change in emissions in the on-change hours ($\Delta\hat{D}_e > 0$ and $\tau \geq \tau^*$)

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