Chapter 2
Pollution Under Hybrid Environmental Regulation: The Case of Space Heating

Abstract Economic literature on environmental policy under imperfect competition provides controversial results. Some contributions find that under specific conditions environmental policy can increase emissions. Others find that environmental policy never increases emissions. However, these contributions are based on symmetric environmental regulation. The same environmental tool is applied to all firms and/or consumers belonging to a specific industrial or service sector. This chapter aims at studying how these results are affected by hybrid regulation when different environmental tools are applied to technologies coexisting in the same sector. This situation is well-suited to describe the structural and technological features of space heating in residential sectors. Looking at polarized market configurations (a dominant firm facing a fringe of producers), the analysis shows that increasing pollution is widely admissible in principle and does not require large environmental asymmetry of firms. However when the real conditions of markets and technologies are accounted for (by means of specific numerical simulations), the probability of increasing pollution seems to be very low in most situations where it is theoretically admissible. The results about the impact of hybrid regulation are ambiguous. Compared to symmetric regulation, hybrid regulation plays a significant role in affecting the probability of increasing pollution. However, this role cannot be generalized.

1 Introduction

Space heating is among the major causes of environmental pollution. It represents one of the most interesting cases of analysis of the relationship between environmental regulation and market structure.

Heat for space heating can be produced by means of several technological solutions using different inputs: light fuel oil or natural gas fired combustion boilers; electric heat pumps; centralized production of hot water transported over relatively long distances by means of pipelines (district heating); etc.

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Different environmental regulation can be applied to the different inputs for useful heat generation (and consequently to the different kinds of useful heat supply): tradable permits (with different types of allowances allocation) or environmental taxes (taxes on producers or taxes on consumers, emissions or input taxes). This implies that hybrid regulation is possible. In fact, since various kinds of heat supply may coexist, various combinations of environmental regulation may indeed coexist for the same final service (useful heat for space heating). For example, when useful heat is produced by natural gas boilers, the most likely regulation is based on input taxes on consumers. If useful heat is delivered by electric heat pumps the most likely regulation is ETS with auctioning or emission taxes on producers. If heat supply is based on district heating, environmental regulation may be based on ETS with free allocation of emissions allowances. Consequently, different kinds of regulation can coexist in the same market (hybrid regulation).

Then the question is: How does hybrid regulation affect the performance of environmental policy and, namely, the probability of increasing pollution? This chapter aims at answering this question.

In several countries, the technological structure of space heating is highly polarized. Generally, a specific technological solution covers the most part of consumption, whereby the other kinds of supply play a residual role (fringe supply).

In turn, input (for useful heat generation) markets may be characterized by quite different structures. Some of them may be close to the conditions of full competition whereas others are highly concentrated and, consequently, characterized by significant market power. Finally, in other input markets prices may be regulated.

In many European countries the leading technology is the gas-fired boiler facing electric heat pumps and/or district heating which play the role of fringe technologies. In other countries, the dominant energy supply technology is district heating or direct and indirect electricity technologies.

A typical situation of polarized market is when the dominant technology is operated by a dominant firm and a large number of price taker firms operates the fringe technology. Consequently, these markets can be adequately simulated by using a dominant firm with fringe model.

In this model, the leader maximizes its profit on residual demand. This implies that the production by the price taker firms belonging to the fringe is partially or totally accommodated depending on cost and demand shape curves. If cost curves are constant over a sufficiently large supply interval the dominant firm practically faces two choices: (1) maximizing its production by setting prices just below the price which would make the end user indifferent when choosing between its own technology and the fringe's technology (the indifference price); (2) setting prices above this price, accommodating the fringe's maximum production.

Given firms' capacities, this choice depends on two factors: (1) the residual monopoly price and (2) the cost structure of the technologies operated by either the dominant firm or the fringe.

Since environmental regulation can modify these two factors, it is in principle able to induce the dominant firm to change its choice when moving from the previous situation to that after the implementation of environmental regulation.

In this chapter, dedicated to space heating, we aim at checking whether and under which conditions this might happen and subsequently how it might undermine the performance of environmental policy, leading to increasing rather than decreasing pollution.

The theoretical literature has devoted great effort to studying environmental policy in presence of imperfect competition. As pointed out in the introduction of this book, the results of the existing literature are controversial. Some authors highlight that increasing pollution is possible under specific conditions in terms of supply and demand (Levin 1985; Requate 2005). Others demonstrate that environmental policy never increases pollution (Canton et al. 2008; Sugeta and Matsumoto 2007).

In line with this framework, this analysis concentrates on pollution taxes and emissions trading and does not engage in describing optimal level of the control policy. It focuses solely on comparative static effects. In fact, given the huge uncertainty about environmental damages,[1] searching for the optimal level of control policies might be less useful than exploring the effects of different levels of pollution prices (tax rates or carbon prices), if we mainly look at the policy implications of the analysis.

Two kinds of environmental regulation are investigated: taxation (on producers or on consumers) and emissions trading (with auctioning or free allocation of emissions allowances). Symmetric regulation arises when the same tool of environmental policy (e.g. only taxes on consumers or only ETS with auctioning) is applied to the different technology cycles. Hybrid regulation occurs when different tools are applied to different technologies.

In line with some contributions of the existing theoretical literature, the analysis confirms that the perverse effect of environmental regulation is widely admissible[2] and does not require large environmental (environmental) asymmetry of firms. However, increasing pollution might be less likely (1) when input taxes are applied to the dominant firm's consumers and (2) especially when environmental regulation is based on ETS with free allocation of emissions allowances combined with regulation of the fringe's prices. Finally, it emerges that hybrid regulation can play a significant role in affecting the probability that environmental regulation could imply a perverse effect. Nevertheless, this role is ambiguous. Compared to symmetric regulation, hybrid regulation can either increase or decrease the probability of increasing emissions depending on several factors.

This chapter is structured as follows. Section 2 presents the assumptions of the model. Section 3 focuses on how the environmental regulation can impact on pollution under imperfect competition. Section 4 carries out numerical simulations. Section 5 concludes.

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[1] We mainly refer to the marginal cost of carbon dioxide emissions.

[2] For the specific case of the electricity markets, see also Gullì (2008).

2 Assumptions

Useful heat is produced in the consumption stage. Its inverse demand, $p(Q)$, depends on the aggregate output Q only and is twice differentiable with $-\infty < \partial p/\partial Q < 0$ for all Q. Firms belonging to the same sector deliver homogenous inputs for useful heat generation. For the sake of simplicity (and without loss of generality), the energy conversion efficiency, namely the ratio between the useful heat and the input, is normalized to one. As a consequence, the input demand and the demand for useful heat coincide (unless taxes on consumers are applied, as it will be explained later).

The pollutant is emitted in the production or in the consumption process and pollution is proportional to output.

Environmental regulation in input markets is based on pollution taxes (on producers or on consumers) or on emissions trading (ETS). Taxation is proportional to emissions and charged to the producers (emissions taxes) or to the consumers (to the input used to produce useful heat).

The pollution price, τ, is the charge per unit of pollutant emitted, namely the tax rate under taxation and the price of the tradable permits under emissions trading. The emission rate, $r > 0$, is the emission per unit of output.

The technologies are represented by their cost functions. We assume linear technologies whose cost per unit of output, q, is $c \geq 0$.

Firms have abatement technologies. Therefore the emission rate depends on τ and it is decreasing and convex, i.e., $\partial r(\tau)/\partial \tau < 0$, $\partial^2 r(\tau)/\partial \tau^2 > 0$ with $r(\tau) > 0$ for all τ. Total emissions are given by the emission rate multiplied by the output, $r \cdot q$, and consequently the total "pollution cost" is equal to the emissions multiplied by the pollution price, that is $r \cdot q \cdot \tau$. Following the literature on this topic (Requate 2005; Sugeta and Matsumoto 2007), the cost functions already incorporate the abatement opportunities. Pollution can be substituted for by using more of other abating inputs which in turn involve higher costs, that is $\partial c/\partial r < 0$. Furthermore, we assume that $\partial^2 c/\partial r^2 > 0$.

Under taxation, taxes will be charged to producers or to consumers. In the latter case, it is reasonable to assume that policymakers set the tax rate by adopting a reference (constant) emission rate. For instance it can be equal to the emission rate before taxation, $r(\tau) = r(0)$. Consequently, with taxes on consumers either the emission rate or the unit production cost does not depend on the tax rate, that is $r(\tau) = r(0)$ and $c(\tau) = c(0)$, $\forall \tau$.

Under ETS, permits are auctioned or allocated free of charge. Given these assumptions, the total cost function (conventional cost plus "pollution cost") for the technology cycle i will be

$$C_i(q_i, r_i, \tau) = c_i q_i + \tau \, r_i q_i - \tau \, \Gamma \tag{2.1}$$

where Γ is the amount of allowances allocated free of charge. This amount is calculated by setting a reference emission rate, r_{bn_i}, and a reference production level, $\bar{q}_i$. Then $\Gamma = r_{bn_i}\bar{q}_i$ and the average production cost will be

$$AC_i(q_i, r_i, \tau) = c_i + \tau\ r_i - \tau\ r_{bn_i}\gamma \tag{2.2}$$

where $\gamma = \bar{q}_i/q_i$ and $r_{bni} \in]0, r_i[$. The public authority chooses $\bar{q}_i$ on the basis of the historic production level (typical grandfathering) or on the basis of the expected (inertial) future production level. Obviously, $\bar{q}_i = 0$ under taxation and under the ETS with auctioning.

By differentiating (2.1) with respect to r_i, we get one of the first-order conditions for total cost minimization

$$\tau = -\frac{\partial c_i}{\partial r_i} \tag{2.3}$$

Therefore, given τ, a firm with inefficient abatement technology (higher $\left|\frac{\partial c_i}{\partial r_i}\right|$) chooses an abatement level lower than that chosen by a firm with efficient abatement technology.

Two groups of technological solutions are available, $i = a, b$, with $c_a < c_b$, $r_b < r_a$ or $r_b > r_a$ and $\left|\frac{\partial c_a}{\partial r_a}\right| < \left|\frac{\partial c_b}{\partial r_b}\right|$ or $\left|\frac{\partial c_a}{\partial r_a}\right| > \left|\frac{\partial c_b}{\partial r_b}\right|$ respectively. Furthermore, when $r_b < r_a$ there exists a pollution price, the "switching price," $\tau_s = (c_b - c_a)/(r_a - r_b)$, such that the marginal cost of the technology a, MC_a, is equal to that of the technology b, MC_b.

It is to be noted that, since $\tau = -\frac{\partial c_i}{\partial r_i}$ then $\frac{\partial MC_i}{\partial \tau} = r_i$.

Furthermore, under taxes on consumers, $MC_i = c_i + r_i(0)\ \tau$ with $i = a,\ b$.

To simulate market power a dominant firm with fringe model is adopted.[3] The leader (d) is more efficient since it operates only the technology a with lower production costs. Consequently, $c_d = c_a$ and $r_d = r_a$. The fringe (f)[4] operates only the technology b with higher production costs and therefore it is the less efficient, $c_f = c_b$ and $r_f = r_b$.

The leader and the fringe supply the market with capacity $\bar{q}_d = \bar{q}_a > 0$ and $\bar{q}_f = \bar{q}_b > 0$ respectively. Their levels of production are $q_d \in [0; \bar{q}_a]$ and $q_f \in [0; \bar{q}_b]$ respectively. The firms' capacities are exogenous and the fringe is capacity constrained while the dominant firm is able to serve the entire market alone, $\bar{q}_d = Q(c_d)$ and $\bar{q}_f < Q(c_f)$.

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[3] Several authors use this model in order to simulate the relationship between market power and environmental regulation. Among them: Conrad and Wang (1993), Chernyavs'ka and Gullì (2008), Gullì (2008), and Chernyavs'ka and Gullì (2009).

[4] It is to be noted that this model is well suited to simulate the structural features of several important environmentally regulated markets (e.g., energy markets).

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, emission rates as well as firms' installed capacity are common knowledge.

Throughout the analysis, efficient rationing is assumed. This means that, when the dominant firm (holding the most efficient technology) and the fringe set the same prices, the former serves the consumers first.

The indifference price of the input i, p_{n_i}, is that price which makes the final consumer indifferent when choosing between technology i and technology j.

For example, under symmetric taxes on consumers (input taxes applied to both the dominant and the fringe technologies), this price is obtained by solving the following equation

$$c_j + \tau\ r_j(0) = p_{n_i} + \tau\ r_i(0)$$

Then

$$p_{n_i} = c_j + \tau(r_j(0) - r_i(0))$$

Under symmetric taxes on producers, it is

$$p_{n_i} = c_j + \tau\ r_j(\tau)$$

and, since $\tau = -\partial c_j / \partial r_j$, then $\partial p_{n_i} / \partial \tau = r_j(\tau)$.

Finally if the prices of technology j are regulated and with ETS and free allocation of emissions allowances, we get

$$p_{n_i} = c_j + \tau\ r_j(\tau) - \tau\ r_{bn_j}\gamma$$

3 Impact on Pollution: Theoretical Analysis

By facing the fringe, the dominant firm will maximize its profit on the residual demand. Given the assumptions described in the previous section, this means that it will choose one of the following strategies: (1) setting prices above the indifference price so as to accommodate the fringe's maximum production (2) setting prices just below the indifference price and maximizing its market share.

By assumption, there will be an increase in market power when, because of the implementation of the environmental regulation, the dominant firm will move from the strategy (2) to the strategy (1). Inversely, there will be a decrease in market power if, because of the environmental regulation implementation, the dominant firm will move from strategy (1) to strategy (2).

The following Lemma describes the conditions under which the environmental regulation can decrease or increase market power.

Lemma 1. *(i) Under emissions taxes (or emissions trading) applied to the dominant firm, the environmental regulation can decrease market power if and only if*

$$d\Pi_u = \left(\frac{\partial p_{n_a}}{\partial \tau} - \frac{\partial MC_d}{\partial \tau}\right) - \alpha_1^2 \frac{\partial p_{n_a}}{\partial \tau} + \alpha_1 \frac{\partial MC_d}{\partial \tau} > 0 \tag{2.4}$$

where $\alpha_1 = \dfrac{\left(Q(p_r) - \bar{q}_f\right)}{Q(p_{n_a})}$ *and* $p_r = \arg\max_p \left[p(Q - \bar{q}_f) - C_d\right]$*;*

(ii) Inversely (increasing market power) when $d\Pi_u < 0$*;*

(iii) If $r_b < r_a$ *and* $\tau \geq \tau_s$ *then market power never decreases.*

Proof. See Appendix. The intuition is straightforward. For example, assume that $r_b < r_a$ and that, before the implementation of the environmental regulation, the dominant firm prefers to accommodate the fringe's maximum production. Neglecting the second-order terms, the first and second members of the right side of (2.4) represent the profit sensitivity of the dominant firm's strategy 2 (change in profit) per unit of dominant firm's maximum production. The second member is the profit sensitivity of the dominant firm's strategy 1 (loss of profit) per unit of dominant firm's maximum production. If the former is positive or, even if negative, is above the latter (the loss of profit of strategy 1 is lower than the loss of profit of strategy 2) then the dominant firm, after the environmental regulation implementation (and if the pollution price is enough high), will prefer to maximize its production. If the pollution price is very high, such that the leader becomes the less efficient firm (so losing its leadership cost), the latter strategy must be excluded.

Corollary 1. *If input taxes are applied to the dominant firm's consumers, the environmental regulation can decrease market power:*

(i) when input taxes are applied to both dominant firm's and fringe's consumers, if and only if

$$d\Pi_u = \left(\frac{\partial p_{n_a}}{\partial \tau} - \frac{\partial MC_d}{\partial \tau}\right) - \alpha_2^2 \left(\frac{\partial p_{n_a}}{\partial \tau} + r_b(0)\right) + \alpha_2 \left(\frac{\partial MC_d}{\partial \tau} + r_a(0)\right) > 0 \tag{2.5}$$

with $\alpha_2 = \dfrac{Q(p_r) - \bar{q}_f + r_a(0)\tau \partial Q/\partial p}{Q(p_{n_a}) + r_b(0)\tau \partial Q/\partial p}$

(ii) when input taxes are applied only to the dominant firm's consumers, if and only if

$$d\Pi_u = \left(\frac{\partial p_{n_a}}{\partial \tau} - \frac{\partial MC_d}{\partial \tau}\right) - \alpha_3^2 \frac{\partial p_{n_a}}{\partial \tau} + \alpha_3 \left(\frac{\partial MC_d}{\partial \tau} + r_a(0)\right) > 0 \tag{2.6}$$

with $\alpha_3 = \dfrac{Q(p_r) - \bar{q}_f + r_a(0)\tau \partial Q/\partial p}{Q(p_{n_a})}$*;*

Proof. See Appendix.

With increasing market power, before environmental policy ($\tau = 0$) the dominant firm (low-cost technology) serves the entire market:

$$\begin{cases} q_a(0) = Q(c_b) \\ q_b(0) = 0 \end{cases}$$

If τ is sufficiently high, after the environmental regulation, the dominant firm prefers to accommodate the fringe technology:

$$\begin{cases} q_a(\tau) = Q(\hat{p}_r(\tau)) - \bar{q}_f \\ q_b(\tau) = \bar{q}_f \end{cases}$$

where $\hat{p}_r = p_r$ under taxes on producers. Under taxes on consumers, $\hat{p}_r$ is the monopoly price on the net residual demand (net of the portion of demand corresponding to the increase in price due to the tax rate applied to consumers, see Appendix) plus the tax on consumers.

Then the change in pollution is:

$$\Delta E = r_b(\tau)\bar{q}_f + r_a(\tau)\left[Q(\hat{p}_r(\tau)) - \bar{q}_f\right] - r_a(0)Q(c_b) \tag{2.7}$$

Consequently, $\Delta E > 0$ if

$$\Delta E_{u_1} = \frac{\Delta E}{\bar{q}_f} = r_b(\tau) + r_a(\tau)\frac{\left[Q(\hat{p}_r(\tau)) - \bar{q}_f\right]}{\bar{q}_f} - r_a(0)\frac{Q(c_b)}{\bar{q}_f} > 0 \tag{2.8}$$

This condition is never satisfied if $r_b < r_a$. If $r_b > r_a$ it may be satisfied when the difference in emission rates between technologies is high (large environmental asymmetry of firms) and/or the price elasticity of demand is very low and abatement technologies are relatively inefficient.

Under imperfect competition and with decreasing market power, before the environmental policy ($\tau = 0$) the fringe exploits its maximum capacity and the dominant firm (operating the low-cost technology) supplies the residual demand:

$$\begin{cases} q_a(0) = Q(p_r(0)) - \bar{q}_f \\ q_b(0) = \bar{q}_f \end{cases}$$

If τ is sufficiently high, after the environmental regulation the dominant firm prefers to maximize its production:

$$\begin{cases} q_a(\tau) = Q(\hat{c}_b) \\ q_b(\tau) = 0 \end{cases}$$

The change in emissions is

$$\Delta E = r_a(\tau)(Q(\hat{c}_b) - r_a(0)\left[Q(p_r(0)) - \bar{q}_f\right] - r_b(0)\bar{q}_f \tag{2.9}$$

Then $\Delta E > 0$ if

$$\Delta E_{u_2} = \frac{\Delta E}{\bar{q}_f} = r_a(\tau)\frac{Q(\hat{c}_b)}{\bar{q}_f} - r_a(0)\frac{\left[Q(p_r(0)) - \bar{q}_f\right]}{\bar{q}_f} - r_b(0) > 0 \tag{2.10}$$

where $\hat{c}_b = c_b + r_b(\tau)\tau$ under emissions taxes on fringe's producers, $\hat{c}_b = c_b + r_b(0)\tau$ under input taxes on fringe's consumers and $\hat{c}_b = c_b + (r_b(\tau) - r_{bn_b}\gamma)\tau$ under ETS with free allocation and pricing regulation.

This condition is satisfied if $r_b < r_a$ and abatement technologies are relatively inefficient. If $r_b > r_a$ it may be satisfied especially when the difference in emission rates between technologies is low and/or the price elasticity of demand is relatively high and abatement technologies are relatively inefficient.

The results described above can be summarized as follows:

Lemma 2. *(i) If* $r_b < r_a$ *decreasing market power is necessary condition for increasing pollution; (ii) If* $r_b > r_a$ *the outcome is ambiguous.*

Proof. See (2.7)–(2.10).

Given Lemma 2, the probability of increasing pollution can be estimated by using condition (2.4) [or (2.5) or (2.6)] and conditions (2.8) and (2.10) simultaneously.

In the following Subsections, firstly symmetric regulation will be taken into account (the same environmental tool applied to different supply technologies). Subsequently, hybrid solutions will be investigated (different environmental tools applied to the different technological solutions).

3.1 Symmetric Regulation

Symmetric regulation arises when the same environmental tool is applied to different technologies.

3.1.1 Symmetric Taxes on Consumers

In this case pollution taxes are directly applied to the input purchased by final consumers. For example, if the space heating technology is based on the use of natural gas boilers, taxes are charged to natural gas consumption (monetary charge per unit of natural gas consumed).

However, it is reasonable to assume that policymakers choose the input tax by looking at the emissions rate before the implementation of environmental regulation. Therefore, the input tax can be expressed as $\tau\ r_i(0)$.

Under symmetric taxes on consumers, the indifference price is obtained by solving the following equation:

$$c_b + \tau\ r_b(0) = p_{n_a} + \tau\ r_a(0)$$

Then

$$p_{n_a} = c_b + \tau(r_b(0) - r_a(0))$$

Since $\dfrac{\partial c_b}{\partial \tau} = 0$, the dominant firm's indifference price sensitivity to pollution price will be

$$\frac{\partial p_{n_a}}{\partial \tau} = r_b(0) - r_a(0)$$

and, since no tax is applied to producers, the dominant firm's cost sensitivity to pollution price will be

$$\frac{\partial MC_d}{\partial \tau} = 0$$

Then from Corollary 1 (2.5), the condition for decreasing market power is:

$$r_b(0) > r_a(0)\frac{1 - \alpha_2^2 - \alpha_2}{1 - 2\alpha_2^2}$$

If $r_b < r_a$ decreasing market power is admissible provided that the difference in emissions rates is very low. Therefore, increasing pollution is admissible although it seems to be unlikely.

If $r_b > r_a$ it is very likely that $d\Pi_u > 0$. Consequently, from condition (2.10), increasing pollution is admissible when the difference in emission rates between technologies is low and/or the price elasticity of demand is high provided that abatement technologies are sufficiently inefficient.

3.1.2 Symmetric Taxes on Producers (or ETS with Auctioning)

In this case, taxes are applied to producers and are proportional to emissions. This time the emissions rate depends on the pollution price. It is also to be noted that taxes on producers are equivalent to ETS with auctioning.

Under symmetric taxes on producers (or symmetric ETS with auctioning), the indifference price is

$$p_{n_a} = c_b(\tau) + \tau\, r_b(\tau)$$

Since from (2.3) $\tau = -\dfrac{\partial c_b}{\partial r_b}$, the indifference price sensitivity to pollution price is

$$\frac{\partial p_{n_a}}{\partial \tau} = r_b(\tau)$$

and, since $\tau = -\dfrac{\partial c_a}{\partial r_a}$, the dominant firm's cost sensitivity to pollution price is:

$$\frac{\partial MC_d}{\partial \tau} = r_a(\tau)$$

Then from Lemma 1, the condition for decreasing market power is

$$r_b(\tau) > r_a(\tau)\frac{1}{1+\alpha_1}$$

Therefore, if $r_b < r_a$ increasing pollution is admissible provided that abatement technologies are relatively inefficient.

If $r_b > r_a$ the condition for decreasing market power is satisfied always. Pollution can increase if the difference in emissions rates is low and abatement technologies are sufficiently inefficient.

It is to be noted that $1/(1+\alpha_1)$ may be lower than $(1-\alpha_2^2-\alpha_2)/(1-2\alpha_2^2)$ when $\alpha_2 < \alpha_1$. Since this always occurs if $r_b < r_a$ then decreasing market power (and consequently increasing pollution) might be more likely under taxes on producers than under taxes on consumers. When $r_b > r_a$ this can occur if the difference in emissions rate is relatively low. Otherwise (sufficiently large environmental asymmetry) increasing emissions is more likely with taxes on consumers.

3.1.3 Symmetric ETS with Free Allocation of Emissions Allowances

Under ETS with free allocation, emissions allowances are allocated free of charge to polluters. The amount of these allowances (expressed in terms of emissions) is equal to the reference emissions rate multiplied by the reference level of production.

In this case it is necessary to distinguish two scenarios of fringe's technology pricing: unregulated prices and regulated prices.

When unregulated, fringe's prices converge to marginal costs. Therefore

$$p_{n_a} = c_b(\tau) + \tau\, r_b(\tau)$$

and, since $\tau = -\frac{\partial c_b}{\partial r_b}$, the fringe's indifference price sensitivity to pollution price is:

$$\frac{\partial p_{n_a}}{\partial \tau} = r_b(\tau)$$

At the same time, since $\tau = -\frac{\partial c_a}{\partial r_a}$, the dominant firm's marginal cost sensitivity to pollution price will be:

$$\frac{\partial MC_d}{\partial \tau} = r_a(\tau)$$

Consequently, from Lemma 1 (2.4) the condition for decreasing market power is

$$r_b(\tau) > r_a(\tau)\frac{1}{1+\alpha_1}$$

Therefore, if $r_b < r_a$ increasing pollution is admissible provided that abatement technologies are not particularly efficient.

If $r_b > r_a$ the condition for decreasing market power is satisfied always. Pollution can increase if the difference in emissions rates is low and abatement technologies are sufficiently inefficient.

Under regulated prices, when prices are equal to the average production cost, the fringe's indifference price is obtained by solving the following equation [from (2.2)]:

$$p_{n_a} = c_b(\tau) + \tau\ r_b(\tau) - \tau\ r_{bn_b}\gamma$$

Then by differentiating the previous equation and given that $\tau = -\frac{\partial c_b}{\partial r_b}$, the indifference price sensitivity will be

$$\frac{\partial p_{n_a}}{\partial \tau} = r_b(\tau) - r_{bn_b}\gamma$$

It is to be noted that γ does not depend on pollution price. In fact we assume that the sector-specific authority set regulated prices by looking at the production level before the change in pollution price (or before the implementation of the environmental policy)

The dominant firm's cost sensitivity to pollution price is

$$\frac{\partial MC_d}{\partial \tau} = r_a(\tau)$$

Consequently, the condition for decreasing market power (from Lemma 1) becomes

$$r_b(\tau) > r_a(\tau)\frac{1}{1+\alpha_1} + r_{bn_b}\gamma$$

If $r_b < r_a$, decreasing market power and increasing pollution are admissible. However they seem to be very unlikely, at least in principle.

If $r_b > r_a$, the condition for decreasing market power is satisfied if the difference in emissions rates is relatively high. However, in this case, increasing pollution is very unlikely [see (2.10)]. Inversely, market power can increase if

$$r_b(\tau) < r_a(\tau)\frac{1}{1+\alpha_1} + r_{bn_b}\gamma$$

This condition is satisfied if the difference in emissions rates is low. However, this drastically reduces the probability of increasing pollution.

In conclusion, increasing pollution seems to be very unlikely.

3.2 Hybrid Regulation

Hybrid regulation arises when different environmental tools are applied to different competing technologies.

3.2.1 Taxes on Consumers Versus Taxes on Producers (or ETS with Auctioning)

Two cases have to be analyzed: (1) taxes on the dominant firm's consumers and taxes on the fringe's producers (or ETS with auctioning); (2) taxes on the fringe's consumers and taxes on the dominant firm's producers (or ETS with auctioning).

In the first case, the indifference price sensitivity to pollution price is

$$\frac{\partial p_{n_a}}{\partial \tau} = r_b(\tau) - r_a(0)$$

and the dominant firm's cost sensitivity to pollution price is

$$\frac{\partial MC_d}{\partial \tau} = 0$$

Consequently, from Corollary 1 (2.6):

$$r_b(\tau) > r_a(0)\frac{1-\alpha_3^2-\alpha_3}{1-\alpha_3^2}$$

If $r_b < r_a$ market power can decrease provided that the environmental asymmetry between firms is sufficiently restricted. Therefore, increasing pollution is admissible.

If $r_b > r_a$ then $d\Pi_u > 0$ always. However, increasing pollution is admissible when the difference in emission rates between technologies is low and/or the price elasticity of demand is sufficiently high provided that abatement technologies are sufficiently inefficient.

It is to be noted that $1/(1+\alpha_1)$ may be lower than $(1-\alpha_3^2-\alpha_3)/(1-\alpha_3^2)$ when $\alpha_3 < \alpha_1$. Since this always occurs always (regardless of whether $r_b < r_a$ or $r_b > r_a$) then decreasing market power (and consequently increasing pollution) might be more likely under taxes on producers than under taxes on consumers.

In the second case:

$$\frac{\partial p_{n_a}}{\partial \tau} = r_b(0)$$

and

$$\frac{\partial MC_d}{\partial \tau} = r_a(\tau)$$

The condition for decreasing market power (2.4) is

$$r_b(0) > r_a(\tau)\frac{1}{1+\alpha_1}$$

Therefore, if $r_b < r_a$, increasing pollution is admissible. If $r_b > r_a$, this condition is always satisfied. Increasing pollution is admissible provided that the difference in emissions rate is low, abatement technologies are inefficient, and the price elasticity of demand is high.

It is to be noted that, this time, decreasing market power (and consequently increasing pollution) may be more likely under taxes on consumers than under taxes on producers.

3.2.2 Taxes on Producers (or ETS with Auctioning) Versus ETS with Free Allocation of Emissions Allowances

Three relevant combinations of environmental regulation have to be analyzed: (1) taxes on dominant firm's production (or ETS with auctioning) and ETS with free allocation on fringe's producers with unregulated fringe's prices; (2) taxes on dominant firm's production (or ETS with auctioning) and ETS with free allocation on fringe's producers with regulated fringe's prices; (3) ETS on dominant firm production and taxes on fringe's producers (or ETS with auctioning).

In the first case, the indifference price sensitivity to pollution price is:

$$\frac{\partial p_{n_a}}{\partial \tau} = r_b(\tau)$$

and the dominant firm's cost sensitivity to pollution price is

$$\frac{\partial MC_d}{\partial \tau} = r_a(\tau)$$

Consequently, the result is the same than under symmetric taxes on producers. The condition for decreasing market power (2.4) is:

$$r_b(\tau) > r_a(\tau)\frac{1}{1+\alpha_1}$$

If $r_b < r_a$, decreasing market power and increasing pollution are admissible.

If $r_b > r_a$, market power decreases always. Increasing pollution is admissible if the difference in emissions rates is low and abatement technologies are inefficient and price elasticity of demand is high.

In the second case, the indifference price sensitivity to pollution price is

$$\frac{\partial p_{n_a}}{\partial \tau} = r_b(\tau) - r_{bn_b}\gamma$$

The dominant firm's cost sensitivity to pollution price is

$$\frac{\partial MC_d}{\partial \tau} = r_a(\tau)$$

Consequently, the condition for decreasing market power (2.4) becomes:

$$r_b(\tau) > r_a(\tau)\frac{1}{1+\alpha_1} + r_{bn_b}\gamma$$

If $r_b < r_a$, increasing pollution is admissible but very unlikely.

If $r_b > r_a$, market power decreases only if the difference in emissions rates is high. However, in this case, the probability of increasing pollution is low. Inversely, increasing market power is likely if the difference in emissions rates is low. Once again this reduces the probability of increasing pollution. In conclusion, increasing pollution is admissible but very unlikely.

Finally, in the third case

$$\frac{\partial p_{n_a}}{\partial \tau} = r_b(\tau)$$

and the dominant firm's cost sensitivity to pollution price is

$$\frac{\partial MC_d}{\partial \tau} = r_a(\tau)$$

Consequently, the condition for increasing pollution (2.4) is

$$r_b(\tau) > r_a(\tau)\frac{1}{1+\alpha_1}$$

If $r_b < r_a$, increasing pollution is admissible. If $r_b > r_a$, this condition is satisfied always. Therefore, increasing pollution is admissible provided that the difference in emissions rate is low and abatement technologies are inefficient.

3.2.3 Taxes on Consumers Versus ETS with Free Allocation of Emissions Allowances

Three relevant hybrid combinations arise: (1) taxes on the dominant firm's consumers and ETS with free allocation to fringe's producers, when fringe's prices are unregulated; (2) taxes on the dominant firm's consumers and ETS with free allocation to the fringe's consumers, when fringe's prices are regulated; (3) taxes on fringe's consumers and ETS with free allocation to the dominant firm's producers.

In the first case

$$\frac{\partial p_{n_a}}{\partial \tau} = r_b(\tau) - r_a(0)$$

and $\frac{\partial MC_d}{\partial \tau} = 0$. Then from Corollary 1 (2.6):

$$r_b(\tau) > r_a(0)\frac{1-\alpha_3^2-\alpha_3}{1-\alpha_3^2}$$

If $r_b < r_a$, market power can decrease if the difference in emissions rates is low. Therefore, increasing pollution is admissible.

If $r_b > r_a$, then this condition is always satisfied ($d\Pi_u > 0$ always). Consequently, increasing pollution is admissible. However, this requires that the difference in emission rates between technologies is low and/or the price elasticity of demand is high. Furthermore, abatement technologies must be sufficiently inefficient.

In the second case,

$$\frac{\partial p_{n_a}}{\partial \tau} = r_b(\tau) - r_{bn_b}\gamma - r_a(0)$$

and $\dfrac{\partial MC_d}{\partial \tau} = 0$. Then, from (2.6) the condition for decreasing market power becomes:

$$r_b(\tau) > r_a(0)\frac{1-\alpha_3^2-\alpha_3}{1-\alpha_3^2} + r_{bn_b}\gamma$$

Therefore, if $r_b < r_a$, increasing pollution is admissible but very unlikely. If $r_b > r_a$, it is admissible. However, the condition for decreasing market power is satisfied if the difference in emissions rates is very high. But in this case the probability of increasing pollution is very low. Inversely, market power increases if the difference in emissions rates is very low. Once again, this drastically reduces the probability of increasing pollution. In conclusion, increasing emissions is very unlikely.

In the third case, this time taxes are directly charged to the fringe's consumers. The indifference price is

$$\frac{\partial p_{n_a}}{\partial \tau} = r_b(0)$$

and

$$\frac{\partial MC_d}{\partial \tau} = r_a(\tau)$$

The condition for decreasing market power (2.4) is

$$r_b(0) > r_a(\tau)\frac{1}{1+\alpha_1}$$

If $r_b < r_a$, increasing pollution is admissible. If $r_b > r_a$, this condition is satisfied always. Therefore, market power decreases always. This leads to increased pollution if the difference in emissions rates is low and abatement technologies are inefficient and price elasticity of demand is high.

3.3 The Overall Framework

Tables 2.1, 2.2, and 2.3 summarize the results described in the previous Subsections. Table 2.1 reports the parameters used to calculate the probability of increasing or decreasing market power. Tables 2.2 and 2.3 summarize the probability of increasing pollution in qualitative terms.

The following considerations arise:

1. Increasing pollution is admissible in principle. Furthermore, it does not require large (environmental) asymmetry of firms. Rather in most cases low asymmetry of firms is necessary.
2. Increasing pollution might be less likely under input taxes on consumers than under emission taxes (or ETS with auctioning) on producers.

Table 2.1 Parameters

	Dominant firm		
Fringe	Taxes on consumers	Taxes on producers or ETS with auctioning	ETS with free allocation
Taxes on consumers	$\frac{\partial p_{n_a}}{\partial \tau} = r_b(0) - r_a(0)$ $\frac{\partial MC_d}{\partial \tau} = 0$	$\frac{\partial p_{n_a}}{\partial \tau} = r_b(0)$ $\frac{\partial MC_d}{\partial \tau} = r_a(\tau)$	$\frac{\partial p_{n_a}}{\partial \tau} = r_b(0)$ $\frac{\partial MC_d}{\partial \tau} = r_a(\tau)$
Taxes on producers or ETS with auctioning	$\frac{\partial p_{n_a}}{\partial \tau} = r_b(\tau) - r_a(0)$ $\frac{\partial MC_d}{\partial \tau} = 0$	$\frac{\partial p_{n_a}}{\partial \tau} = r_b(\tau)$ $\frac{\partial MC_d}{\partial \tau} = r_a(\tau)$	$\frac{\partial p_{n_a}}{\partial \tau} = r_b(\tau)$ $\frac{\partial MC_d}{\partial \tau} = r_a(\tau)$
ETS with free allocation (unregulated prices)	$\frac{\partial p_{n_a}}{\partial \tau} = r_b(\tau) - r_a(0)$ $\frac{\partial MC_d}{\partial \tau} = 0$	$\frac{\partial p_{n_a}}{\partial \tau} = r_b(\tau)$ $\frac{\partial MC_d}{\partial \tau} = r_a(\tau)$	$\frac{\partial p_{n_a}}{\partial \tau} = r_b(\tau)$ $\frac{\partial MC_d}{\partial \tau} = r_a(\tau)$
ETS with free allocation (regulated prices)	$\frac{\partial p_{n_a}}{\partial \tau} = r_b(\tau) - r_{bn_b}\gamma - r_a(0)$ $\frac{\partial MC_d}{\partial \tau} = 0$	$\frac{\partial p_{n_a}}{\partial \tau} = r_b(\tau) - r_{bn_b}\gamma$ $\frac{\partial MC_d}{\partial \tau} = r_a(\tau)$	$\frac{\partial p_{n_a}}{\partial \tau} = r_b(\tau) - r_{bn_b}\gamma$ $\frac{\partial MC_d}{\partial \tau} = r_a(\tau)$

Table 2.2 Probability of increasing pollution $(r_b < r_a)$

	Dominant firm		
Fringe	Taxes on consumers	Taxes on producers or ETS with auctioning	ETS with free allocation
Taxes on consumers	Admissible (low environmental asymmetry)	Admissible	Admissible
Taxes on producers or ETS with auctioning	Admissible (low environmental asymmetry)	Admissible	Admissible
ETS with free allocation (unregulated prices)	Admissible (low environmental asymmetry)	Admissible	Admissible
ETS with free allocation (regulated prices)	Admissible (very unlikely)	Admissible (very unlikely)	Admissible (very unlikely)

Table 2.3 Probability of increasing pollution $(r_b > r_a)$

	Dominant firm		
Fringe	Taxes on consumers	Taxes on producers or ETS with auctioning	ETS with free allocation
Taxes on consumers	Admissible (low environmental asymmetry)	Admissible (low environmental asymmetry)	Admissible (low environmental asymmetry)
Taxes on producers or ETS with auctioning	Admissible (low environmental asymmetry)	Admissible (low environmental asymmetry)	Admissible (low environmental asymmetry)
ETS with free allocation (unregulated prices)	Admissible (low environmental asymmetry)	Admissible (low environmental asymmetry)	Admissible (low environmental asymmetry)
ETS with free allocation (regulated prices)	Admissible (very unlikely)	Admissible (very unlikely)	Admissible (very unlikely)

3. Free allocation of emissions allowances combined with pricing regulation drastically reduces the probability of increasing pollution.
4. Hybrid regulation can play a significant role in affecting the probability that environmental policy could lead to increased emissions. Nevertheless, this role is ambiguous. Compared to symmetric regulation, hybrid regulation can increase or decrease the probability of increasing pollution depending on several factors.
5. Increasing pollution (where admissible) seems to be relatively likely in several situations where the dominant technology is highly polluting (more polluting than the fringe technology).

The main findings are summarized by the following proposition and corollary.

Proposition 1. *(i) Increasing pollution is widely admissible in principle. (ii) Its probability might be lower with input taxes on consumers and (ii) decreases with free allocation of emissions allowances. (iii) The role of hybrid regulation is significant but ambiguous.*

Proof. See Tables 2.2 and 2.3.

Finally, it is to be noted that, if the dominant technology is more polluting than the fringe one, increasing pollution is admissible and seems to be likely, unless input taxes are applied to the dominant firm's consumers.

This result suggests that when polarized configurations are due to energy policies promoting the deployment of cleaner technologies (fringe technologies), the implementation of environmental regulation may lead to a dual perverse effect. This may increase the risk that the dominant firm prefers to undercut the cleaner technology rather than to accommodate its production at the same time leading to increasing rather than decreasing pollution.

4 Impact on Pollution: Simulations

The analysis described above highlights that increasing pollution is admissible in principle in most combinations of environmental regulation. A last question remains: where admissible, how much is it really likely?

To answer this question, it is helpful to carry out the simulation of the typical cases of space heating which can be appropriately described by the dominant firm with fringe model.

Three possible technological solutions (natural gas boilers, district heating, and electric heat pumps) are simulated:

1. Natural gas fired boiler (technology 1). When this cycle is used, most part of pollution occurs in the consumption stage. This is the reasons why the most likely environmental regulation of this cycle is based on taxes applied to consumers (input taxes on natural gas consumption).
2. Combined Heat and Power (CHP) district heating using natural gas (technology 2). In this case, the useful heat for space heating is produced by a CHP plant located

Table 2.4 Technical parameters used for simulations (*)

		Natural gas boiler (1)	District Heating (CHP-gas) (2)	Electric Heat Pump (3)
$\bar{r}_i(0)$	tCO_2/MWh	0.30	0.20	0.10
c_a	€/MWh		30	
c_a/c_a			1.0	
c_b/c_a			1.5	
σ_b	tCO_2/MWh		0.05	
Cost function			$MC_i/c_a = c_i/c_a + (r_i\tau)/c_a$	
Emission rate function			$r_b(\tau) = \bar{r}_b(0) \cdot \exp(-0.007 \cdot \tau)$ $r_a(\tau) = \bar{r}_a(0) \cdot \exp(-0.01 \cdot \tau)$	
r_{bn_i}	tCO_2/MWh		$\bar{r}_i(0)$	
γ			0.8	
$\bar{q}_f$			$0.3 \cdot Q(c_a/c_a)$	
Inverse demand function			$p/c_a = 4 - 0.5 \cdot Q(p/c_a)$	

(*) Parameters account for the energy conversion efficiency (the ratio between the useful heat and the input)

relatively far from the consumers. Then the generated heat is transported over relatively long distances by means of a grid of pipelines and delivered to final consumers. Most pollution is concentrated in the generation stage (by the CHP plant). Therefore, almost all environmental tools can be applied. However, ETS with free allocation of allowances is most likely (this is the regulation adopted by the EU-ETS). In this case, we assume that the advantage due to free allocation is entirely attributed to heat production.

3. Heat pump using electricity generated by gas-fired power installations (technology 3). This typology of heat supply provides significant energy savings. The useful heat is produced by converting electricity in the consumption stage. Pollution is concentrated in the generation (power generation) stage. The efficiency of this cycle is given by the COP (Coefficient of Performance) which is equal to the useful heat produced divided by the electricity consumption of the heat pump. Even in this case, almost all environmental tools can be applied; however, ETS with auctioning of emissions allowances is the most likely of them. Finally, for the sake of simplicity, it is assumed that the power spot market (including only gas-fired power plants) is entirely "dedicated" to serve the space heating market.

Table 2.4 reports the technical and economic parameters related to each technology analyzed.

Given a specific technology, it is assumed that the fringe's emission rate is distributed normally around the corresponding mean value with a standard deviation σ_b. This distribution allows us to account for the dispersion of energy efficiency of different technological solutions: the dispersion of the electric efficiency of CHP district heating and power installations; the different possible coefficient of performance (COP) of electric heat pumps; the dispersion of thermal efficiency of gas-fired boilers.

The probability of increasing pollution is estimated by using the following procedure. In the same graph the condition for change in market power ($d\Pi_u$) and the condition for change in pollution (ΔE_u) are depicted (in terms of cumulative distributions). If the former is positive (negative), decreasing (increasing) market power is admissible. If the latter is positive (negative), increasing (decreasing) pollution is admissible. Then increasing pollution will occur when $d\Pi_u < 0$ combines with $\Delta E_{u_1} > 0$ or when $d\Pi_u > 0$ combines with $\Delta E_{u_2} > 0$. Obviously, since $d\Pi_u > 0$ (decreasing market power) is necessary condition for increasing pollution when $r_b < r_a$, in this case the probability of increasing emissions can be estimated by depicting just the probability of change in pollution when market power decreases (2.10). Furthermore, if $r_b < r_a$ and $d\Pi_u < 0$ always, pollution never increases.

By using this procedure, the expressions in Table 2.1 and the values in Table 2.4, the cumulative distributions illustrated in Figs. 2.1, 2.2, 2.3, 2.4, 2.5, and 2.6 follow.

These figures suggest the following considerations:

1. When the natural gas boiler is the dominant technology, there is a significant probability of increasing pollution only when the fringe technology is district heating and provided that the fringe's prices are not regulated. If the fringe technology is heat pump, increasing pollution is excluded or very unlikely. This confirms the theoretical findings. In fact, the most likely regulation of natural gas cycles is based on taxes on consumers since most part of pollution is concentrated in the stage of natural gas conversion to useful heat (by means of heat boilers directly exploited by consumers purchasing the energy input). Therefore, the numerical simulations confirm that under input taxes on consumers the probability of increasing emissions may be relatively low, especially if the dominant technology is more polluting than the fringe one.
2. When district heating is the dominant technology, increasing pollution is relatively likely under all combinations of environmental regulation. If the fringe technology is the natural gas boiler ($r_b > r_a$), the probability of increasing pollution is higher under symmetric taxes on consumers than under taxes on producers. If the fringe technology is heat pump ($r_b < r_a$), increasing pollution is less likely under symmetric taxes on consumers than under symmetric taxes on producers. These results confirm the theoretical predictions.
3. If the electric heat pump is the dominant technology, increasing pollution is excluded or very unlikely in all combinations of technologies and regulation.
4. Overall increasing pollution is virtually excluded or very unlikely in many situations where it is admissible in principle.
5. The numerical simulations also confirm that increasing pollution, where admissible, is more likely when the environmental asymmetry between firms is low. In fact the probability of increasing pollution becomes positive for high values of the cumulative distributions if $r_b < r_a$ (these values correspond to low difference

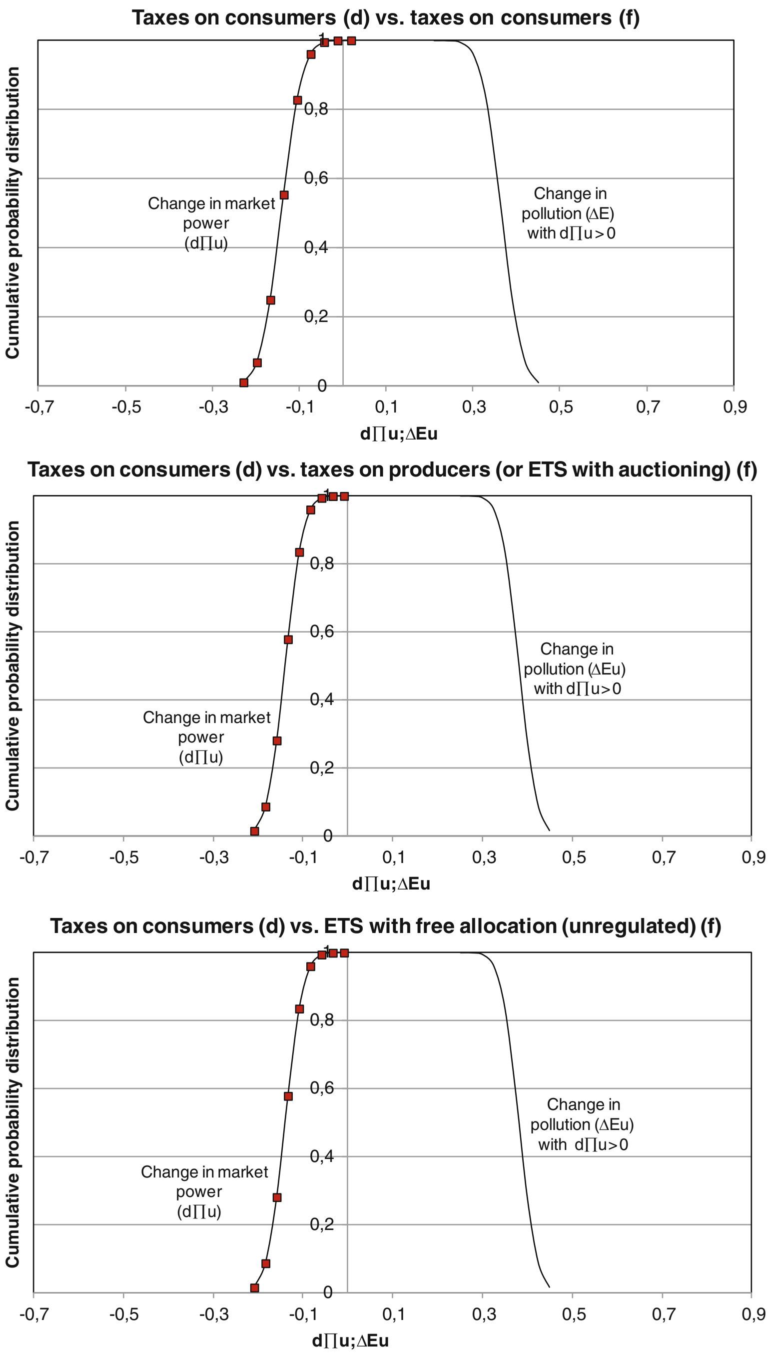

Fig. 2.1 Natural gas boiler (d) vs. heat pump (f) $(r_b < r_a)$

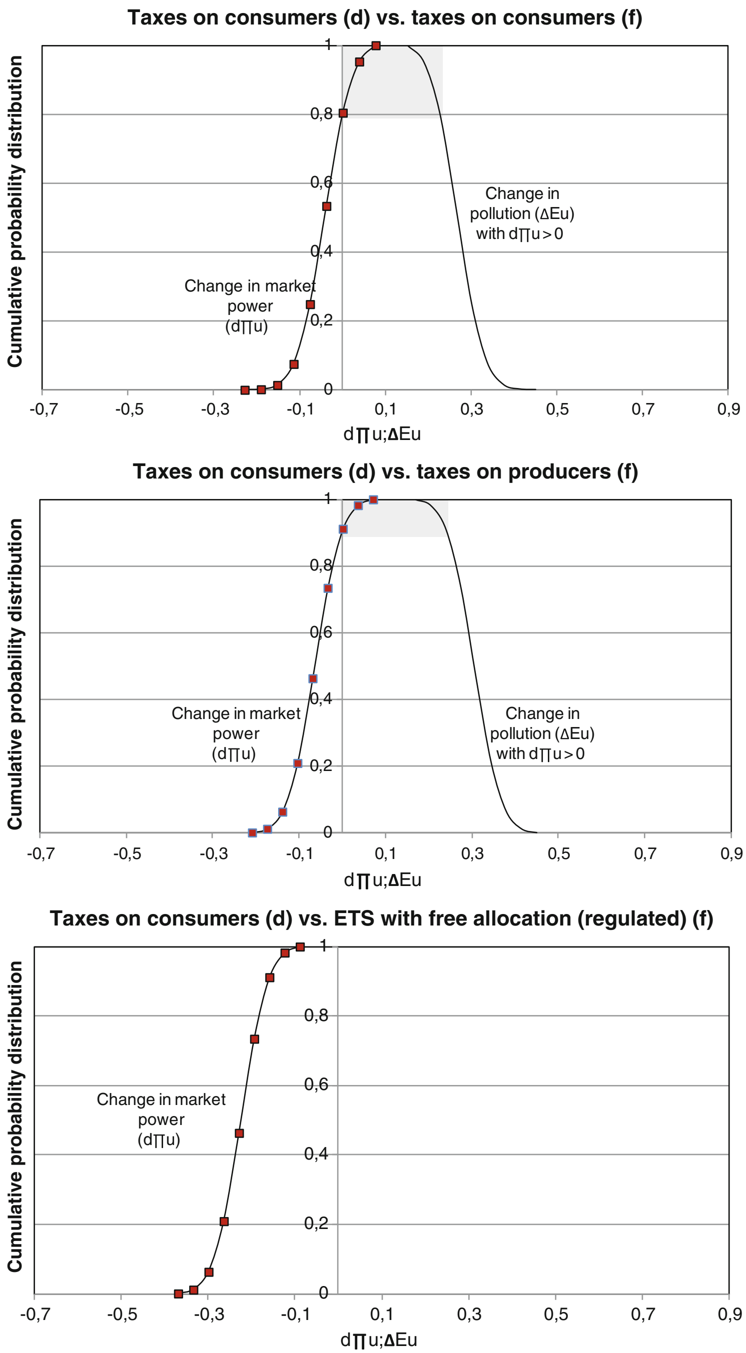

Fig. 2.2 Natural gas boiler (*d*) vs. district heating (*f*) $(r_b < r_a)$

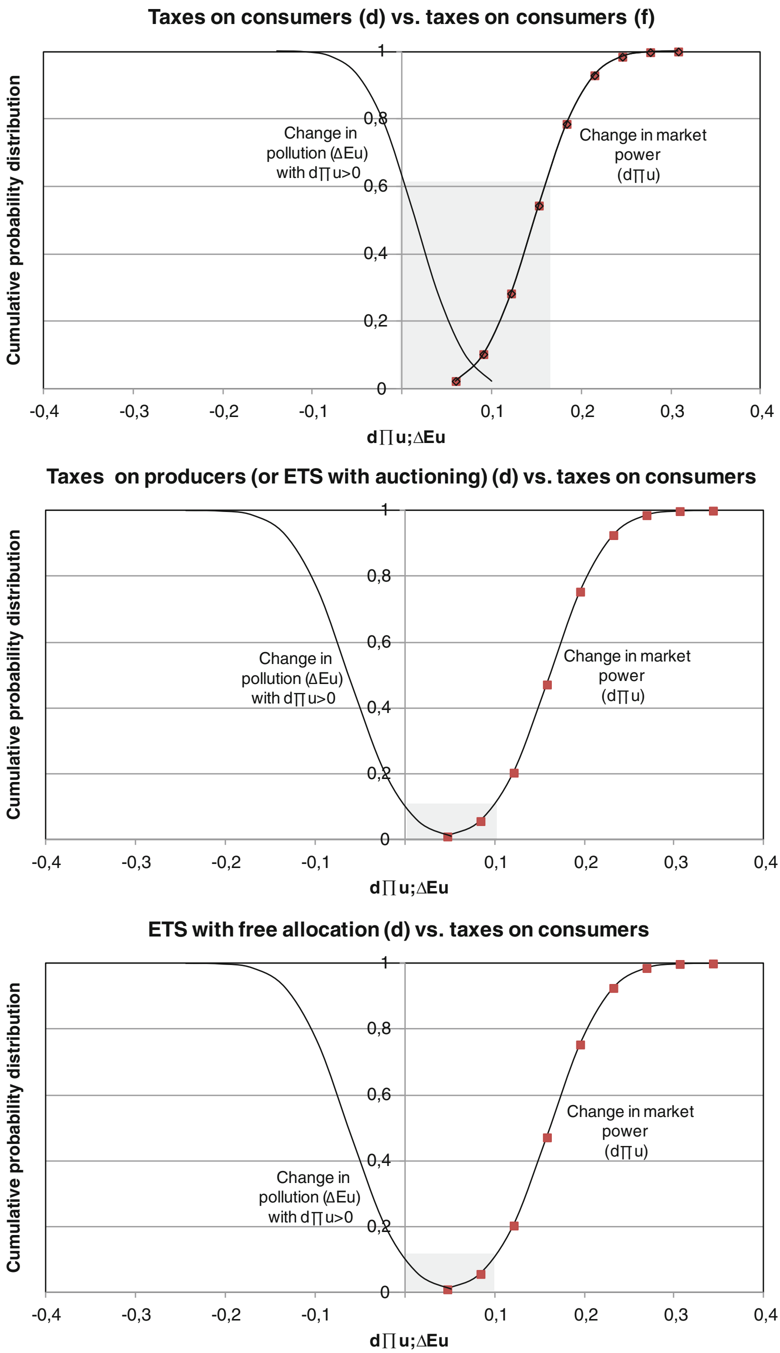

Fig. 2.3 District heating (*d*) vs. natural gas boiler (*f*) ($r_b > r_a$)

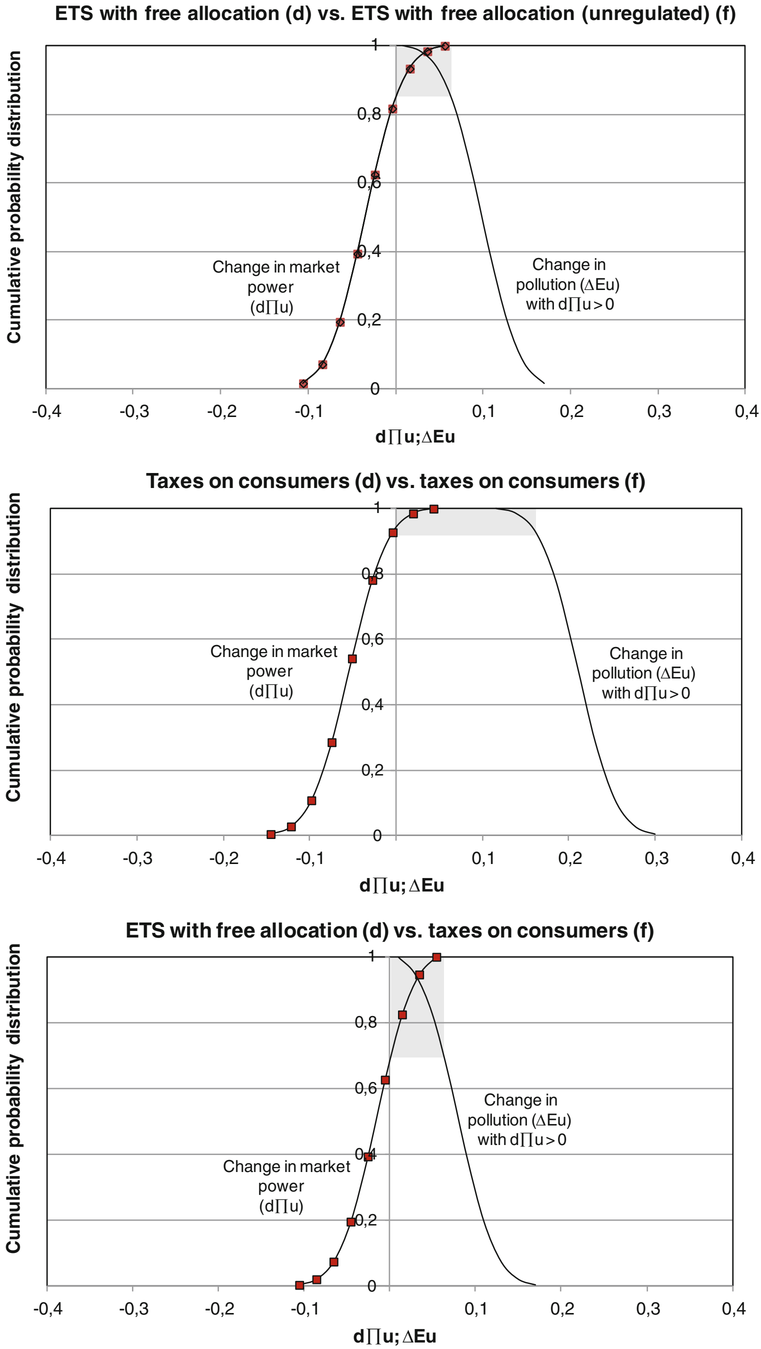

Fig. 2.4 District heating (*d*) vs. heat pump (*f*) ($r_b < r_a$)

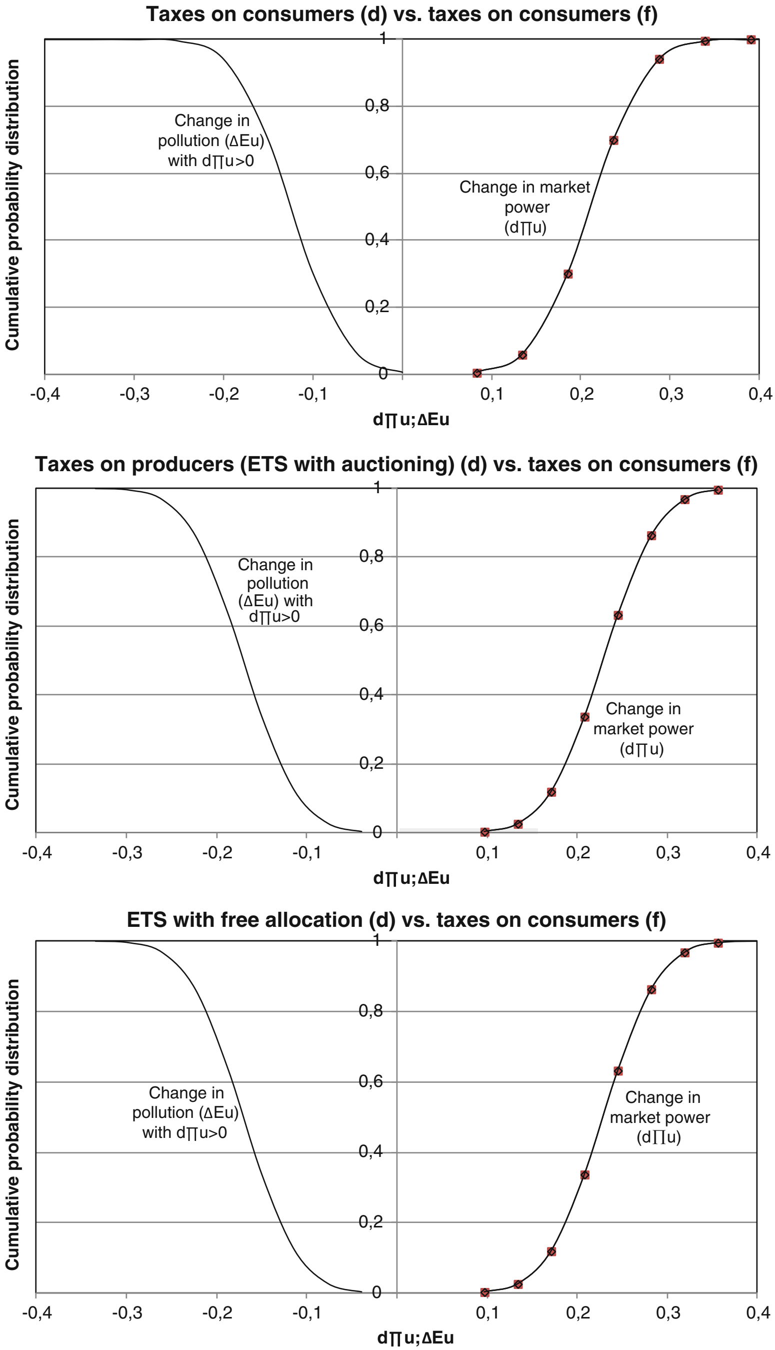

Fig. 2.5 Heat pump (*d*) vs. natural gas boiler (*f*) $(r_b > r_a)$

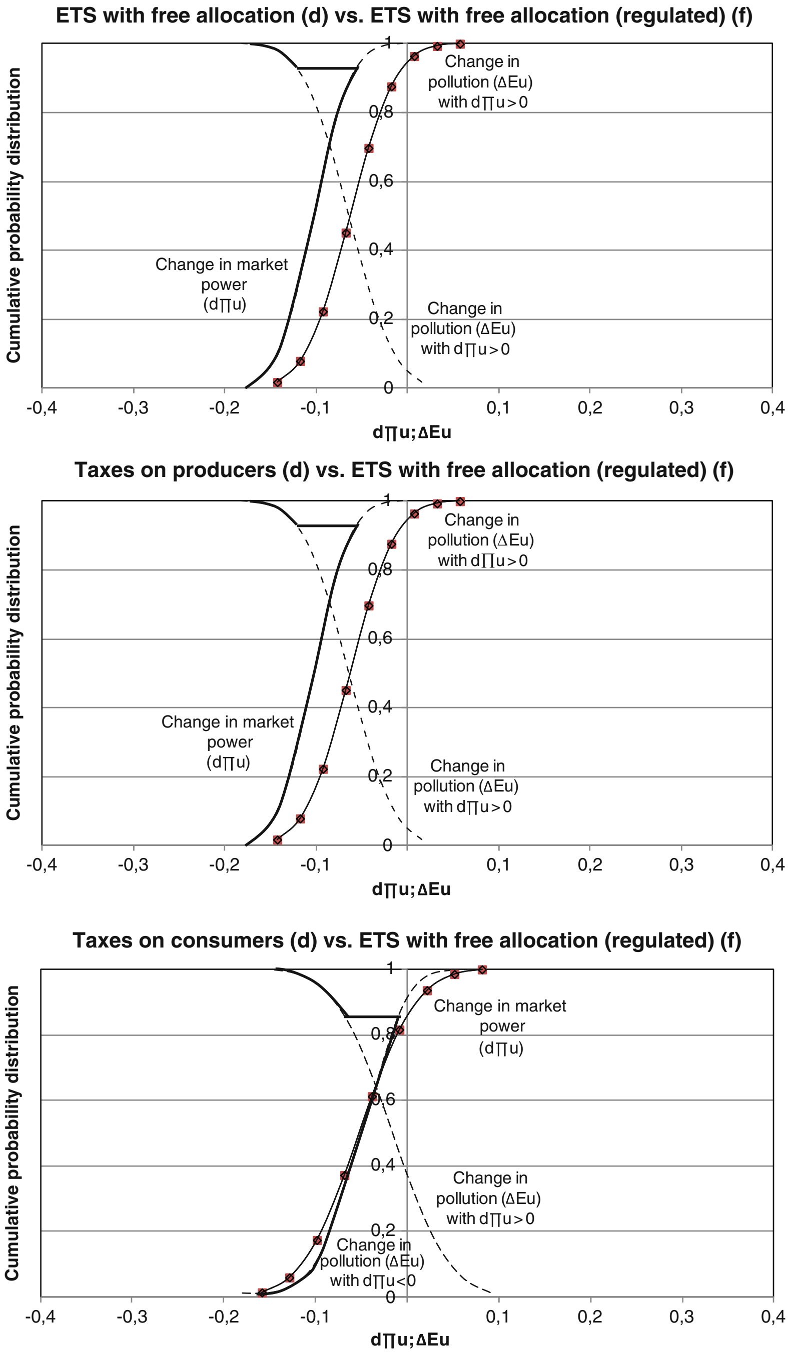

Fig. 2.6 Heat pump (*d*) vs. district heating (*f*) $(r_b > r_a)$

of emissions rates) and for low values of the cumulative distributions if $r_b > r_a$ (these values correspond to low difference of emissions rates).

Overall, numerical simulations only partially confirm the theoretical results. Increasing pollution is unlikely or very unlikely in several situations where it is theoretically admissible.

In addition, the simulations highlight that the perverse effect of environmental policy is admissible in several situations where the dominant technology is more polluting than the fringe technology. However, in these situations its probability is relatively restricted.

This only partially confirms the risk that environmental policies, within polarized situations due to energy policies promoting low polluting technologies, could have a dual perverse effect, as suggested by the theoretical model.

5 Conclusions

This chapter analyses how environmental regulation works in imperfectly competitive markets with dominant firm. The focus is on space heating, a service sector in which different technological solutions can coexist. Consequently, environmental regulation may be hybrid. In fact different environmental tools (alone or combined) can be applied to the coexisting technological cycles.

In line with part of the current literature, the theoretical analysis proves that environmental regulation may increase pollution at least in principle. However, this analysis also demonstrates that this result does not require either extreme curvature (sharp concavity) of the inverse demand function or sufficiently large (environmental) asymmetry of firms.

In addition, some apparently counterintuitive results arise. Firstly, under taxation the perverse effect might be more likely if taxes are charged to producers rather than to consumers whereas common sense would suggest that taxation should always work better when regulation is able to stimulate emissions abatement and not only the decrease in demand through the impact on prices. Secondly, free allocation of emissions allowances (combined with pricing regulation) drastically reduces the probability of increasing pollution.

Finally, hybrid regulation seems to play a significant role in affecting the probability that environmental policy could lead to a perverse effect (or could avoid it). Nevertheless, this role is ambiguous. Compared to symmetric regulation, hybrid regulation can increase or decrease the probability of increasing pollution depending on several factors.

The numerical simulations only partially confirm the theoretical results. In fact, in several situations where increasing pollution is theoretically admissible, it is virtually excluded or very unlikely in reality.

In addition, the simulations highlight that the perverse effect of environmental policy is admissible in several situations where the dominant technology is more polluting than the fringe technology. This result partially might confirm the risk of trade-off between environmental regulation and policies aimed at supporting cleaner technologies. In fact, when polarized configurations are due to energy policies promoting the deployment of cleaner technologies (fringe technology), environmental regulation can lead to a dual effect, at least in principle. It might increase the risk that the dominant firm prefers to undercut the cleaner technology rather than to accommodate its production, and, at the same time, leading to increasing rather than decreasing pollution. However, the numerical simulations also show that in these situations the probability of increasing pollution, although admissible, is relatively low. As a consequence the risk of the above-mentioned dual effect, in real terms, is modest.

Finally the analysis also shows that the perverse effect of environmental policy arises only for particular pollution price intervals, namely if the pollution price is sufficiently low, lower than that value involving a switch in cost-efficiency between the dominant firm and the fringe (provided that $r_b < r_a$). This result suggests that, in some sectors and in some conditions of market structures, when the environmental policy is too modest its effect might be not only insufficient to meet the environmental target but also perverse.

Appendix

Proof of Lemma 1

By facing the rival, the more efficient firm has two alternative strategies: (1) behaving as the residual supplier by pricing above the indifference price or (2) maximizing its own production by setting the price just below the indifference price.

Let π_1^d and π_2^d be the profits corresponding to the first and second strategies above, respectively. The profit the dominant firm earns by choosing the first strategy is

$$\pi_1^d = (p_r - MC_d)(Q(p_r) - \bar{q}_f) + \tau\ \Gamma \tag{2.11}$$

where

$$p_r = \arg\max_p\ (p - MC_d)(Q - \bar{q}_f) + \tau\ \Gamma \tag{2.12}$$

and Γ is the amount of allowances allocated free of charge where $\Gamma \neq 0$ only with benchmarking of emissions allowances.

If the leader chooses the second strategy, it earns

$$\pi_2^d = (p_{n_a} - MC_d)Q(p_{n_a}) + \tau\ \Gamma \tag{2.13}$$

Thus the leader will choose the second strategy if and only if $\pi_1^d < \pi_2^d$, i.e. from (2.11) and (2.13) if and only if

$$(p_{n_a} - MC_d) > \frac{p_r - MC_d}{Q(p_{n_a})}(Q(p_r) - \bar{q}_f)$$

Then, by reasoning at margin and because of environmental regulation implementation, the dominant firm will move from strategy (1) to strategy (2) (decreasing market power) if

$$\begin{aligned}&\left(\frac{\partial p_{n_a}}{\partial \tau} - \frac{\partial MC_d}{\partial \tau}\right)Q(p_{n_a}) + (p_{n_a} - MC_d)\frac{\partial Q}{\partial p}\frac{\partial p_{n_a}}{\partial \tau} > \\ &\left(\frac{\partial p_r}{\partial \tau} - \frac{\partial MC_d}{\partial \tau}\right)(Q(p_r) - \bar{q}_f) + \frac{\partial Q}{\partial p_r}\frac{\partial p_r}{\partial \tau}(p_r - MC_d)\end{aligned} \tag{2.14}$$

and from strategy (1) to strategy (2), vice versa.

Since from (2.12)

$$\frac{\partial p_r}{\partial \tau}(Q(p_r) - \bar{q}_f) + \frac{\partial p_r}{\partial \tau}\frac{\partial Q}{\partial p}(p_r - MC_d) = 0$$

condition (2.14) becomes

$$\begin{aligned}d\Pi_u = &\left(\frac{\partial p_{n_a}}{\partial \tau} - \frac{\partial MC_d}{\partial \tau}\right) - \frac{\left(Q(p_r) - \bar{q}_f\right)^2}{Q^2(p_{n_a})}\frac{\partial p_{n_a}}{\partial \tau} + \\ &\frac{\partial MC_d}{\partial \tau}\frac{\left(Q(p_r) - \bar{q}_f\right)}{Q(p_{n_a})} > 0\end{aligned} \tag{2.15}$$

Inversely, if the leader will move from strategy (1) to strategy (2) (increasing market power).

It is to be noted that if the pollution price is very high such that the leader becomes the less efficient firm (so losing its cost and price leadership), after regulation the former leader always prefers to set its residual price since it can never undercut the rival. Therefore, demand and pollution will always decrease.

Proof of Corollary 1

If input taxes are applied to both dominant firm's and fringe's consumers then the residual demand curve will be:

$$QR = \left(Q(p_r) - \bar{q}_f + r_a\tau\frac{\partial Q}{\partial p}\right)$$

Equation (2.11) becomes:

$$\pi_1^d = (p_r - MC_d)\left(Q(p_r) - \bar{q}_f + r_a(0)\ \tau \frac{\partial Q}{\partial p}\right)$$

At the same time, (2.13) becomes:

$$\pi_2^d = (p_{n_a} - MC_d)\left(Q(p_{n_a}) + r_b(0)\tau \frac{\partial Q}{\partial p}\right)$$

By following the same procedure adopted in the proof of Lemma 1, condition (2.5) follows.

If input taxes are applied only to the dominant firm's consumers then the residual demand curve will be:

$$QR = \left(Q(p_r) - \bar{q}_f + r_a \tau \frac{\partial Q}{\partial p}\right)$$

Equation (2.11) becomes:

$$\pi_1^d = (p_r - MC_d)\left(Q(p_r) - \bar{q}_f + r_a(0)\ \tau \frac{\partial Q}{\partial p}\right)$$

At the same time the profit corresponding to the strategy 2 is:

$$\pi_2^d = (p_{n_a} - MC_d)Q(p_{n_a})$$

By following the same procedure adopted in the proof of Lemma 1, condition (2.6) follows.

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