Technology Adoption in Emission Trading Programs with Market Power*

Francisco J. André [a] and Carmen Arguedas [b]

[a]Dept. Fundamentos del Análisis Económico I, Universidad Complutense de Madrid

[b]Dept. Análisis Económico: Teoría e Historia Económica, Universidad Autónoma de Madrid

Abstract

In this paper we study the relationship between market power in emission permit markets and endogenous technology adoption. The presence of market power results in a divergence of both abatement and technology adoption levels with respect to the benchmark scenario of perfect competition, as long as technology adoption becomes more effective in reducing abatement costs. Also, the initial distribution of permits, in particular, the amount of permits initially given to the dominant firm, is crucial in determining over- or under-investment in relation to the benchmark model. Specifically, if the dominant firm is initially endowed with more permits than the corresponding cost effective allocation, this results in under- investment by the dominant firm and over- investment by the competitive fringe, regardless of the specific amount of permits given to the latter firms. The results are reversed if the dominant firm is initially endowed with relatively few permits. Our findings seem consistent with some empirical evidence about the performance of the power sector in the initial phases of the European Union Emission Trading System.

JEL classification: C72, D43, D62, L51, Q55, Q58.

Key words: environmental policy, emission permits, market power, environmentally-friendly technologies.

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*Corresponding author: Francisco J. André, Department of Economic Analysis, Complutense Univesity of Madrid. Campus de Somosaguas, 28223 Madrid, Spain. E-mail: andre@ccee.ucm.es. The authors wish to thank the participantes of the First AERNA Workshop on Game Theory and the Environment, the VII AERNA Conference on Environmental and Resource Economics, and the V Meeting on International Economics, for very useful comments and suggestions on earlier drafts. Francisco J. André acknowledges financial support from research projects ECO2012-39553-C04-01 (Spanish Ministry of Science and European Regional Development Fund, ERDF), SEJ 04992 and SEJ-6882 (Andalusian regional government). Carmen Arguedas acknowledges financial support from the Spanish Government under research project ECO2014-52372-P.

1 Introduction

This article focuses on two main tools to fight against climate change: on the one hand, technology adoption, and, on the other hand, emission trading, which is becoming the main policy approach in this field. Our research is motivated by some empirical evidence on the performance of the European Union Emission Trading System (EU ETS) so far. On the one hand, some authors (e.g. Hintermann 2011, 2016) claim that large electricy firms might have benefited from strategically increasing the permits price during Phase I of the EU ETS, since the pattern and extent of these firms' allowance holdings during this phase are consistent with strategic price manipulation. On the other hand, Rogge et al. (2010) and Hoffmann (2007) find limited impact of the EU ETS on innovation and large scale investment decisions in the German power sector; see also Laing et al. (2013). Moreover, the initial permit allocation to the electricy sector has been proven to be excessive on Phases I and II of the EU ETS.[1]

Based on this evidence, we aim to answer the following general questions: Is there a systematic link between market power in emission permit markets and the adoption of cleaner technologies? How do these two aspects relate to permit allocation?

By studying the interaction between market power in emissions trading and the incentives for technology adoption, we contribute to two strands of the literature. The first focuses on cap-and-trade programs with market power, where a dominant firm coexists with a competitive fringe. The path-breaking paper in this literature is Hahn (1984), who showed that some of the desirable properties that cap-and-trade systems have under perfect competition do no longer hold under market power. Montgomery (1972) proved that, if the permit market is perfectly competitive, the equilibrium distribution of permits is cost-effective for any initial allocation of

[1] On Phases I an II of the EU ETS, all permits where allocated for free. In 2013, 40% of the annual allowances to the power sector were auctioned. This share is progressively increasing year after year, as the volume of allowances allocated for free decreases faster than the cap, see the European Comission's Climate Action webpage for more information on this issue (https://ec.europa.eu/clima/policies/ets/auctioning/index_en.htm). André and Alvarez (2015, 2016) compare grandfathering to auctioning in terms of cost-effectiveness.

permits among the participant firms but Hahn (1984) noticed that, under market power, the initial distribution of permits does matter and the cost-effective allocation is reached only when the dominant firm initially receives exactly the same amount of permits that it would get under perfectly competitive pricing. Otherwise, it is optimal for the dominant firm to manipulate the permit price. If it receives more permits than the competitive amount, it acts as a net seller of permits and sets the price above the competitive one. On the contrary, if it receives less permits than in the competitive equilibrium, it acts as a net buyer and manipulates the price down. An overview of the literature on permit markets with market power can be found in Montero (2009).

Our contribution to this literature is to ask how the possibility to adopt new technology modifies the position of the dominant firm in the permit market and its optimal strategy. In our framework, the dominant firm now has two strategic variables (the demand for permits and the level of technology adoption) instead of one, and it becomes relevant to ask about the interaction between the two variables as complements or substitutes in manipulating the permit price. In other words: *Does the consideration of new technology adoption weaken or reinforce the dominant firm's incentives to manipulate the price of permits up or down?* Or put differently: *Does the possibility of technology adoption dilute or exacerbate market power?*

The second strand of the literature studies the incentives provided by different environmental policies for firms to invest in more efficient abatement technologies (the so-called dynamic efficiency); see for example, Milliman and Prince (1989), Jung et al. (1996), Requate and Unold (2003), and Requate (2005) for a survey of this literature. Generally, this literature shows that the ranking of environmental policies when promoting the investment in cleaner technologies depends on regulatory commitment issues, (im)perfect competition considerations in the output market, and characteristics of the damage function. However, to our knowledge, this literature is silent about the incentives to adopt better abatement technologies under emission trading with maket power (see, e.g., Requate, 2005). By including this consideration, we can address the following question: d*oes the existence of market power weaken or strenghen the incentives to invest in new abatement technologies?* In particular, we are interested in analyzing whether the dominant firm has more or less incentives to invest in new technologies than the competitive firms, and also if it has more or less incentives than it would have in the absence of market power.

To answer all these questions, we present a model in which a group of firms make decisions regarding technology adoption and permit trading, after they become aware of their initial permit allocation. Technology adoption is costly, but it decreases abatement costs. We first consider a benchmark scenario without market power, i.e, all the firms are price-takers in the permit market. In this setting, all the firms simultaneously decide on their amounts of technology adoption and permit holding. Then, we consider an alternative situation where one firm takes a leading role in the permit market, as a price-setter. For the sake of interpretation, and to connect our research to the empirical evidence, the dominant firm could be assimilated to the power sector, as it is the largest and most influential in the EU ETS. In this scenario, all the firms first decide on their technology investments, then the dominant firm selects its abatement level (i.e., the permit price), and finally the remaining firms select their respective abatement levels, taking the permit price as given.

In some sense, our results are aligned with Hahn (1984)'s: In the presence of market power, the equilibrium is cost-effective only if the dominant firm is initially required to do the same abatement as in the benchmark perfectly competitive allocation. Our addition to this literature is to show that the consideration of technology adoption results in a divergence of both abatement and technology adoption levels with respect to the scenario of perfect competition, as long as technology adoption becomes more effective in reducing abatement costs. In other words, the possibility to adopt new technologies aggravates rather than alleviates the efficiency loss due to market power. We also find that the initial distribution of permits is crucial in determining over- or under-investment by any specific firm in relation to the benchmark model. Thus, if the dominant firm is initially endowed with more (less) permits than its corresponding cost effective allocation, this will result in the dominant firm's under- (over-)investment and the competitive fringe's over- (under-)investment, regardless of the specific amount of permits given to the other firms. These results highlight that regulators should be specially careful about the number of permits allocated to dominant firms, especially if technology efforts are really effective in reducing abatement costs. Our results are thus consistent with the features of the power sector and the EU ETS that we have mentioned above, namely (i) excess of initial permit allocation, (ii) market power, and (iii) under-investment in clean technologies.

To the best of our knowledge, there are only three studies (Montero 2002a, 2002b, and Storrosten, 2010) addressing the incentives to invest in advanced abatement technology in emission markets with market power. Storrosten (2010) considers a setting with n Cournot competitors and a competitive fringe where the Cournot competitors (but not the competitive firms) face a discrete technology choice (old-new). Storrosten (2010) compares the performance of taxes versus auctioned permits in terms of technology adoption, and he finds that the number of firms adopting the new technology may be higher with emission trading if there is imperfect competition in the permit market. While firms may free ride on the lower permit price triggered by the investments of other firms under emissions trading and reduce their willingness to adopt the new technology (a result first noted by Requate and Unold (2003)), if there is imperfect competition a firm's ability to manipulate the permit price through technology adoption might increase the incentives to adopt. If the latter effect dominates the former, then incentives to adopt may be higher under permit trading than under taxes.

Our paper differs from Storrosten (2010) in several respects. Most importantly, permits are freely allocated in our setting (instead of auctioned) and all the firms can adopt advanced technologies (and not only the one exercising market power). In some sense, our assumptions are more consistent with the features of the initial phases of the EU ETS, where permits have been mostly allocated for free (by means of grandfathering) and firms in sectors with no evidence of market power have undertaken investment and innovation activities.[2] Considering grandfathering instead of auctioning is relevant as the combination of a given initial permit allocation with market power in emissions trading are the main drivers of all the under- or over-investment results in our setting.

Montero (2002a, 2002b) incorporates market power in both permit trading and the output market in a model with two firms. He finds that the ranking of regulatory instruments regarding incentives for technology adoption depends on market structures (Cournot or Bertrand) and regulatory instruments (standards, tradable permits or taxes). He finds that tradable permits may provide more, equal or less incentives to adopt advanced technologies than emission standards or taxes, depending on the market structure in the output and permit markets. The main difference with our approach (besides the fact that we do not consider the output market in our analysis) is that we allow one firm to take a dominant role regarding permit price setting. This makes it possible to have some firms under-investing and others over-investing in advanced technologies, even if firms are equal in all other respects. In fact, we show that this effect crucially depends on the particular distribution of permits among the firms and the existence of market power.

The remainder of the paper is organized as follows. In the next section we introduce the model. In Section 3, we respectively present the general results in the perfectly competitive case (benchmark scenario) and the results under market power. In Section 4, we present a detailed comparative statics analysis for the case where firms' abatement costs are quadratic.

[2] See Martin et al. (2011) for anecdotal evidence on the manufacturing sector, or Petsonk and Cozijnsen (2007), who look at case studies in France, Germany, the Netherlands, and the UK, finding innovative activity in a number of sectors.

In Section 5, we discuss on the robustness of our results regarding two specific elements of our specification. First, we consider an alternative timing in which the dominant firm chooses technology adoption and abatement levels in the first place, while the remaining firms choose their corresponding levels at a later stage. Second, we consider an alternative cost function outside the quadratic specification introduced in Section 4. Our results do not qualitatively change under these alternative approaches. We conclude in section 6. All the proofs are in the Appendix.

2 The Model

We consider a group of N polluting firms indexed by i. Each firm i can abate pollution facing abatement costs given by $c^i \equiv c(q_i, k_i)$, where q_i is the amount of abated pollution (defined as the difference between the business-as-usual level and the realized emissions[3]) and k_i is the level of environmentally-friendly technology adoption. Both q_i and k_i are decision variables of firm i. We assume the usual signs for the partial derivatives, that is, $c^i_q > 0$, $c^i_k < 0$ and $c^i_{qk} < 0$.[4] This means that abatement costs are increasing in the amount of abatement, and also that both total and marginal abatement costs are decreasing in the degree of technology adoption. We further assume that the abatement cost function is stictly convex in (q_i, k_i).

For the purpose of our analysis, and without loss of generality, it is convenient to specify the abatement cost function as follows:

$$c(q_i, k_i) \equiv \gamma G(q_i, k_i) + (1-\gamma) H(q_i), \qquad \text{with } \gamma \in [0,1] \tag{1}$$

where $G^i \equiv G(q_i, k_i)$ is such that $G^i_q > 0$, $G^i_k < 0$ and $G^i_{qk} < 0$, and $H^i \equiv H(q_i)$ is such that $H^i_q > 0$. We further assume that $G^i_q \leq H^i_q$ and that both G and H are convex, with the linear

[3] For the sake of clarity, it is convenient to write the model in terms of abatement. An equivalent formulation would be in terms of realized emissions defined as $e_i = e_i^0 - q_i$, where e_i^0 is firm i's business-as-usual emissions.

[4] A subscript to a function denotes partial derivation. A suscript to a variable or a superscript to a function identifies the firm.

convex combination given in (1) being strictly convex.

Parameter γ is key in our analysis, as it determines the effectiveness of technology adoption to reduce abatement costs. The specification given in (1) allows us to consider a continuum of cases for the abatement cost function. The case $\gamma = 0$ corresponds to the limiting situation where technology adoptions is not effective at all. In that case, we have $c(q_i, k_i) \equiv H(q_i)$, that is, abatement costs are fully determined by the amount of abatement. All the analysis of the previous literature on emission permits where technology adoption is not considered, would correspond to this particular case. As the value of γ increases, the weight of the first component in (1) also increases, which implies that technology adoption becomes more effective in reducing abatement costs. In the limit, if $\gamma = 1$, (1) collapses to $c(q_i, k_i) \equiv G(q_i, k_i)$, which is the most favourable case regarding the effectiveness of technology adoption. We assume that each firm i can decide its level of investment in abatement technology, k_i, at a unit price r.

We consider an exogenous aggregate amount of abatement required by a regulator, Q^0. We assume that the regulator aims at implementing this aggregate level of abatement by distributing permits among the firms. Thus, each firm i is initially required to abate the amount q_i^0, such that $q_1^0 + q_2^0 + ... + q_N^0 = Q^0$.[5] However, each firm can adjust its abatement level by either selling or buying additional emission permits in a secondary market at price p, where p is the market clearing price. Thus, if a firm i decides to do less abatement than the initially required level $(q_i < q_i^0)$, it will need to buy additional permits at a cost of $p \cdot (q_i^0 - q_i)$. If, on the contrary, the firm intends to do more abatement than required $(q_i > q_i^0)$, it will sell permits in the market and will earn a revenue of $p \cdot (q_i - q_i^0)$.

Then, the total costs faced by a typical firm in this market, denoted as C, consist of abatement costs, technology adoption costs and the purchase of additional permits as follows:

[5] In practice, q_i^0 is determined by giving a certain number of permits, say x_i, to firm i, in such a way that $x_i = e_i^0 - q_i^0$, where e_i^0 is firm i's *business-as-usual* level of emissions.

$$C(q_i, k_i) := c(q_i, k_i) + rk_i + p \cdot \left(q_i^0 - q_i\right) \tag{2}$$

where the latter term is negative if the firm is a seller of permits.

Once the required abatement levels are announced, we assume that firms decide on the degree of technology adoption, and their corresponding abatement levels. We solve the problem backwards to obtain the subgame perfect equilibrium. We analyse a benchmark case where there is no market power in the permit market and an alternative situation where firm $i = 1$ has a dominant position as a price-setter.

3 General results

3.1 Benchmark model

As a benchmark situation, we consider that no firm has a dominant position in the permit market. In the first stage, all the firms select their technology adoption levels, k_i $(i = 1, ..., N)$ simultaneously. In the second stage, all the firms select the abatement level q_i, simultaneously, taking the permit price p, and the levels of technology adoption as given. We assume that the solution is interior in the sense that all the firms do positive amounts of abatment and investment.[6]

To obtain a subgame-perfect Nash equilibrium, we start solving the second stage. Each firm i chooses the value of q_i to minimize its total cost function as given by (2). From the first order conditions we conclude:

$$c_q^i = p, \text{ for all } i, \tag{3}$$

which is the well-known cost-effective condition, which states that firms should abate until the corresponding marginal abatement cost equals the permit price. From (3) we implicitly obtain

[6] In the general approach to the benchmark case and the market power case, we restrict the analysis to interior solutions. In the quadratic specification analyzed below in Section 4 we illustrate that the solution can be corner or interior depending on the parameters of the model.

each firm's abatement level as a function of the permit price, the technology adoption level and parameter γ, that is, $q_i = q_i(p, k_i, \gamma)$. Straightforward application of the implicit function theorem results in $\frac{\partial q_i}{\partial p} = \frac{1}{c^i_{qq}} > 0$. Thus, the abatement level of each firm is increasing in the permit price or, equivalently, the net demand for permits is decreasing in the permit price.

The market clearing condition for permits states that the sum of all the firms' abatement levels should equal the required abatement level imposed by the government, that is:

$$\sum_{i=1}^{N} q_i(p, k_i, \gamma) = Q^0, \tag{4}$$

which, jointly with (3), implicity defines the permit price as a function of the technlogy adoption levels and the effectiveness parameter γ.

Now, in the first stage, each firm i $(i = 1, 2, ..., N)$ chooses its corresponding technology abatement level, k_i, with the aim of minimizing $C(q_i, k_i)$ as given by (2). Applying the envelope theorem, the first order condition with respect to k_i reduces to:

$$c^i_k + r = 0, \text{ for all } i. \tag{5}$$

Since all the firms are ex-ante identical, they all end up choosing the same abatement and technlogy adoption levels, respectively denoted as q and k. Applying the market clearing condition (4), this implies that, in equilibrium, each firm will do one $N-$th of total abatement, regardless of the particular value of the effectiveness parameter γ and the initial allocation of permits.

The following proposition summarizes the conditions that characterize the interior solution for the benchmark scenario without market power.

Proposition 1 *In the benchmark model without market power, assuming interior solution, the firms' abatement levels, technology adoption levels, and the resulting permit price are implicitly determined by the following conditions:*

$$q_i = q = Q^0/N, \quad c^i_q = p, \quad \textit{and} \quad c^i_k + r = 0, \quad \textit{for all } i. \tag{6}$$

It is immediately clear from the optimality conditions given in (6) that the initial distribution of permits does not affect any of the equilibrium variables, namely, abatement levels, technology adoption levels and the permit price. Straightforward application of Cramer's rule in the optimality conditions provides the comparative statics of the benchmark solution regarding the technology effectiveness parameter γ. These are summarized in the following:

Proposition 2 *In the benchmark model without market power, the equilibrium variables* (q, k, p) *depend on the effectiveness parameter* γ *as follows:*

$$\frac{dq}{d\gamma} = 0; \ \frac{dk}{d\gamma} = -\frac{c_{k\gamma}}{c_{kk}} > 0; \ \frac{dp}{d\gamma} = -\frac{c_{qk}}{N}\frac{c_{k\gamma}}{c_{kk}} + c_{q\gamma} < 0.$$

Therefore, for a given level of aggregate abatement and any initial distribution of permits among the firms, the optimal abatement level per firm in the benchmark model is independent of the effectiveness parameter. As expected, the corresponding technology investment level is increasing in the effectiveness parameter, while the equilibrium permit price is decreasing in the effectiveness parameter.

3.2 Market power in permit trading

Assume now that firm 1 has a dominant position in the permit market and the remaining firms belong to a competitive fringe. We assume that all the firms select k_i simultaneously in the first stage. Then, firm 1 (the dominant firm) selects q_1 in the second stage, and the remaining firms $2, ..., N$ select q_i simultaneously in the third stage, taking the price p as given.

We begin with the third stage of the game. In this stage, the price-taking firms select their respective abatement levels solving the first order condition:

$$c_q^F = p, \tag{7}$$

where $F = 2, ..., N$, and each firm's abatement level $q_F = q_F(p, k_F, \gamma)$ is derived implicitly from the above expression, with $\frac{\partial q_F}{\partial p} = \frac{1}{c_{qq}^F} > 0$.

In the second stage, the dominant firm, 1, solves the problem:

$$\min_{e_1} \quad c^1 + rk_1 + p \cdot \left(q_1^0 - q_1\right),$$
$$s.t. \quad q_1 + (N-1) \cdot q_F = Q^0,$$

where $q_F = q_F(p, k_F, \gamma)$ is implicitly given in (7). The optimality conditions for an interior solution result in:

$$c_q^1 = p + \frac{\left(q_1^0 - q_1\right)}{(N-1) \cdot \frac{\partial q_F}{\partial p}}, \tag{8}$$
$$q_1 + (N-1) \cdot q_F = Q^0, \tag{9}$$

where $\frac{\partial q_F}{\partial p} = \frac{1}{c_{qq}^F}$.

From (8) and (9), we implicitly obtain firm 1's abatement level and the equilibrium permit price, as a function of the technology adoption levels and the effectiveness parameter γ, that is, $q_1 = q_1(k_1, k_F, \gamma)$ and $p = p(k_1, k_F, \gamma)$.

In the first stage, all the firms simultaneously choose their technology abatement levels, k_i. Applying the envelope theorem, the first order condition for all the firms is simply:

$$c_k^i + r = 0, \text{ for } i = 1, F, \tag{10}$$

and combining this expression with the previous equations (7), (8) and (9), we obtain the equilibrium values.

All the equilibrium conditions for the interior solution are summarized next.

Proposition 3 *In the model with a dominant firm in the permit market, the interior firms' abatement levels, technology adoption levels, and the resulting permit price are implicitly deter-*

mined by the following conditions:

$$c_q^F = p; \tag{11}$$

$$c_q^1 = p + \frac{(q_1^0 - q_1) \cdot c_{qq}^F}{N-1}; \tag{12}$$

$$q_1 + (N-1) \cdot q_F = Q^0; \tag{13}$$

$$c_k^i + r = 0, \quad i = 1, F. \tag{14}$$

Note that the solution of this problem coincides with the benchmark solution given in Proposition 1 only if firm 1's requested abatement level coincides with the benchmark abatement level, that is, only if $q_1^0 = Q^0/N$. Therefore, the equilibrium allocation is cost-effective only in that particular case. In any other scenario, both solutions differ. Therefore, the way the amount of permits are initially allocated (in particular the amount of permits initially given to firm 1) is crucial. This contrasts with the benchmark scenario where the specific initial allocation of permits is irrelevant for the equilibrium.

We are now interested in performing a comparative statics analysis regarding the effects of the required level of abatement for the dominant firm and the effectiveness parameter γ on all the equilibrium variables (abatement and investment levels for the dominant and the remaining firms, as well as the equilibrium price). Unfortunately, the results are ambiguous at this level of generality. The quadratic specification analyzed in the following section will help us to solve these ambiguities.[7]

4 Quadratic case

In this section, we consider a quadratic specification for the abatement cost function given in (1). Specifically, we assume $G(q,k) = \frac{q^2+k^2-\alpha qk}{2}$, $\alpha \in (0,2)$, and $H(q) = \frac{q^2}{2}$, which imply that

[7]Nevertheless, in Section 5 we present an alternative specification outside the quadratic case to test the robustness of the results.

the resulting abatement cost function is:

$$c(q_i, k_i, \gamma) \equiv \frac{q^2 + \gamma(k^2 - \alpha q k)}{2}. \tag{15}$$

This specification satisfies all the conditions imposed on the abatement cost function provided that $k < \frac{\alpha q}{2}$.[8]

4.1 Benchmark

Starting with the benchmark case, we combine the interior solution presented in Proposition 1 with the corner solution as follows:

$$q_i = q_B = \frac{Q^0}{N}, \quad \text{for all } i; \tag{16}$$

$$k_i = k_B = \begin{cases} \frac{\alpha}{2}\frac{Q^0}{N} - \frac{r}{\gamma}, & \text{if } \gamma \geq \bar{\gamma}, \\ 0, & \text{otherwise;} \end{cases} \tag{17}$$

$$p_B = \begin{cases} \left(1 - \gamma\frac{\alpha^2}{4}\right)\frac{Q^0}{N} + \frac{\alpha r}{2}, & \text{if } \gamma \geq \bar{\gamma}, \\ \frac{Q^0}{N}, & \text{otherwise.} \end{cases} \tag{18}$$

where $\bar{\gamma} \equiv \frac{2rN}{\alpha Q^0}$, and B stands for benchmark.

If the effectiveness of technology adoption to reduce abatement costs is small enough ($\gamma < \bar{\gamma}$), it is optimal for the firms not to invest at all, that is, $k = 0$. Hence, the equilibrium permit price is fully dependent on the average required abatement, $\frac{Q^0}{N}$, and the cost of technology adoption does not matter.

If, on the other hand, the effectiveness of technology to reduce abatement costs is large enough ($\gamma \geq \bar{\gamma}$), it is optimal for the firms to invest in technology adoption in such a way that the larger γ, the larger the investment. The equilibrium permit price now depends positively on the required aggregate abatement and the price of the technology adoption. Interestingly, the larger the effectiveness parameter γ, the weaker the dependence of the price on the required aggregate abatement.[9]

[8] It is easy to show that this is always the case in equlibrium. Check below equations (16) and (17) for the benchmark case and (46) for the market-power case.

[9] In the particular case where $\alpha = 2$ and $\gamma = 1$, the equilibrium permits price only depends on the price of

4.2 Market power in permit trading

Now, we study the case of market power presented in Proposition 3. The interior solution characterized in the proposition is given by the following expressions:[10]

$$
\begin{aligned}
q_1 &= \frac{4q_1^0 + \left(4 - \gamma\alpha^2\right) Q^0}{4\left(N+1\right) - \gamma\alpha^2 N}; &(19)\\
q_F &= \frac{\left[4N - \alpha^2\gamma\left(N-1\right)\right] Q^0 - 4q_1^0}{\left(N-1\right)\left[4\left(N+1\right) - \gamma\alpha^2 N\right]}; &(20)\\
k_1 &= \frac{\alpha}{2}\frac{4q_1^0 + \left(4 - \gamma\alpha^2\right) Q^0}{4\left(N+1\right) - \gamma\alpha^2 N} - \frac{r}{\gamma}; &(21)\\
k_F &= \frac{\alpha}{2}\frac{\left[4N - \alpha^2\gamma\left(N-1\right)\right] Q^0 - 4q_1^0}{\left(N-1\right)\left[4\left(N+1\right) - \gamma\alpha^2 N\right]} - \frac{r}{\gamma}; &(22)\\
p &= \frac{\alpha r}{2} + \frac{4 - \gamma\alpha^2}{4}\frac{\left[4N - \alpha^2\gamma\left(N-1\right)\right] Q^0 - 4q_1^0}{\left(N-1\right)\left[4\left(N+1\right) - \gamma\alpha^2 N\right]}. &(23)
\end{aligned}
$$

An inspection of these equations leads us to conclude that, in contrast with the benchmark solution presented in expressions (16) to (18), the equilibrium variables crucially depend on q_1^0, that is, the amount of abatement required to the dominant firm. Indeed the results depend on whether the dominant firm is required to abate less or more than the average abatement, Q^0/N. We refer to these case as "the monopoly case" (if $q_1^0 < Q^0/N$) and "the monopsony case" (if $q_1^0 > Q^0/N$) respectively. The following proposition shows the effect of the initial permit allocation on abatement and technology adoption.

Proposition 4 *In the model with a dominant firm in the permit market and the quadratic cost*

the technology. Intuitively, the initial increase in the permits price due to a restriction in the supplied amount of permits (or a larger required abatement) is fully compensated with the reduction in the price caused by the induced increase in technology investment. In the general case, this second effect need not fully compensate the first effect.

[10] In the Appendix, we show a detailed derivation of the results, as well as the analysis of corner solutions.

function (15) the following results hold in equilibrium:

$$\text{If } q_1^0 < Q^0/N, \text{ then} \quad \begin{cases} q_1^0 < q_1 < Q^0/N < q_F, \\ \text{and} \\ k_1 < k_B < k_F. \end{cases}.$$

$$\text{If } q_1^0 > Q^0/N, \text{ then} \quad \begin{cases} q_F < Q^0/N < q_1 < q_1^0, \\ \text{and} \\ k_F < k_B < k_1. \end{cases}.$$

The proof immediately follows by manipulating expressions (19)-(22).

Consider first that the dominant firm is required to do less abatement than the average, i.e., $q_1^0 < Q^0/N$. This means that the dominant firm is endowed with more permits than the average. Proposition 4 implies that, in this case, $q_1^0 < q_1 < Q^0/N < q_F$. Thus, the dominant firm will do more abatement than initially required, but less than average abatement and less than the competitive firms. Therefore, the dominant firm will be a net seller of permits, acting as a monopolist. Consistent with these findings, the corresponding technology adoption levels also depart from the benchmark solution. In this case, the dominant firm under-invests in technology adoption as compared to the benchmark solution, while the firms in the competitive fringe over-adopt. Finally, the equilibrium price is larger than the perfectly competitive price, as a consequence of the presence of monopoly power.

The opposite case, $q_1^0 > Q^0/N$, involves monopsony behaviour and results in over-abatement and over-adoption by the dominant firm and a permit price lower than the competitive one.

The next step is to analyze the dependence of the equilibrium variables on the key parameters of the model, q_1^0 and γ. Moreover, we are also interested in whether the equilibrium choices of the dominant firm and the firms in the competitive fringe converge or diverge with respect to each other as the parameters change, and also whether the equilibrium choices under market power converge to or diverge from the benchmark solution. The results are shown in Table 1. All the technical details are in the Appendix.

	Market power							M. Power vs. Benchmark		
	q_1	q_F	$q_1 - q_F$	k_1	k_F	$k_1 - k_F$	p	$q_1 - q_B$	$k_1 - k_B$	$p - p_B$
q_1^0	+	-	+	+	-	+	-	+	+	-
γ ($q_1^0 < Q^0/N$)	-	+	-	+/-	+	-	-	-	-	-
γ ($q_1^0 > Q^0/N$)	+	-	+	+	+/-	+	-	+	+	+

Table 1. Comparative statics with respect to q_1^0 and γ.

Columns 2-8 of Table 1 show the effect of the parameters of the model on the equilibrium variables under market power, as well as the effects on the difference in abatement and adoption levels by the dominant firm and the firms in the competitive fringe. Columns 9-11 show the effect of the same parameters on the difference between the dominant firm's optimal policy as well as the permit price under market power and the benchmark scenario, that is, (19)-(16), (21)-(17) and (23)-(18).

We start our discussion by analyzing the effects of changing q_1^0, i.e., the amount of abatement initially required from the dominant firm, keeping the remaining parameters constant (third row of the table). Expressions (19) to (23) imply that, under market power, the abatement and technology adoption levels of the dominant firm increase with q_1^0, while the corresponding levels for the competitive firms and the equilibrium price decrease with q_1^0. Linking these result with our previous conclusion regarding under- abatement and under- investment of the dominant firm and over- abatement and over- investment of the competitive fringe found in the monopoly case, we can conclude that the amount of under- abatement and under- investment of the dominant firm decrease with q_1^0 and the amount of over- abatement and over- investment of the competitive fringe decrease with q_1^0, and the opposite happens in the monopsony case.

Finally, the negative effect of q_1^0 on the price can be interpreted in the following way: in the monopoly case the dominant firm is a net seller of permits and is interested in distorting the price upwards. As q_1^0 increases (and approaches $\frac{Q^0}{N}$), the monopoly power weakens and then the resulting price decreases and approaches the competitive one. When q_1^0 is large enough to enter the monosony region, the dominant firm becomes a net seller of permits and is interested in distorting the price downwards. In the latter region, further increases of q_1^0 makes the solution further from the benchmark and therefore the price is more distorted below the competitive one.

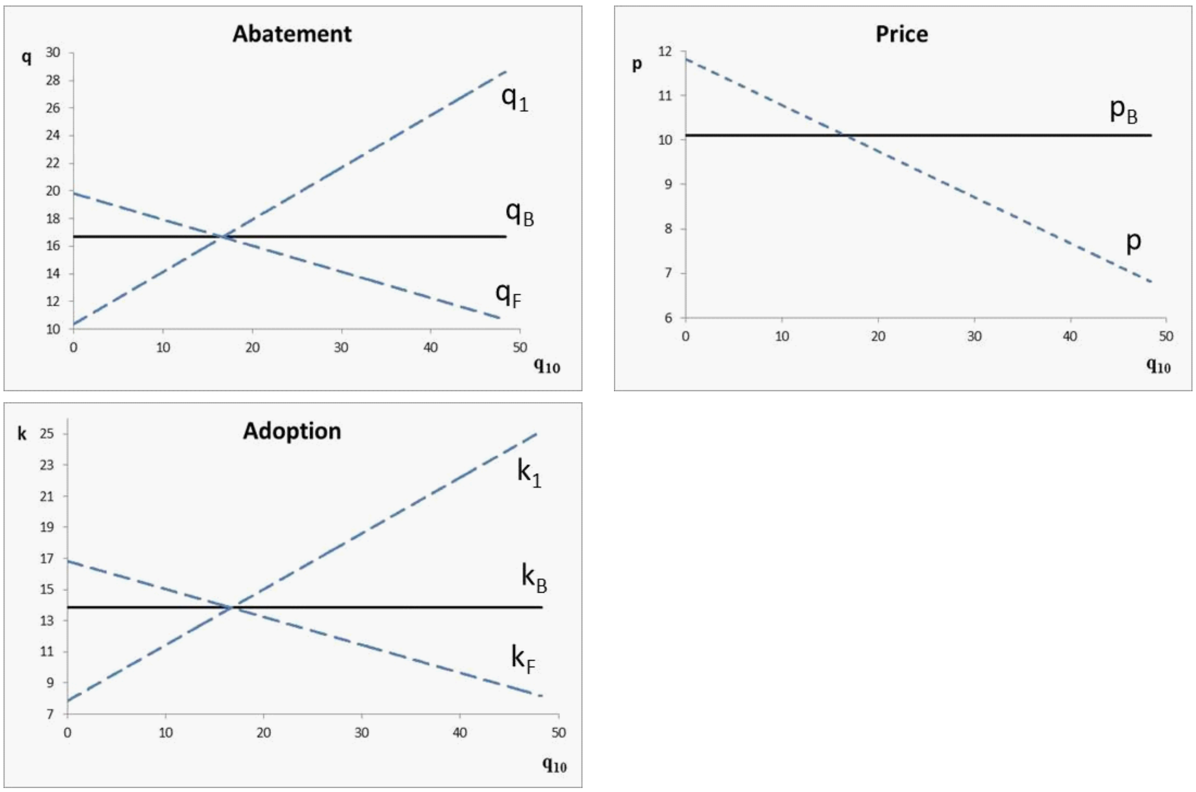

FIGURE 1: Sensitivity analysis w.r.t q_{10}. Parameters: $Q_0 = 50$, $\gamma = 0.5$, $N = 3$, $\alpha = 1.9$, $r = 1$. Solid (dashed) lines correspond to the Benchmark (market power) case.

These results are illustrated in Figure 1, which compares the equilibrium values of abatement, technology adoption and permit price under market power and perfect competition in a specific example. Notice that, when q_1^0 is below the benchmark allocation, (in the example, $q_1^0 < \frac{50}{3}$), we are in the monopoly case. Then the dominant firm under-abates and under-adopts, while the competitive firms over-abate and over-adopt. Also, the permit price is above the benchmark due to monopolistic behaviour. As q_1^0 increases and approaches $\frac{Q^0}{N}$, the market power of the dominant firms weaknes and the solution approaches the benchmark. If q_1^0 increases further, we enter the monopsony region and the results get reversed: the dominant firm over-abates and over-adopts, the competitive ones under-abate and under-adopt and the permit price gets lower than the benchmark value.

As a general conclusion, all the equilibrium variables under market power depart from the benchmark solution as long as q_1^0 differs from the cost effective solution, and the further q_1^0 is from the benchmark, the larger the divergence of the equilibrium variables under market power, as compared to perfect competition.

We now move to the comparative statics regarding γ, the effectiveness parameter (forth and fifth rows of Table 1. For the sake of brevity, we focus our discussion on the monopoly case (forth row of Table 1), which, to some extent, can be assimilated to the situation of the power firms in the EU ETS (at least in the early stages) as arguably, the firms in this sector have been over-endowed with emission permits. The monopsony case (fifth row) can be explored in the same way.

The first thing to notice is that γ has opposing effects on the abatement levels of the dominant firm and the firms in the competitive fringe. Specifically, in the monopoly case, the equilibrium abatement level of the dominant firm is decreasing in γ, while the corresponding levels for the competitive firms are increasing in γ. Given that, in this case, we have $q_1 < q_F$, we conclude that the corresponding abatement levels diverge with γ.

Next, the effectiveness parameter γ affects technology investment in two ways. First, there is a direct effect on the incentives to adopt, which is always positive. Everything else equal, the larger this effectiveness, the larger the cost reduction achieved form such an investment. Second, there is an indirect effect associated with the incentives to abate, which can be positive or negative. For any given firm, if the optimal response to an increase in γ is to abate more, this will be better accomplished with an increase in technology investment. On the other hand, if the optimal response is to abate less when γ increases, the firm will reduce its technology investment. In the monopoly case we know that the equilibrium abatement levels of the competitive firms are increasing in γ, which implies that the corresponding equilibrium levels of technology adoption are clearly increasing as well because both the direct and the indirect effects are positive. However, the sign of the total effect for the dominant firm is ambiguous, since abatement for this firm decreases with γ and thus the indirect effect is negative. Interestingly, it can be the case (depending on the parameter values) that technology adoption of the dominant firm increases for low values of γ, and decreases for larger values of γ, which means that technology adoption for the dominant firm can be inverse U-shaped in γ (see Figure 2 below). In any case, the corresponding investment levels of the dominant and competitive firms clearly diverge with γ.

Finally, an increase in the effectiveness parameter induces a decrease in the permit price. The intuition behind this result is straightforward: as it becomes easier to decrease abatement costs through technology adoption, there are less incentives to buy permits and, as supply is fixed, a smaller demand results in a lower price.

To perform the comparison of the market power case versus the benchmark scenario, recall that, in the latter case, γ does not affect the abatement levels, it has a positive effect on technology investments, and a negative effect on the equilibrium price. Thus, an increase in γ makes the equilibrium abatement and technology investment levels under market power diverge with respect to the benchmark.

These results have important implications regarding our research questions. In the monopoly case, the higher the value of γ, the less the dominant firm abates (i.e., the less permits it sells), and the more the competitive firms abate. Thus, the equilibrium allocation of permits (and thus abatement effort) gets further away from the cost-effective allocation as long as γ increases. This means that the distortion derived from market power is aggravated rather than alleviated as technology investment becomes more effective.

Paradoxically, although the abatement and adoption levels depart from the benchmark values, the permit price becomes closer to the competitive price. The reason is that, as γ

increases, the dominant firm takes less part in the permit market and thus, its role as a price-setter decreases. In the limit, only the competitive firms will trade and the permit market will work competitively (althugh with a market size lower than Q^0). As an extreme case of this effect, q_1 tends to q_1^0 as α tends to 2 and γ tends to 1 (simply substitute $\alpha = 2$ and $\gamma = 1$ in expression (19)). In this extreme situation, the dominant firm would not intervene in the permit market at all, but it would remain with its initial allocation.

Figure 2 illustrates the sensitivity analysis of the equilibrium variables with respect to γ in a numerical example. We can see how for very low values of γ we get corner results and, therefore, equilibrium investments are zero and the permit price is independent of γ. However, when γ becomes large enough, it is optimal to invest and the competitive firms start making positive investments for a lower value of γ than the dominant firm.

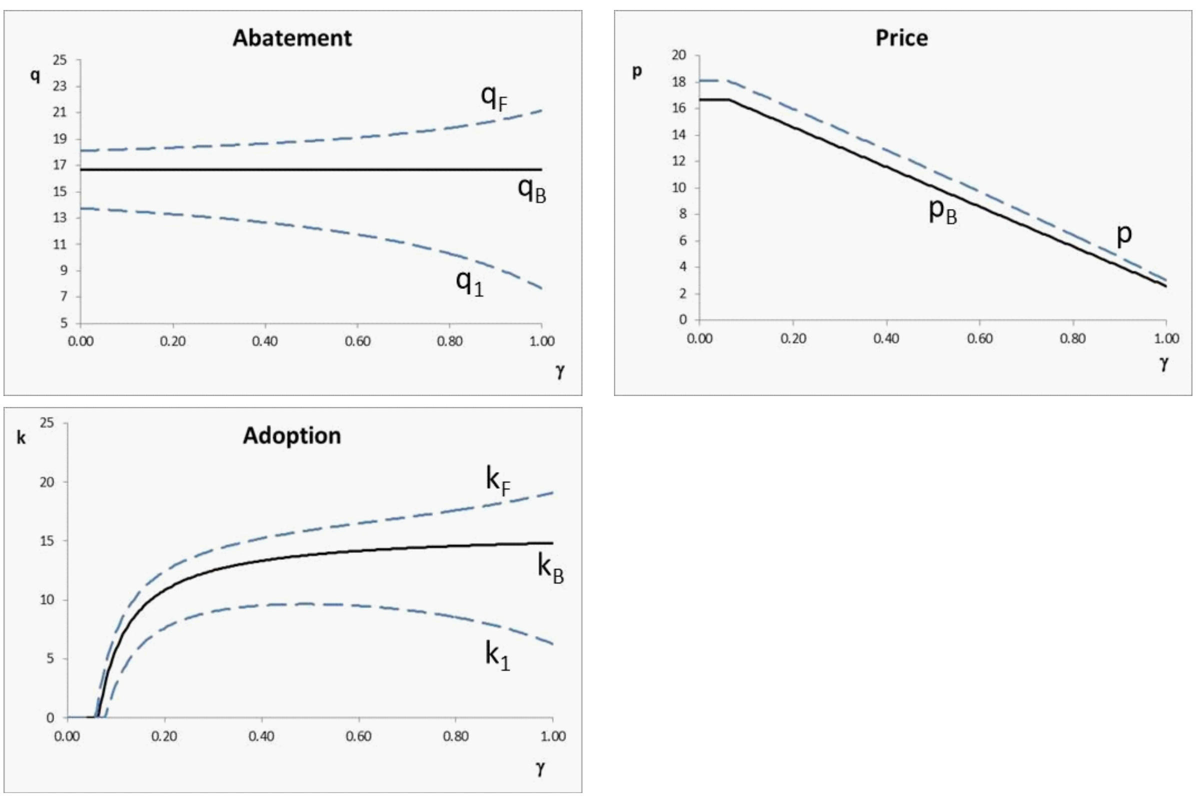

FIGURE 2: Sensitivity analysis w.r.t γ. Parameter values: $Q_0 = 50$, $q_{10} = 5$, $N = 3$, $\alpha = 1.9$, $r = 1$ Solid (dashed) lines correspond to the Benchmark (market power) case.

Our results about the behavior of the dominant firm in the so-called monopoly case seem consistent with the empirical evidence on the performance of the power sector in the initial phases of the EU ETS. As explained in the Introduction, this sector is characterized by (i) excess of initial permit allocation (see, e.g. Ellerman et al., 2010), (ii) market power, (see e.g. Hintermann 2011, 2016) and (iii) under-investment in clean technologies, (see Rogge et al., 2010 and Hoffmann, 2007). As a policy implication, our conclusions suggest that allocating an excessive amount of permits to dominant firms can induce them, not only to under-abate (as it was already noted by Hahn, 1984), but also to under-invest in cleaner technologies. Moreover, we conclude that the distortion due to the presence of market power (i.e., the difference from the equilibrium allocation to the cost-effective one) is aggravated when the role of technology adoption is very important.

5 Discussion

In this section we wonder how general our results are. For that purpose, we investigate some specific elements of the model in order to check to what extent our conclusions are sensitive to the specification. First, we consider an alternative timing and, second, a different cost function outside the quadratic specification. Qualitatively, our main results remain valid under these alternative versions of the model.[11]

5.1 An alternative timing

Assume that the dominant firm selects q_1 and k_1 in the first stage. Then, the remaining firms react by choosing q_i and k_i in the second stage. This case can be thought of as one in which the dominant firm also has a leadership position in technology adoption.[12] For the sake of clarity

[11] For the sake of brevity, in these extensions we only present the main results, omitting the technical details. Additional information is available upon request.

[12] Note, however, that the leadership in technology adoption is limited in the sense that the dominant firm cannot affect the price r, which is exogenously given. This fact prevents the dominant firm from having an additional first-mover advantage. Actually, our conclusions show that it is the other way around: if the dominant firm is forced to chose the technology first, its market power is somewhat reduced rather than increased.

we refer to this new case as "Timing II", and the previous market power case as "Timing I". We first present the general results and then we comment on the quadratic specification.

Starting with the last stage, the firms in the competitive fringe, $F = 2, ..., N$, choose their abatement and adoption levels according to conditions (7) and (10). Differentiating both expressions with respect to q_F, k_F and p and using the Cramer's rule, we get $\frac{\partial q_F}{\partial p} = \frac{c_{kk}^F}{c_{qq}^F c_{kk}^F - \left(c_{qk}^F\right)^2} > 0$, since $c_{kk}^F > 0$ and $c_{qq}^F c_{kk}^F - \left(c_{qk}^F\right)^2 > 0$. Thus, the competitive firms' abatement is increasing in the price and more responsive than in Timing I (the corresponding effect being given by $\frac{\partial q_F}{\partial p} = \frac{1}{c_{qq}^F}$). The reason is that the competitive firms now have two reaction variables instead of one: abatement and adoption, which allow them to defend better against the dominant firm's power in setting the permit price.

Now, in the first stage, the dominant firm solves the problem:

$$\begin{aligned} \min_{e_1} \quad & c^1 + rk_1 + p \cdot \left(q_1^0 - q_1\right), \\ s.t. \quad & q_1 + (N-1) \cdot q_F = Q^0, \end{aligned}$$

where $q_F = q_F\left(p, k_F, \gamma\right)$ is implicitly given in (7) and (10). The optimality conditions of this problem are exactly the same as those presented in (8), (9), and (10) for $i = 1$. Thus, the only difference is that we now have $\frac{\partial q_F}{\partial p} = \frac{c_{kk}^F}{c_{qq}^F c_{kk}^F - \left(c_{qk}^F\right)^2}$.

All the equilibrium conditions for the interior solution of this aternative timing are summarized next.

Proposition 5 *Under Timing II, the interior firms' abatement levels, technology adoption levels, and the resulting permit price are implicitly determined by the following conditions:*

$$c_q^F = p; \tag{24}$$

$$c_q^1 = p + \frac{\left(q_1^0 - q_1\right)}{N-1} \frac{c_{qq}^F c_{kk}^F - \left(c_{qk}^F\right)^2}{c_{kk}^F}; \tag{25}$$

$$q_1 + (N-1) \cdot q_F = Q^0; \tag{26}$$

$$c_k^i + r = 0, \quad i = 1, F. \tag{27}$$

Qualitatively similar conclusions to those under Proposition 3 can be obtained here. Apart from this, the only thing that we can conclude at this level of generality is that the solution of this timing is closer to the benchmark than the solution under Timing I. The reason is that the competitive firms' response to the permit price in this case is larger and, everything else equal, the departure of firm 1's marginal abatement costs from the permit price is smaller (see (25) versus (12)). This result is highlighted in the following Proposition, which follows directly from the comparsion between expresssions (12) and (25).

Proposition 6 *For given parameters $(\gamma, Q^0, q_1^0, N, r)$, the equilibrium abatement and technology levels under Timing II are closer to the benchmark solution than the corresponding equilibrium levels under Timing I.*

We now particularize the solution in the quadratic cost case, getting the following expressions for an interior solution:[13]

$$q_1 = \frac{Q^0 + q_1^0}{N+1}; \; q_F = \frac{NQ^0 - q_1^0}{(N-1)(N+1)}; \tag{28}$$

$$k_1 = \frac{\alpha}{2}\frac{Q^0 + q_1^0}{N+1} - \frac{r}{\gamma}; \; k_F = \frac{\alpha}{2}\frac{NQ^0 - q_1^0}{(N-1)(N+1)} - \frac{r}{\gamma}; \tag{29}$$

$$p = \frac{4-\alpha^2\gamma}{4}\frac{NQ^0 - q_1^0}{(N-1)(N+1)} + \frac{\alpha r}{2}. \tag{30}$$

As under Timing I, the equilibrium levels crucially depend on q_1^0, and specifically, on whether $q_1^0 \lesseqgtr Q^0/N$. In qualitative terms, the same conclusions that we have presented for Timing I in the previous subsection are also valid under Timing II. If $q_1^0 > Q^0/N$, the dominant firm acts as a monopsonist in the permits market, and over-abates and over-invests with respect to the benchmark situation. If, on the contrary, $q_1^0 < Q^0/N$, the dominant firm acts as a monopolist

[13] Again, the possibility of corner solutions crucially depends on the amount of abatement initially required for the dominant firm, in relation to average abatement. In the case where $q_1^0 > Q^0/N$, it is possible that the competitive firms decide not to invest at all. In the alternative case where $q_1^0 < Q^0/N$, it is possible that the dominant firm decides not to invest at all.

in the permit market, and thus under-abates and under-invests with respect to the benchmark case. In any case, the departure from the benchmark is softer in this case than under Timing I.

Regarding the comparative statics in this case, the effects of the different parameters on the equilibrium levels are also softer. For example, it is interesting to see that the effectiveness parameter γ does not affect abatement levels in this case, which implies that both technology investment levels of the dominant and the competitive firms are clearly increasing, although non-diverging, in γ. Thus, unlike Timing 1, the distance of the equilibrium values of abatement and technology investment with respect to the benchmark case does no depend on γ, which means that the effectiveness of technology does not aggravate (or alleviate) the inefficiency cost due to market power.[14]

5.2 An alternative cost function

In this subsection, we consider an alternative functional form for the abatement cost function outside the quadratic specification. Specifically, we assume $G(q,k) = \frac{q^2}{2(k+1)}$ and $H(q) = \frac{q^2}{2}$, which implies that the resulting abatement cost function is:

$$c(q_i, k_i, \gamma) \equiv \frac{q^2 [1 + (1-\gamma) k]}{2(k+1)}.$$

Consider first Timing I. Starting with the benchmark case, the solution is given by the following set of equations:

[14] The two last results are specific features of the quadratic case. In the following subsection, under an alternative specification, we find that technology investment levels do diverge as long as γ increases and the effectiveness of technology adoption aggravates the inefficiency due to market power under both timings.

$$q_i = \frac{Q^0}{N}, \quad \text{for all } i; \tag{31}$$

$$k_i = \left(\frac{\gamma}{2r}\right)^{1/2} \frac{Q^0}{N}, \quad \text{for all } i; \tag{32}$$

$$p = (1-\gamma)\,\frac{Q^0}{N} + \gamma\left(\frac{2r}{\gamma}\right)^{1/2}. \tag{33}$$

In the extreme case $\gamma = 0$ where technology adoption is uneffective, it is optimal for all the firms not to adopt at all, that is, $k = 0$, and the permit price is given just by the required aggregate abatement, $p = \frac{Q^0}{N}$. In the opposite extreme case, $\gamma = 1$, the permit price is given by $p = (2r)^{1/2}$, and it does not depend on the required aggregate abatement but only on the price of the technology adoption.

The market power case under Timing I cannot be solved in general terms.[15] To gain same intuition, we first explore the two extreme scenarios where $\gamma = 0$ and $\gamma = 1$ respectively. We first consider the case $\gamma = 0$. In this case we get get $k_1 = k_F = 0$. The equilibrium price and the abatement levels reduce to:

$$p = \frac{NQ^0 - q_1^0}{(N+1)(N-1)} \tag{34}$$

$$q_1 = \frac{Q^0 + q_1^0}{N+1}, \tag{35}$$

$$q_F = \frac{NQ^0 - q_1^0}{(N+1)(N-1)}. \tag{36}$$

Once again, we conclude that the equilibrum under market power coincide with the benchmark solution only if the regulator initially requires the dominant firm to abate one N-th of

[15] It is possible to manipulate the first order equations in such a way that all the variables can be written in terms of k_F and k_F is implicitly given by a cubic equation that cannot be analytically solved except for the extreme cases $\gamma = 0$ and $\gamma = 1$. Details are available upon request.

total abatement, that is, $q_1^0 = \frac{Q^0}{N}$. However, $q_1^0 < (>) \frac{Q^0}{N}$ results in firm 1 acting as a monopolist (monopsonist) in the permit market, which prevents the equilibrium solution from being cost-effective.

In the opposite extreme case, $\gamma = 1$, the equilibrium levels are given by:

$$k_1 = \frac{q_1^0}{\sqrt{2r}}. \tag{37}$$

$$k_F = \frac{Q^0 - q_1^0}{\sqrt{2r}\,(N-1)}. \tag{38}$$

$$p = (2r)^{1/2}, \tag{39}$$

$$q_1 = q_1^0,$$
$$q_F = \frac{Q^0 - q_1^0}{N-1}.$$

Again, these results mimic those of the benchmark case only if $q_1^0 = \frac{Q^0}{N}$. The distinctive feature of this limiting case is that the dominant firm does not trade permits in the secondary market as it ends up doing exactly the same abatement as it is initially required to do while the firms belonging to the competitive fringe do exactly the same abatment (one $N-1$th of the remaining required abatement). Thus, if these firms are initially endowed with different amounts of permits, they will trade until all of them exert exactly the same abatement effort. As a consequence, the price is the same as under the benchmark case. This is in contrast to Hahn (1984), where the dominant firm always trades permits and acts either as a monopolist or a monopsonist except if it receives exactly the cost-effective amount of permits in the initial allocation. Thus, regarding cost-effectiveness, in this limiting case the way permits are initially allocated becomes particularly relevant as long as technology adoption is effective enough for reducing abatement costs.

Due to the difficulty of extracting general conclusions for intermediate values of γ, we have to rely on numerical examples. All the examples analyzed display the same qualitative behavior as the one shown in Figures 1 and 2 for the quadratic specification. The only difference is that the divergence of abatement and technology investment levels is more drastic here, since the dominant firm decides not to trade permits at all when tehcnology investment is most effective, that is, when $\gamma = 1$.

The alternative timing presented in Proposition 5 can also be analyzed under this cost secification, and the resulting abatement and technology adoption levels are given by:

$$q_1 = \frac{Q^0 + q_1^0}{N+1};\; q_F = \frac{NQ^0 - q_1^0}{(N+1)(N-1)};$$
$$k_1 = \sqrt{\frac{\gamma}{2r}\frac{Q^0 + q_1^0}{N+1}};\; k_F = \sqrt{\frac{\gamma}{2r}\frac{NQ^0 - q_1^0}{(N+1)(N-1)}}.$$

As in the quadratic specification under this timing, the abatement levels do not depend on the effectiveness parameter γ. Also, the corresponding expressions mimic those of Timing I when $\gamma = 0$, see (35) and (36). Thus, abatement levels under Timing II again lie between those of Timing I and the benchmark scenario.

6 Conclusions

In this paper, we have considered a permit market characterized by market power and the fact that firms can adopt more efficient abatement technologies. Our first objective is to study the effect of technology adoption on emission permit markets with market power, in an aim to enrich Hahn (1984)'s results. Our second objective is to analyze how the technology adoption decisions are affected by the presence of market power in the emission permit market, in an aim to contribute to the literature on technology adoption (see e.g. Requate (2005)).

By comparing a benchmark model of perfect competition in permit trading with a situation of market power with a dominant firm, we conclude that the specific amount of abatement required for the dominant is crucial in determining not only under- or over-abatement with respect to the benchmark case, but also under- or over-adoption in clean technology. Thus, if the dominant firm is initially endowed with more permits, its monopolistic position will prompt it to under-abate and under-adopt with respect to the benchmark case of perfect competition. The opposite arises if the dominant firm is initially given relatively less permits, acting then as a monopsonist.

We also find that the existence of market power results in a divergence of abatement and technology adoption levels with respect to the cost-effective solution as the effectiveness of technology adoption in reducing abatement costs increases. Paradoxically, this happens while the permit price under market power converges to the permit price under perfect competition due to the fact that the role of the dominant price as a price-setter decreases.

As a policy implication, our results reinforce and qualify those of Hahn (1984) by noting that, when technology investment is very effective, the regulator should be especially careful with the initiall allocation of permits and, more specifically, with the amount of permits initially given to dominant firms. In fact, it is not difficult to construct limiting scenarios where a dominant firm may decide not to trade permits at all, and simply adjust to this decision by investing much less or much more in technology adoption than under perfect competition. Although these extreme situations may not be realistic they serve to stress the point that the distortion due to market power can be particularly severe when technology adoption is a very relevant factor.

We have also shown that our main messages are robust to alternative timings and abatement cost functions outside the quadratic specification. However, several extensions of our model are possible. For example, we could consider heterogeneity in abatement costs, situations with more than one dominant firm, or the possibility of non-compliance. Although the mathematical analysis is surely more complex, we believe that the main conclusion of our work holds, that is, the abatement level required for the dominant firm(s) is specially crucial as long as technology investment becomes more effective in reducing abatement costs.

7 Appendix: Derivation of the solution of Timing I in the quadratic case

Conditions (11), (12) and (13) reduce to the following set of equations :

$$q_F = p + \frac{\alpha\gamma k_F}{2}; \tag{40}$$

$$q_1 = p + \frac{\alpha\gamma k_1}{2} + \frac{q_1^0 - q_1}{N-1}; \tag{41}$$

$$q_1 + (N-1)\, q_F = Q^0. \tag{42}$$

Substituting (40) and (41) into (42), and rearranging terms, we obtain the permit price as a function of technology investment and the parameters of the model:

$$p = \frac{NQ^0 - q_1^0 - (N-1)\frac{\alpha\gamma}{2}(k_1 + Nk_F)}{(N-1)(N+1)}, \tag{43}$$

and substituting this expression in (40) and (41) results in:

$$q_1 = \frac{Q^0 + q_1^0}{N+1} + \frac{N-1}{N+1}\frac{\alpha\gamma}{2}(k_1 - k_F); \tag{44}$$

$$q_F = \frac{NQ^0 - q_1^0}{(N-1)(N+1)} - \frac{1}{N+1}\frac{\alpha\gamma}{2}(k_1 - k_F). \tag{45}$$

We now consider condition (14) of Proposition 3, which in this context reduces to:

$$k_i = \frac{\alpha}{2} q_i - \frac{r}{\gamma},\ i = 1, F. \tag{46}$$

The latter expression reveals that the solution is interior (i.e., both firms decide to make some investment) unless the price of investment r is too high or the effectiveness of investment is too low in terms of the equilibrium abatement. We derive the interior solution first. Substituting (44) and (45) in (46) and rearranging terms, we obtain:

$$k_1 - k_F = \frac{2\alpha\,(Nq_1^0 - Q^0)}{(N-1)\left[4(N+1) - \gamma\alpha^2 N\right]}, \tag{47}$$

and substituting this expression back in (44) and (45), we respectively obtain the abatement levels of the dominant and competitive firms in terms of the parameters of the model:

$$q_1 = \frac{4q_1^0 + (4-\gamma\alpha^2)\,Q^0}{4\,(N+1) - \gamma\alpha^2 N}; \tag{48}$$

$$q_F = \frac{\left[4N - \alpha^2\gamma\,(N-1)\right]Q^0 - 4q_1^0}{(N-1)\left[4\,(N+1) - \gamma\alpha^2 N\right]}. \tag{49}$$

Substituting expressions (48) and (49) in (46), we obtain the closed-form expressions for the corresponding technology investment levels:

$$k_1 = \frac{\alpha}{2}\frac{4q_1^0 + (4-\gamma\alpha^2)\,Q^0}{4\,(N+1) - \gamma\alpha^2 N} - \frac{r}{\gamma}, \tag{50}$$

$$k_F = \frac{\alpha}{2}\frac{\left[4N - \alpha^2\gamma\,(N-1)\right]Q^0 - 4q_1^0}{(N-1)\left[4\,(N+1) - \gamma\alpha^2 N\right]} - \frac{r}{\gamma}. \tag{51}$$

Assuming that both conditions are positive, we now use condition (46) to obtain:

$$k_1 + Nk_F = \frac{\alpha}{2}\left(q_1 + Nq_F\right) - (N+1)\,\frac{r}{\gamma} \equiv \frac{\alpha}{2}\left(Q^0 + q_F\right) - (N+1)\,\frac{r}{\gamma}.$$

We finally substitute this expression in (43), and we make use of (42) and (49) to obtain the equilibrium permit price:

$$p = \frac{\alpha r}{2} + \frac{4-\gamma\alpha^2}{4}\frac{\left[4N - \alpha^2\gamma\,(N-1)\right]Q^0 - 4q_1^0}{(N-1)\left[4\,(N+1) - \gamma\alpha^2 N\right]} \tag{52}$$

We now analyze the corner solutions. These crucially depend on the amount of abatement initially required for the dominant firm, in relation to average abatement. Consider first the case where $q_1^0 > Q^0/N$. In this case, we have $q_F < q_1$, see (48) and (49). Going back to expression (46), this means that $k_F < k_1$. Hence, it is more likely that expression (46) is negative for the competitive firm than for the dominant firm. Thus, two possible corner solutions arise: (i) only $k_F = 0$, and (ii) both $k_1 = k_F = 0$. These are computed substituting either $k_F = 0$ or

$k_1 = k_F = 0$ in expressions (43), (44) and (45). The corresponding equilibrium expressions in these two corner cases when $q_1^0 > Q^0/N$ are the following:

(i) If $\frac{\alpha}{2}\frac{\left[4N-\alpha^2\gamma(N-1)\right]Q^0-4q_1^0}{(N-1)[4(N+1)-\gamma\alpha^2 N]} \leq \frac{r}{\gamma} \leq \frac{\alpha}{2}\frac{4q_1^0+\left(4-\gamma\alpha^2\right)Q^0}{4(N+1)-\gamma\alpha^2 N}$, then:

$$
\begin{aligned}
q_1 &= \frac{4\left(Q^0+q_1^0\right)-2\left(N-1\right)\alpha r}{4\left(N+1\right)-\gamma\alpha^2\left(N-1\right)}; \\
q_F &= \frac{\left[4N-\gamma\alpha^2\left(N-1\right)\right]Q^0-4q_1^0+2\alpha r\left(N-1\right)}{\left(N-1\right)\left[4\left(N+1\right)-\gamma\alpha^2\left(N-1\right)\right]}; \\
k_1 &= \frac{2\alpha\gamma\left(Q^0+q_1^0\right)-4\left(N+1\right)r}{\gamma\left[4\left(N+1\right)-\gamma\alpha^2\left(N-1\right)\right]}; \\
k_F &= 0; \\
p &= \frac{\left[4N-\gamma\alpha^2\left(N-1\right)\right]Q^0-4q_1^0+2\alpha r\left(N-1\right)}{\left(N-1\right)\left[4\left(N+1\right)-\gamma\alpha^2\left(N-1\right)\right]}.
\end{aligned}
$$

(ii) If $\frac{r}{\gamma} \geq \frac{\alpha}{2}\frac{4q_1^0+\left(4-\gamma\alpha^2\right)Q^0}{4(N+1)-\gamma\alpha^2 N}$, then:

$$
\begin{aligned}
q_1 &= \frac{Q^0+q_1^0}{N+1}; \\
q_F &= \frac{NQ^0-q_1^0}{\left(N-1\right)\left(N+1\right)}; \\
k_1 &= k_F = 0; \\
p &= \frac{NQ^0-q_1^0}{\left(N-1\right)\left(N+1\right)}.
\end{aligned}
$$

If, on the contrary, $q_1^0 < Q^0/N$, we then have $q_1 < q_F$. Going back to expression (46), this means that $k_1 < k_F$. The two possible corner solutions in this case are: (i) only $k_1 = 0$, and (ii) both $k_1 = k_F = 0$. The former case arises as long as $\frac{\alpha}{2}\frac{4q_1^0+\left(4-\gamma\alpha^2\right)Q^0}{4(N+1)-\gamma\alpha^2 N} \leq \frac{r}{\gamma} \leq \frac{\alpha}{2}\frac{\left[4N-\alpha^2\gamma(N-1)\right]Q^0-4q_1^0}{(N-1)[4(N+1)-\gamma\alpha^2 N]}$, and the corresponding equilibrium expressions are the following (the latter are equivalent to the previous case when $q_1^0 > Q^0/N$ and $k_1 = k_F = 0$) :

$$
\begin{aligned}
q_1 &= \frac{\left(4-\alpha^2\gamma\right)Q^0+4q_1^0+2\left(N-1\right)\alpha r}{4\left(N+1\right)-\alpha^2\gamma}; \\
q_F &= \frac{4\left(NQ^0-q_1^0\right)-2\left(N-1\right)\alpha r}{\left(N-1\right)\left[4\left(N+1\right)-\alpha^2\gamma\right]}; \\
k_1 &= 0; \\
k_F &= \frac{2\alpha\left(NQ^0-q_1^0\right)-4\left(N-1\right)\left(N+1\right)r}{\left(N-1\right)\left[4\left(N+1\right)-\alpha^2\gamma\right]}; \\
p &= \frac{\left(4-\alpha^2\gamma\right)\left(NQ^0-q_1^0\right)+2\alpha\gamma N\left(N-1\right)r}{\left(N-1\right)\left[4\left(N+1\right)-\alpha^2\gamma\right]}.
\end{aligned}
$$

To analyze the comparative statics, we start by taking the partial derivatives of the equilibrium expressions (19) to (23) with respect to γ. These are the following:

$$
\begin{aligned}
\frac{\partial q_1}{\partial\gamma} &= \frac{4\alpha^2\left(Nq_1^0-Q^0\right)}{\left[4\left(N+1\right)-\gamma\alpha^2N\right]^2}; && (53) \\
\frac{\partial q_F}{\partial\gamma} &= \frac{4\alpha^2\left(Q^0-Nq_1^0\right)}{\left(N-1\right)\left[4\left(N+1\right)-\gamma\alpha^2N\right]^2}; && (54)
\end{aligned}
$$

(the corresponding expressions have opposite signs and such signs are fully dependent on the sign of $Nq_1^0-Q^0$ or, equivalently, on the sign of $q_1^0-\frac{Q^0}{N}$)

$$
\begin{aligned}
\frac{\partial k_1}{\partial\gamma} &= \frac{2\alpha^3\left(Nq_1^0-Q^0\right)}{\left[4\left(N+1\right)-\gamma\alpha^2N\right]^2}+\frac{r}{\gamma^2}; && (55) \\
\frac{\partial k_F}{\partial\gamma} &= \frac{2\alpha^3\left(Q^0-Nq_1^0\right)}{\left(N-1\right)\left[4\left(N+1\right)-\gamma\alpha^2N\right]^2}+\frac{r}{\gamma^2}; && (56)
\end{aligned}
$$

$$
\frac{\partial p}{\partial\gamma}=-\frac{\alpha^2q_F}{4}\left\{1-\frac{4\left(4-\gamma\alpha^2\right)\left(Q^0-Nq_1^0\right)}{\left[4\left(N+1\right)-\gamma\alpha^2N\right]\left\{\left[4N-\alpha^2\gamma\left(N-1\right)\right]Q^0-4q_1^0\right\}}\right\}<0. \quad (57)
$$

The last expression is obtained computing the partial derivative of expression (23) with respect to γ and using (54):

$$
\begin{aligned}
\frac{\partial p}{\partial\gamma} &= -\frac{\alpha^2q_F}{4}+\frac{4-\gamma\alpha^2}{4}\frac{\partial q_F}{\partial\gamma} \\
&= -\frac{\alpha^2q_F}{4}+\frac{4-\gamma\alpha^2}{4}\frac{4\alpha^2\left(Q^0-Nq_1^0\right)}{\left(N-1\right)\left[4\left(N+1\right)-\gamma\alpha^2N\right]^2}.
\end{aligned}
$$

This expression is combined with (20), we obtain (57) .[16]

To analyze differences in abatement levels, we combine (19) and (20) to have:

$$q_1 - q_F = \frac{4\left(Nq_1^0 - Q^0\right)}{(N-1)\left[4\left(N+1\right) - \gamma\alpha^2 N\right]} \tag{58}$$

from which we know

$$q_1 - q_F > 0 \Leftrightarrow q_1^0 > \frac{Q^0}{N}$$

Simple inspection of expression (58) lead us to conclude that abatement levels diverge with respect to γ, and they also diverge with respect to the required abatement level for the dominant firm.

We now continue with the comparison of technology investment levels. From (46), we have

$$k_1 - k_F = \frac{\alpha}{2}\left(q_1 - q_F\right) = \frac{2\alpha\left(Nq_1^0 - Q^0\right)}{(N-1)\left[4\left(N+1\right) - \gamma\alpha^2 N\right]}$$

and then $k_1 - k_F$ displays qualitatively the same behavior as $(q_1 - q_F)$.

Next, we compare the results for the dominant firm versus the benchmark. Since total abatement is constant both with and without market power, it suffices to study the deviation of the dominant firm with respect to the benchmark, as the remaininf firms' deviations must be the same with opposite sign.

Using the relevant expressions we have

[16] To prove this, it is enough to show that $\frac{4\left(4-\gamma\alpha^2\right)\left(Q^0-Nq_1^0\right)}{\left[4(N+1)-\gamma\alpha^2 N\right]\left\{\left[4N-\alpha^2\gamma(N-1)\right]Q^0-4q_1^0\right\}} < 1$. This expression holds, since $4-\gamma\alpha^2 < 4\left(N+1\right)-\gamma\alpha^2 N$ (because $N \geq 2$) and $4\left(Q^0 - Nq_1^0\right) < \left[4N - \alpha^2\gamma\left(N-1\right)\right] Q^0 - 4q_1^0$. The latter can be seen by rearranging terms as follows: $\left[4 - 4N + \alpha^2\gamma\left(N-1\right)\right] Q^0 < 4\left(N-1\right) q_1^0$, or alternatively, $\left(4 - \alpha^2\gamma\right)\left(1-N\right) Q^0 < 4\left(N-1\right) q_1^0$.

$$q_1 - q_B = \frac{4q_1^0 + (4-\gamma\alpha^2) Q^0}{4(N+1) - \gamma\alpha^2 N} - \frac{Q^0}{N} \tag{59}$$

$$= \frac{N\left[4q_1^0 + (4-\gamma\alpha^2) Q^0\right] - \left[4(N+1) - \gamma\alpha^2 N\right] Q^0}{N\left[4(N+1) - \gamma\alpha^2 N\right]} \tag{60}$$

$$= \frac{4\left(Nq_1^0 - Q^0\right)}{N\left[4(N+1) - \gamma\alpha^2 N\right]} = \frac{N-1}{N}(q_1 - q_F) > 0 \Leftrightarrow q_1^0 > \frac{Q^0}{N} \tag{61}$$

and the partial derivative with respect to γ results in:

$$\frac{\partial}{\partial\gamma}(q_1 - q_B) = \frac{4\alpha^2\left(Nq_1^0 - Q^0\right)}{\left[4(N+1) - N\gamma\alpha^2\right]^2}$$

Regarding investment, we have shown above that total investment is the same with and without market power, and therefore, once again, it suffices to study the behavior of the dominant firm. Using the relevant expressions we have

$$k_1 - k_B = \frac{\alpha}{2}\frac{4q_1^0 + (4-\gamma\alpha^2) Q^0}{4(N+1) - \gamma\alpha^2 N} - \frac{\alpha}{2}\frac{Q^0}{N}$$

$$= \frac{\alpha}{2}\frac{N\left[4q_1^0 + (4-\gamma\alpha^2) Q^0\right] - Q^0\left[4(N+1) - \gamma\alpha^2 N\right]}{N\left[4(N+1) - \gamma\alpha^2 N\right]}$$

$$= \frac{2\alpha\left(Nq_1^0 - Q^0\right)}{N\left[4(N+1) - \gamma\alpha^2 N\right]} = \frac{(N-1)}{N}(k_1 - k_F)$$

and so, the deviation of the dominant firm with respect to the benchmark has the same sign as the deviation of the dominant firm with respect to the competitive firms.

Finally, we compare the price with and without market power.

$$p - p_B = \frac{4-\gamma\alpha^2}{4}\left\{\frac{N\left[4N - \alpha^2\gamma(N-1)\right]Q^0 - 4Nq_1^0}{N(N-1)\left[4(N+1) - \gamma\alpha^2 N\right]} - \frac{Q^0(N-1)\left[4(N+1) - \gamma\alpha^2 N\right]}{N(N-1)\left[4(N+1) - \gamma\alpha^2 N\right]}\right\}$$

$$= \frac{(4-\gamma\alpha^2)\left(Q^0 - Nq_1^0\right)}{N(N-1)\left[4(N+1) - \gamma\alpha^2 N\right]} > 0 \Leftrightarrow q_1^0 < \frac{Q^0}{N}$$

Taking the partial derivative with respect to γ, we obtain:

$$\frac{\partial}{\partial\gamma}(p - p_B) = \frac{4\alpha^2\left(Nq_1^0 - Q^0\right)}{N(N-1)\left[4(N+1) - \gamma\alpha^2 N\right]^2} < 0 \Leftrightarrow q_1^0 < \frac{Q^0}{N}.$$

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