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Diffusion of Abatement Technologies in a Differentiated Industry

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Abstract

This paper studies the timing pattern of adoption of green technologies in a differentiated oligopolistic industry. A firm, faced with an emission tax, has incentive to buy the new technology that reduces its per-unit of output emissions in order to gain market share from its rivals. It is shown that the adoption pattern depends on the level of emission tax, the type of product market competition, the degree of product differentiation, and also on the ability of firms to pre-commit, or not, to a certain adoption date. The last adoption is always earlier under Cournot competition than under Bertrand in both the pre-commitment and the pre-emptive equilibria. Also, in a pre-commitment equilibrium the first adoption under Bertrand is earlier than under Cournot but only if the goods are sufficiently close substitutes. However, in a pre-emptive equilibrium the first adoption under Bertrand is always earlier than under Cournot. Finally, comparative static results with respect to the level of emission tax are presented.

Keywords: Abatement Technology, Diffusion, Differentiated Industry, Oligopoly

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1. Introduction

The threat of climate change due to the accumulation of carbon dioxide, as well other greenhouse gases (GHGs) in the atmosphere has become recently a major economic and political issue. There is by now a general consensus that the socioeconomic consequences of global warming could be very harmful to our planet, and could be even disastrous for some geographic areas or countries. This attitude was reflected on the Convention for the Climate Change organized by the United Nations in Kioto (Japan), in December 1997, and in which as many as 160 countries participated. The main issue at stake for the participants was to control their GHGs emissions in order to achieve a stabilization of the global GHGs emissions in 2010 to their level of 1990. This stabilization can be only achieved if the most-industrialized countries can commit to a substantial decrease of their pollutants. The agreement reached in Kioto, a 5.2% emission reduction on average for the 39 most-developed countries, is a satisfactory first step towards the stabilization of the global GHGs emissions. In particular, the EU has committed to a reduction of its emissions by 8% (which however will not be distributed evenly among its country members). The EU's common posture is that an 8% reduction of its emissions level in 2010, with respect to their level of 1990, can be achieved exclusively through a wide diffusion of the Best Available Technologies (BATs) in their most polluting sectors (such as transportation, industrial sector, energy production etc.). Therefore, the investigation of the economic forces that facilitate, or hinder, the diffusion of existing "clean" technologies becomes all the more important. Yet, the literature on the diffusion of green technologies is rather scarce.

Recently, a number of empirical studies investigate the private incentives for adoption of the Best Available Technology in the absence of environmental policies, as well how these incentives are influenced by policies such as emission taxes and innovation subsidies[2]. Boetti and

[2] Velthuijsert (1993) discusses factors hindering the diffusion of energy-saving technologies. For a

adoption process innovations.

We analyze both the pre-commitment and the preemptive equilibria of the adoption game. If there are long information lags, or it is prohibitively costly for a firm to alter its adoption plans, firm i can *pre-commit* at date 0 to an implementation date T_i. If, on the contrary, there are no information lags and moreover, altering adoption plans has no cost for a firm, each firm adopts *preemptively* to prevent, or delay, adoption by its opponent. As a result, firms' profits are equal in the preemptive equilibrium. We are thus able to investigate the extent to which diffusion rates depend on the flexibility a firm has in altering its plans of implementation of the green technology. Further, by studying a differentiated industry with symmetric demands, we are able to explore the impact of product differentiation on the rate of diffusion of the clean technology.

It is shown that, as the tax rate on emissions increases, firms adopt earlier the abatement technology in both the preemptive and pre-commitment equilibria. The diffusion pattern of the green technology depends on the type of market competition, the degree of product differentiation, the ability of firms to precommit, or not, to a specific adoption date, as well the size of the market and the degree to which the innovation reduces firms unitary emissions. In particular, in both the pre-commitment and preemptive equilibria, the Cournot follower always adopts earlier than the Bertrand follower. Also, in a pre-commitment equilibrium the Bertrand leader adopts earlier than the Cournot leader, but only if the goods are sufficiently close substitutes. The opposite is true for lower values of substitutability. However, in a preemptive equilibrium the Bertrand leader adopts *always* earlier than the Cournot leader.

Our findings suggest that the dynamic inefficiencies introduced by the market imperfections cannot be corrected through a uniform tax on emissions. For each firm, there exists an emissions tax rate inducing the firm to adopt the clean technology at the socially optimal date, but these tax

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firms compete in prices or quantities.

Botteon (1996) report that a widespread adoption of some energy-saving technologies is likely to lead to a reduction in CO_2 emissions of approximately 10% compared to 1990 levels. However, in the absence of any environmental policy, this reduction could be only of the order of 2.5%. In this light, the design of environmental policies influences the firms' incentives to adopt an abatement technology and hence plays a crucial role in their effectiveness to reduce emissions.

On the other hand, to my knowledge, there is hardly any theoretical paper addressing the issue of diffusion of green technologies. The exception is Carraro and Soubeyran (1996) where the incentives of a firm to adopt a clean technology under different environmental policies are analyzed. However, this paper assumes away any strategic considerations[3]. For instance, when firms compete in the market and also face emissions taxes, a firm may have incentive to adopt earlier the clean technology to reduce the tax burden on its emissions and thus gain market share from its rivals.

This paper analyzes the firms' incentives to adopt an existing abatement technology (for instance, the BAT) in a differentiated industry where two firms compete in prices, or quantities, in the product market. Pollution is a by-product of their production process, and firms' emissions are taxed at a rate τ. The firms choose their dates of adoption of a green technology that becomes available in the market at time 0. A firm, by adopting the green technology, can reduce its per unit of output emissions, and thus decrease its emissions tax burden. The costs of purchasing and implementing the green technology decreases, at a decreasing rate, over time. These costs may decline substantially as the development horizon becomes longer due to either learning-by-doing or

discussion of some issues concerning the payback time of a green technology see Krause et al. (1993).

[3] Note, however, that there is an extensive strategic-theoretic literature on the related subject of diffusion of cost-reducing innovations. Reinganum (1981a&b, 1983), Fudenberg & Tirole (1985) and Quirmbach (1986)) analyze a homogeneous industry, while Petrakis (1994) studies a differentiated industry. Reinganum (1981a&b, 1983) investigates the diffusion of new technologies in an oligopoly where each firm can commit to a specific adoption date, while Fudenberg & Tirole (1985) consider the opposite case where firms can preempt their rivals. Quirmbach (1986) compares the diffusion rates under alternative innovation market structures and shows that, in a precommitment equilibrium, the rate of diffusion is faster in market structure A than in B if and only if all the incremental benefits of adopting the new technology are larger in A than in B. Petrakis (1994) extends the above analyses in the case of a differentiated product market where

current technology.

At date t=0 an abatement technology that reduces emissions is available in the market. A firm can acquire the green technology at any date $t\geq 0$ and reduce thereafter its unitary emissions to λ-δ, $0<\delta<\lambda$. Thus, the green technology reduces the firm's "effective" marginal cost by $\tau\delta$. Let $k(t)$ be the *present value* of the costs of purchasing and implementing the green technology by date t. As it is standard in this literature, we assume that the current cost, $k(t)e^{rt}$, is decreasing over time, at a decreasing rate; that is, $(k(t)e^{rt})'<0$ and $(k(t)e^{rt})''>0$, where r is the interest rate, $0<r<1$ (see e.g. Fudenberg & Tirole (1985)). Due to either economies of learning, or new results from basic research facilitating the adoption process, adoption costs typically decline as the development horizon becomes longer. To avoid corner solutions, we further assume that (a) $\lim_{t\to 0} k(t)=-\lim_{t\to 0} k'(t)=\infty$, a sufficient condition for immediate adoption to be prohibitively costly; and (b) $\lim_{t\to\infty} k'(t)e^{rt}= 0$, a condition guaranteeing that all adoptions occur in finite time. Finally, we assume that no further green innovations are anticipated in the industry.

The market operates every date $t\geq 0$. Market demands are stationary over time. Following Dixit (1979), the representative consumer's utility over the differentiated goods (x_1, x_2) and the numeraire good m is,

$$U(x_1, x_2) = a(x_1 + x_2) - (x_1^2 + 2\gamma x_1 x_2 + x_2^2)/2 + m \qquad (1)$$

where $a> c_0+\tau\lambda$ and $0<\gamma<1$. The assumption that utility is linear in the numeraire good eliminates income effects and allows us to perform partial equilibrium analysis. This specification of $U(.)$ generates a linear symmetric demand system,

$$p_1 = a - x_1 - \gamma x_2 \qquad p_2 = a - x_2 - \gamma x_1 \qquad (2)$$

which permits us to study how the adoption timing of the green technology depends upon the substitutability of the two goods. The latter is measured by the parameter γ. As γ increases the

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commit to a specific policy.

rates differ among firms. Therefore, subsidization of the implementation costs of the green technology, coupled with a uniform tax on emissions, is necessary for the social optimum diffusion pattern to be restored. Further, the right mix of policy tools is sensitive to all the factors mentioned above.

The paper is organized as follows. Section 2 presents the model and outlines the basic assumptions. It also analyzes the per-period product market competition under cost asymmetries. In section 3 the adoption patterns in a pre-commitment equilibrium are derived and compared when firms are competing a la Cournot, or a la Bertrand, in the product market. Section 4 derives and compares those adoption patterns observed in a preemptive equilibrium. Finally, Section 5 concludes.

2. The Model

We consider an economy with an oligopolistic sector, consisting of two firms that produce differentiated goods, and a competitive numeraire sector. The firms possess identical constant returns to scale technologies and compete in quantities, or in prices, in the product market. The marginal cost of production equals c_0. Pollution of the environment is a by-product of the firms' production process. In particular, one unit of output produced with the current technology generates λ units of emissions. Firms face an exogenously given per-unit of emissions tax, τ. We assume that τ has been chosen by the government in the past, and that the government has the ability to commit to a specific policy[4]. Then a firm, due to its emissions, has an additional cost, $\lambda\tau$, per unit of output. Therefore, $c=c_0+\tau\lambda$ is the *effective marginal cost* of a firm producing with its

[4] Since the tax rate aggravates the firm's emissions only during the production stage, the government often has incentive to alter its emissions tax level after a firm has adopted the green technology. A firm then will decide on its adoption date taking into account that the government's policy will change according to the number of firms that have already adopted the green technology. In this paper we abstract from issues of time consistency of the government policy. We will assume throughout that the government is able to credibly

quantities? As we will see, the answer is no. As in Bester & Petrakis (1993) there is an additional effect, *the market share effect*, which plays an important role. Whenever the green technology leads to a substantial increase of its market share, the firm has a stronger incentive to adopt the innovation earlier since the reduction of its effective marginal cost applies to a higher volume of production. As previously, we restrict ourselves to parameter values for which both firms operate in the market. This happens if and only if $p_i^B(c_i, c_j)>c_i$. From (5) this holds if $\gamma<\gamma_B(\rho,\lambda,\delta)$, where γ_B is implicitly defined by $\gamma_B \equiv \gamma_C[2-\gamma_B^2]/2$. Thus, $\gamma_B< \gamma_C$.

3. Adoption Patterns under Pre-commitment

In this section we assume that firms can pre-commit to a specific adoption date. At date 0, firm i chooses its adoption date T_i. Firms then compete in the product market each date $t\geq 0$. Adoption date refers to the date by which the green technology can be implemented. In general, implementation of a new technology requires long term plans that can be altered later, but only at some cost. Pre-commitment at date 0 is then a time-consistent behavior for the firm only if the costs of altering the adoption plans are prohibitively high. In this case, the threat of altering one's adoption date as a response to its rival's past actions is not credible.

Let π_0^m, π_2^m be the per-period profits when none, or both firms have adopted the green technology. Also, π_l^m, π_f^m be the per-period profits of the leader (firm that has already adopted), and the follower (firm that has not yet adopted), $m=C,B$. Then $\pi_0^m=\pi^m(c_0+\tau\lambda,c_0+\tau\lambda)$, $\pi_2^m=\pi^m(c_0+\tau\lambda-\tau\delta, c_0+\tau\lambda-\tau\delta)$, $\pi_l^m=\pi_1^m(c_0+\tau\lambda-\tau\delta, c_0+\tau\lambda)$ and $\pi_f^m=\pi_2^m(c_0+\tau\lambda-\tau\delta, c_0+\tau\lambda)$. At date 0 firm i, $i=1,2$ chooses T_i^m to maximize its discounted sum of profits:

$$\begin{aligned}\Pi_1^m(T_1,T_2)&=\int_0^{T_1}\pi_0^m e^{-rt}dt+\int_{T_1}^{T_2}\pi_l^m e^{-rt}dt+\int_{T_2}^{\infty}\pi_2^m e^{-rt}dt-k(T_1)\\ \Pi_2^m(T_1,T_2)&=\int_0^{T_1}\pi_0^m e^{-rt}dt+\int_{T_1}^{T_2}\pi_f^m e^{-rt}dt+\int_{T_2}^{\infty}\pi_2^m e^{-rt}dt-k(T_2)\end{aligned} \qquad (6)$$

goods become better substitutes, and for $\gamma=1$ they are perfect substitutes. As γ goes to zero, each firm becomes virtually a monopolist for its product. For tractability reasons, define $\rho=\tau/(a-c_0)$. As $(a-c_0)$ is a measure of the market size, ρ represents the emissions tax rate per unit of market size.

We first analyze Cournot competition. Given the demand system (2), firm i chooses x_i to maximize profits, $[p_i-c_i]x_i$, where c_i is its *effective* marginal cost which, of course, depends on how green the firm's technology is. Then the equilibrium per-period quantities are, $i,j=1,2$,

$$x_i^C(c_i,c_j) = [2(a-c_i)-\gamma(a-c_j)]/(4-\gamma^2) \tag{3}$$

and the equilibrium per-period profits are, $\pi_i^C(c_i,c_j)=[x_i^C(c_i,c_j)]^2$. Firm i's adoption of the abatement technology decreases its effective marginal cost, and thus increases its market share, x_i^C, and decreases the market share of its rival, x_j^C. This latter effect is strategically advantageous for firm i, since from (2) its own price is negatively related to the firm j's quantity. Thus, under emissions taxes, quantity competition creates a *positive strategic effect* for green innovations. To avoid corner solutions, we restrict attention to the range of the substitutability parameter where both firms are always active in the market. From (3), this is the case if and only if $\gamma<\gamma_C(\rho,\lambda,\delta)$, where $\gamma_C\equiv min[1, 2(1+\rho\lambda)/(1+\rho\lambda-\rho\delta)]$.

We now analyze Bertrand competition. By inverting (2) we obtain the demand functions

$$x_1 = [(a-p_1)-\gamma(a-p_2)]/(1-\gamma^2); \quad x_2 = [(a-p_2)-\gamma(a-p_1)]/(1-\gamma^2) \tag{4}$$

Firm i chooses p_i to maximize its profits $[p_i-c_i]x_i$. Then the equilibrium prices are, $i,j = 1,2$,

$$p_i^B(c_i, c_j) = [(2+\gamma)(1-\gamma)a+2c_i+\gamma c_j]/(4-\gamma^2) \tag{5}$$

and the equilibrium per-period profits are, $\pi_i^B(c_i,c_j)=[p_i^B(c_i,c_j)-c_i]^2/(1-\gamma^2)$. When firm i adopts the green technology, its effective marginal cost decreases, and thus both p_i^B and p_j^B decrease. The latter is disadvantageous for firm i, because its output is positively related with p_j. Contrary to Cournot, Bertrand competition creates a *negative strategic effect*. Now, does this imply that firms competing in prices always adopt the abatement technology later than if they were competing in

Proposition 1: *In a pre-commitment equilibrium, all the adoptions of the green technology occur earlier when (i) the tax rate on emissions is higher, (ii) the effectiveness of the green technology in reducing emissions is higher, (iii) the initial emissions-output rate is higher and (iv) the market size is larger.*

We turn now to the comparison of the adoption timing patterns of Cournot and Bertrand markets. Let $g(\rho,\delta)\equiv 2(1+\rho\lambda)/[2(1+\rho\lambda)+\rho\delta]$. It can be easily checked that $g<\gamma_B$ for all (ρ,δ). Proposition 2 summarizes the results:

Proposition 2: *Let $\gamma<\gamma_B$. Then in a pre-commitment equilibrium:*

(i) *For each (ρ,δ) there is a $g(\rho,\delta)$ such that $T_1^C<T_1^B$ for $\gamma<g$ and $T_1^C>T_1^B$ for $\gamma>g$. Moreover, $g(.)$ is decreasing in both ρ and δ.*

(ii) $T_2^C<T_2^B$ *for all* γ.

Proof: From (8) and (10), $I_1^C>I_1^B$ if and only if $[(2-\gamma)(1+\rho\lambda)-\gamma(1+\rho\lambda-\rho\delta)]\gamma^3\rho\delta/(1-\gamma^2)(4-\gamma^2)^2>0$, or equivalently if $(1+\rho\lambda)/(1+\rho\lambda-\rho\delta)>\gamma/(2-\gamma)$, which is true if $\gamma<g$. Also from (9) and (11), $I_2^C>I_2^B$ if and only if $[2(1-\gamma)(1+\rho\lambda)+(2-\gamma)\rho\delta]\gamma^3\rho\delta/(1-\gamma^2)(4-\gamma^2)^2>0$, which is always true. Then by (7) we obtain the results. Q.E.D.

The intuition for part (i) is that for low values of γ the difference in the strategic effect under Cournot and Bertrand competition is dominant. While as γ increases the *market share effect* (Bester & Petrakis (1993)) becomes more important. In fact, when the two commodities are poor substitutes their demands are hardly related, so a firm's output hardly differs in the two types of market. Thus the reduction of the total effective costs due to adoption is of the same magnitude in both Bertrand and Cournot markets. However, for low values of γ the innovation is more profitable for a Cournot leader because it decreases its rival's output whereas for a Bertrand leader it decreases its competitor's price. Therefore, a Bertrand leader will adopt in a later moment when the implementation costs of the green technology are lower.

The first order conditions of (6) are:

$$\begin{aligned} \pi_1^m - \pi_0^m &= -k'(T_1^m)\, e^{rT_1^m} \\ \pi_2^m - \pi_f^m &= -k'(T_2^m)\, e^{rT_2^m} \end{aligned} \tag{7}$$

Let $I_1^m=\pi_1^m-\pi_0^m$, and $I_2^m=\pi_2^m-\pi_f^m$. I_i^m is then firm i's incremental benefit from the adoption of the green technology in market m. Then from (3) we obtain the incremental benefits of the leader and the follower in the Cournot market:

$$I_1^C = 4(a-c_0)^2\rho\delta[(2-\gamma)(1+\rho\lambda)+\rho\delta]/(4-\gamma^2)^2 \tag{8}$$

$$I_2^C = 4(a-c_0)^2\rho\delta[(1+\rho\lambda)(2-\gamma)+\rho\delta(1-\gamma)]/(4-\gamma^2)^2 \tag{9}$$

Also, from (5) we get the corresponding expressions for the Bertrand market

$$I_1^B = (a-c_0)^2\rho\delta(2-\gamma^2)[2(1+\rho\lambda)(1-\gamma)(2+\gamma)+\rho\delta(2-\gamma^2)]/(1-\gamma^2)(4-\gamma^2)^2 \tag{10}$$

$$I_2^B = (a-c_0)^2\rho\delta(2-\gamma^2)[2(1+\rho\lambda)(1-\gamma)(2+\gamma)+\rho\delta(2-\gamma^2-2\gamma)]/(1-\gamma^2)(4-\gamma^2)^2 \tag{11}$$

Thus $I_i^m>0$ and $I_1^m>I_2^m$ for all $\rho,\delta,\lambda>0$ and $0<\gamma<1$ in both markets. Moreover, I_i^m is increasing in ρ, δ, λ *and* $(a-c_0)$. Both the leader's and the follower's incremental benefit from adopting the green technology increase with the emissions tax rate, as firms save more on tax bills. These incremental benefits increase also with the effectiveness of the green technology in reducing a firm's per-unit emissions. Finally, the higher a firm's emissions with the current technology, or the larger the size of the market, the higher are the firm's incremental benefits from adoption.

Now, given (7), T_i^m depends only on I_i^m and by our assumption on $k(.)$, we get $T_1^m>T_2^m$ for $m=B,C$. As Quirmbach (1986) noted, the diffusion of new technologies in the market is not due to strategic behavior, but rather to a pattern of decreasing incremental benefits. Therefore, in order to compare adoption timing patterns under different market structures, we need only compare their respective incremental benefits. Note further that T_i^m is decreasing in ρ, δ, λ *and* $(a-c_0)$. The following proposition summarizes the results:

The leader then, facing preemption, will innovate at an earlier moment such that the follower is indifferent between adopting just before that moment and adopting much later. Thus, in a preemptive equilibrium the *Rent-Equalization Principle* holds.

The specification of the game is the same except that history now matters. As a result we need to look for time consistent innovative behavior. Once the leader has adopted the new technology, the follower's adoption is a one-player decision problem. It chooses τ_2^m to maximize its profits $\Pi_2^m(T_1, T_2)$ (given in (6)) with the only restriction that $\tau_2^m \geq \tau_1^m$. The first-order condition of this problem is the same as in the pre-commitment equilibrium, and is given by (7) with τ_2^m replacing T_2^m. Therefore, in both the preemptive and the pre-commitment equilibria the follower adopts at the same date, i.e. $\tau_2^m = T_2^m$ for $m = C,B$.

Further, from the Rent Equalization Principle, τ_1^m is determined by equating the discounted sum of profits, i.e. $\Pi_1^m(\tau_1^m, \tau_2^m) = \Pi_2^m(\tau_1^m, \tau_2^m)$. From (7) and after some manipulations we get:

$$\pi_l^m - \pi_f^m = r\,\frac{k(\tau_1^m) - k(\tau_2^m)}{e^{-r\tau_1^m} - e^{-r\tau_2^m}} \tag{12}$$

with π_l^m and π_f^m, the leader's and follower's flow of profits respectively, in market m, $m=C,B$. Note, given $\tau_2^m = T_2^m$ the leader's optimal adoption date depends only on the differential of the per-period profits of being the leader and being the follower. This is the *preemptive incentive* (see e.g. Katz & Shapiro (1987)). A comparison of the preemptive incentives created by Bertrand and Cournot markets is given in the following proposition.

Proposition 3: *For all $\gamma < \gamma_B$, the preemptive incentives in Bertrand and Cournot markets are equal, i.e. $\pi_l^C - \pi_f^C = \pi_l^B - \pi_f^B$. Moreover, the preemptive incentive increases with ρ, δ, λ and $(a-c_0)$.*

Proof: Using (3) and (5), we have $\pi_l^C - \pi_f^C = (a-c_0)^2[2(1+\rho\lambda)+\rho\delta]\rho\delta/(4-\gamma^2) = \pi_l^B - \pi_f^B$. Q.E.D.

On the other hand, when the goods are very close substitutes, an innovation that reduces the effective marginal cost of a firm has a significant impact on its market share. Especially, if γ is close enough to γ_B, the adoption of green technology by the leader reduces its rival's market share almost to zero. In Cournot competition, the rival's reduction of market share is less drastic, because $\gamma_B<\gamma_C$ implies that the follower stays with a "decent" market share even after the leader's adoption. Therefore, for high values of γ the Bertrand market creates a stronger incentive for the leader to adopt the green technology than the Cournot market. The market share effect dominates and the leader adopts earlier in price competition.

Part (ii) of Proposition 2 tells us that a Cournot follower always adopts earlier than the Bertrand follower. The strategic effect dominates the market share effect for all substitutability values. For low values of γ the intuition is given above. But for high γ it is the strength of price competition that matters: post-adoption profits do not increase much, even if the market share of the follower increases substantially. This is due to the fierce competition between firms that are producing very similar goods. The post-innovation competition is much softer for a Cournot follower, thus its profits increase sufficiently despite the fact that its market share increases much less than the Bertrand follower's.

4. Adoption patterns in the Preemptive Equilibrium

If adoption is perfectly observable and instantaneous, and if the costs of altering adoption plans are rather insignificant (Fudenberg & Tirole (1983), Riordan (1992)), a firm cannot credibly commit to maintain its date of the implementation of the green technology regardless of what happened in the past. In a pre-commitment equilibrium the leader makes higher profits than the follower. However, if preemption is possible this cannot happen. The follower would have incentive to adopt the new technology just before the leader does in order to increase its profits.

convex, the right hand term of (14) in square brackets [..]< $r\{C'(t_1)(t_2-t_1) + (C(t_1)-C(t_2))\}<0$. Thus, $f(t_1, t_2)$ is decreasing in t_1 and in t_2 by the symmetry of (13). Hence, $\tau_2^B>\tau_2^C$ implies $f(t_1, \tau_2^B)< f(t_1,\tau_2^C)$. Then from (12) and Proposition 3 we have $\tau_1^B<\tau_1^C$. Finally, the second part of the Proposition 4 is a direct consequence of Propositions 1 and 3. Q.E.D.

The leader in a Bertrand market always adopts the green technology earlier than the Cournot leader. In fact, the leader under price competition enjoys the leadership longer than under quantity competition. Given that the preemptive incentives per-period are the same in both markets, the leader has a stronger overall incentive to preempt in a Bertrand than in a Cournot market.

5. Conclusions

In recent years, there is a growing interest of scientists and politicians in a number of environmental issues, such as the global warming associated with the greenhouse effect, the depletion of the ozone layer, the acid rain etc. The climate change due to global warming has received much attention as it is expected to cause major economic or natural damages to many countries or areas. Currently, there is a widespread conviction that the concentration of GHGs could be stabilized in 2010 at its 1990 level, and thus global warming could be avoided to a major extent, if the Best Available Technologies (BATs) could be implemented by the majority of the countries. Under this light, it becomes all the more important the design of policies from the governments that provide the right incentives for the private sector to adopt the existing clean technologies.

My paper contributes to this line of research by studying the firms' incentives to adopt an abatement technology in a differentiated oligopolistic industry where firms compete in prices, or quantities. The firms, faced with a tax on their emissions, have incentive to adopt the green

This result is rather specific to the linear demand structure. Nevertheless, it suggests that the preemptive incentives in Cournot and Bertrand competition are often of similar magnitude in a broader class of demand conditions. The intuition is that for fixed γ, the Bertrand market is more competitive than the Cournot market. This suggests a larger profit differential between the low-cost leader and the high-cost follower in the Bertrand market. However, the leader's adoption generates positive externalities for the follower in the Bertrand market, but negative externalities in the Cournot market. The latter counterbalances the competitiveness effect.

As we saw above, the follower adopts at the same time in both the pre-commitment and the preemptive equilibria. Further, the higher the emissions tax is, or the higher the effectiveness of the technology in reducing emissions, the earlier the follower adopts the green technology. The following proposition summarizes the results:

Proposition 4: *In a preemptive equilibrium,* $\tau_1^B < \tau_1^C$, *and* $\tau_2^B > \tau_2^C$ *for all* γ *and* (ρ,δ). *Moreover, all the adoptions of the green technology occur earlier when (i) the tax rate on emissions is higher, (ii) the effectiveness of the green technology in reducing emissions is higher, (iii) the initial emissions-output rate is higher and (iv) the market size is larger.*

Proof: To compare the leader's optimal adoption date in a price-setting and a quantity-setting game, define

$$f(t_1,t_2)=\frac{k(t_1)-k(t_2)}{e^{-rt_1}-e^{-rt_2}} \tag{13}$$

Let $C(t)=k(t)e^{rt}$. By assumption $C(t)$ is strictly decreasing and strictly convex. Differentiating (13) we have

$$\frac{\partial f(t_1,t_2)}{\partial t_1}=\frac{e^{-r(t_1+t_2)}[C'(t_1)(e^{r(t_2-t_1)}-1)+r(C(t_1)-C(t_2))]}{(e^{-rt_1}-e^{-rt_2})^2} \tag{14}$$

By strict convexity of $exp(x)$ we have $exp[r(t_2-t_1)]-1>r(t_2-t_1)$. As $C(t)$ is decreasing and strictly

technology not only in order to reduce their tax burden, but also to steal business from their rivals. The higher is the emission tax chosen by the government, the sooner the firms adopt the abatement technology. The diffusion pattern depends on a number of market and technological parameters, such as the type of competition (Cournot or Bertrand), the substitutability between the goods, the ability, or not, of firms to precommit to a specific adoption date, the size of the market and on how drastically the emissions are reduced by the clean technology. The analysis thus provides further insights for the design of environmental policies aiming at correcting the inefficiencies of the laissez-faire.

However, the design of optimal policies would require an estimation of the damage function for the country (or all countries on the globe as it is the case of GHGs). This task is left for further research. Note, however, that my findings suggest that the socially optimal diffusion pattern cannot be implemented through the use of a uniform emissions tax. It would rather require an appropriate mix of emissions taxes and subsidies on green technologies adoption costs. Another important issue that is not treated here is the credibility of government policies. If the government cannot commit to a level of emissions tax, then the firms would decide on their adoption dates as if the policy were chosen after their own adoption decision.

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