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Abstract

We consider in this paper a duopoly competing in quantities and where firms can invest in R&D to control their emissions. We distinguish between effort carried out to acquire first-hand knowledge (original R&D) and effort to develop an absorptive capacity to be able to capture part of the knowledge developed by rival. There are also free R&D spillovers between firms. We show that a regulator can reach the social optimal outcome by implementing a taxation and subsidy policy. The regulator subsidizes at a higher rate original R&D effort than its absorptive capacity counterpart when the free spillovers are high, and the contrary may occur when the free spillovers are low. When the cost of original research is lower than the one of absorptive research, or when the learning parameter of the latter is low, then the socially optimal level of original research is higher than the one of absorptive capacity. We have the opposite result when the cost of absorptive capacity is lower than the one of original research and when the learning parameter is high.

Key Words: Pollution Control; Original R&D; Absorptive Capacity; Taxes and Subsidies; Social Optimum.

1 Introduction

It is widely recognized that (i) development and diffusion of cleaner technologies play an important role in achieving environmental quality goals; (ii) firms benefit from each other's investments in research and development (R&D) through voluntary (e.g., joint venture) and/or involuntary spillovers, and (iii) regulators can influence firms' R&D efforts for emissions reduction through economic incentives (e.g., taxes and subsidies). The aim of this paper is to characterize the socially optimal production (or emissions), investment in R&D and absorptive capacity, tax and subsidy rates in a game played by two duopolists and a regulator.

One of the early studies in this area is Milliman and Prince (1989). The authors considered a competitive industry formed of identical firms and evaluated the relative merits of different environmental policy instruments for promoting technological change in pollution control, namely, direct controls, emissions subsidies, emissions taxes, free marketable permits, and auctioned marketable permits. Milliman and Prince showed that emissions taxes and auctioned permits provide the highest firm incentives to promote technological change. Jung, Krutilla and Boyd (1996) extended this comparative approach to a heterogeneous industry. Stranlund (1997) considered public aid to encourage the adoption of superior emissions-control technologies combined with monitoring. This strategy is attractive when monitoring is difficult because the sources of pollution are widely dispersed or the emissions are not easily measured as in non-point pollution problems. Technological aid reduces the direct enforcement effort necessary for firms to reach the compliance goal. Consequently, firms adopt better control technologies, which may serve to promote further innovative activity. Requate and Unold (2003) investigated incentives given by environmental policy instruments to adopt advanced abatement technology. Fischer and Newell (2008) assessed different policies for reducing carbon dioxide emissions and encouraging innovation and diffusion of renewable energy. They evaluated the relative performance of policies according to incentives provided for emissions reduction, efficiency, and other outcomes. They also assessed how the nature of technological progress through learning and R&D, and the degree of knowledge spillovers, affected the desirability of different policies. Because of the knowledge spillovers, optimal policy involves a portfolio of different instruments targeted at emissions, learning, and R&D. Although the relative cost of individual policies in achieving reductions depends on parameter values and the emissions target, in a numerical application to the U.S. electricity sector, the ranking is roughly as follows: (1) emissions price, (2) emissions performance standard, (3) fossil power tax, (4) renewables share requirement, (5) renewables subsidy, and (6) R&D subsidy. Nonetheless, an optimal portfolio of policies achieves emissions reductions at a significantly lower cost than any single policy.

Dosi and Moretto (1997) studied the regulation of a firm which can switch to a green technology by incurring an irreversible investment cost. This technological switch is expected to provide appropriable benefits surrounded, however, by a certain degree of uncertainty. To bridge the gap between the private and the policy-maker's desired timing of innovation, they recommended that the regulator should stimulate the innovation by subsidies and by reducing the uncertainty surrounding the profitability of the new technology through appropriate announcements. Farzin and Kort (2000) studied the regulation of a competitive firm and examined the effect of a higher pollution tax rate on abatement investment, both under full certainty and when the timing or the size of the tax increase is uncertain. They showed the possibility that a higher pollution tax rate induces more pollution and that a credible threat to accelerate the tax increase can lead to more abatement investment. Ben Youssef (2009) considered a non-cooperative and symmetric three-stage game played by two regulator-firm hierarchies. He showed that R&D spillovers and the competition of firms on the common market help non-cooperating countries to better internalize transboundary pollution. Surprisingly, international competition increases the per-unit emissions-tax and decreases the per-unit R&D subsidy. Ulph (1996) studied the strategic behavior of governments and producers by taking the context of a world market. Moreover, he assumed that R&D reduces production costs and that governments can use only one instrument, an emissions-tax or an emissions-standard, to control pollution. Conrad (1993) constructed a model of international duopoly with negative externalities in production in which optimal environmental policy responses to foreign emissions-tax and subsidy programs can be calculated. However, he did not consider R&D possibilities and took the context of an international market. Also, with a model of imperfectly competitive international markets and without pollution, Spencer and Brander (1983) showed that there are national incentives to subsidize R&D if export subsidies are not available.

In the above literature, the assumption is either there are no technological spillovers between the firms or when they occur, they are free. As pointed out in many papers in the industrial organization literature, this assumption may be strong in the sense that firms need to acquire an absorptive capacity to assimilate and exploit available information to benefit from these technological spillovers.

Cohen and Levinthal (1989) were the first to introduce the idea of absorptive capacity in the (process or cost reduction) R&D literature. Contrary to the result in the seminal paper by d'Aspremont and Jacquemin (1988,1990) were R&D spillovers are assumed exogenous and cost free, Cohen and Levinthal showed that intra-industry spillovers may encourage R&D investment. Poyago-Theotoky (1999) analyzed a simple non-tournament model of R&D where firms engage to reduce their cost of innovation. She showed that, when spillovers of information are endogenized, non-cooperative firms never disclose any of their information, whereas they will always fully share their information when they cooperate in R&D. Kamien and Zang (2000) modeled a firm's "effective" R&D level that reflects how both its R&D approach (firm specific or general) and R&D level influence its "absorptive capacity". The choice of the R&D approach is made in the first stage, while the firms' R&D budgets and output levels are chosen in the second and third stages of the game, respectively. They found that when firms cooperate in R&D, they choose identical R&D approaches. Nevertheless, when they do not form a research joint venture (RJV), they choose firm-specific R&D approaches unless there is no danger of exogenous spillovers. In contrast to the Kamien and Zang's finding, Wiethaus (2005) showed that competing firms choose identical R&D approaches in order to maximize knowledge flows between each other.

Grünfeld (2003), considered a two-stage game and showed that the absorptive capacity effects of own R&D drive up the incentive to invest in R&D when the market size is small or the absorptive capacity effect is weak. Otherwise, firms will really choose to cut down on R&D. Finally, he showed that strong learning effects of own R&D are not necessarily good for welfare and that, if the market size is large, welfare will be at its highest when the learning effect is small. Leahy and Neary (2007) specified a general model of the absorptive capacity process and showed that costly absorption raises the effectiveness of own R&D and lowers the effective spillover coefficient thus weakening the case for encouraging RJV even if there is complete information sharing between firms. Milliou (2009) showed that the lack of full appropriability can lead to an increase in R&D investments. Hammerschmidt (2006) considered a two-stage game in which R&D plays a dual role: First, it generates new knowledge and second, it develops a firm's absorptive capacity. She found that firms will invest more in R&D to strengthen absorptive capacity when the spillover parameter is higher.

We consider a three-stage game consisting of a regulator and two identical firms competing in quantities and producing the same homogeneous good. The production process generates pollution and firms can invest in R&D to lower their emissions/output ratio. Firms invest in "original research" which directly reduce their emissions/output ratios. They also invest in "absorptive capacity" research enabling a firm to exploit the original research made by others. There are also free R&D spillovers between firms. Since firms constitute a duopoly and pollute the environment, they are regulated. In the first stage, the regulator announces a tax per-unit of pollution to induce the socially optimal level of pollution and production, a subsidy per-unit of original research to induce the socially optimal level of original research, and a subsidy per-unit of absorptive capacity research to induce the socially optimal level of absorptive capacity research. In the second stage, firms invest in R&D and in the third one they compete in quantities on the product market.

We show that, by means of the emissions-tax and R&D subsidies, the regulator can induce firms to implement the socially optimal levels of production and R&D. The regulator subsidizes at a higher rate absorptive capacity R&D effort than its original research counterpart when the free spillovers are low and the marginal disutility of pollution is high, and the contrary occurs when the free spillovers are high. When the cost of absorptive research is lower than the one of original research and the learning parameter is high, then the socially optimal level of absorptive research is higher than the one of original research. We have the opposite result when the cost of original research is lower than the one of absorptive capacity, or when the learning parameter is low.

The paper has the following structure. Section 2 presents the model and Section 3 provides the conditions verified by the socially optimal production and R&D levels. In Section 4, we study the reaction of firms and derive the socially optimal regulatory instruments. Section 5 concludes.

2 The model

We consider an industry made up of two firms producing a homogeneous good sold on a market having the following inverse demand function:

$$p(q_i, q_j) = a - (q_i + q_j), \quad a > 0.$$

When producing, firm i emits some pollutants which are subject to a per-unit tax t_i imposed by the regulator. To reduce the tax burden, firms can either decrease their outputs or invest in abatement capacity to decrease their emissions per unit of production. We suppose that this abatement capacity requires, and is positively related to, R&D activities. We shall distinguish between two types of R&D effort, namely, original R&D, denoted x_i^o,and absorptive capacity R&D, denoted x_i^a. To fix ideas, think about original R&D as activities related to, e.g., develop better air-filtering systems, whereas absorptive capacity R&D corresponds to effort dedicated to improve firm's technological monitoring capacity through, e.g., hiring engineers and technicians and buying information technologies (IT) equipment. Following the R&D literature (see, e.g., Kamien and Zang (2000)), we assume that the total knowledge available (referred also to as effective R&D level in the literature) to firm i:

$$x_i = x_i^o + (\beta + l x_i^a)\, x_j^o,$$

where $\beta \in [0, 1)$ is a parameter capturing the free and exogenous spillover and $l > 0$ is a learning parameter.

Denote by $e_i\left(x_i^o, x_i^a, x_j^o\right)$ the emissions per unit of production. It is assumed that $e_i\left(x_i^o, x_i^a, x_j^o\right)$ is decreasing in all its arguments. For simplicity, we adopt the following functional form[1]

$$e_i(x_i^o, x_i^a, x_j^o) = 1 - x_i^o - (\beta + l x_i^a)\, x_j^o.$$

Consequently, total emissions by firm i are given by:

$$E_i(q_i, x_i^o, x_i^a, x_j^o) = \left[1 - x_i^o - (\beta + l x_i^a)\, x_j^o\right] q_i.$$

The damage cost resulting from these emissions is given by $D_i = \alpha E_i$, where $\alpha > 0$ is the marginal disutility of pollution.

We suppose that the cost of R&D activity of type $m = o, a$, given by $C^m\left(x_i^m\right)$, as well as the production cost $g_i\left(q_i\right)$, are given by increasing convex functions satisfying $C^m(0) = g_i(0) = 0$. For simplicity, we adopt the

[1] Actually, one needs first to translate R&D effort into abatement. One easy way of doing it is to suppose that

$$e_i(x_i^o, x_i^a, x_j^o) = e_i^0 - f_i\left(x_i^o, x_i^a, x_j^o\right),$$

where e_i^0 corresponds to emissions per unit of production in the absence of any abatement effort and $f_i\left(x_i^o, x_i^a, x_j^o\right)$ is a function transforming R&D effort into abatement. Our formulation assumes

$$e_i^0 = 1 \text{ and } f_i\left(x_i^o, x_i^a, x_j^o\right) = x_i^o + (\beta + l x_i^a)\, x_j^o.$$

following quadratic functional forms

$$\begin{aligned} C^m\left(x_i^m\right) &= k^m\left(x_i^m\right)^2, \quad k^m>0, \quad m=o,a, \\ g_i\left(q_i\right) &= q_i^2. \end{aligned}$$

On the top of regulating the firms through taxation, the regulator subsidizes R&D activities; he offers a per-unit subsidy r_i^o for original R&D, and a per-unit subsidy r_i^a for absorptive capacity R&D effort.

The before taxes and subsidies profit of firm i is given by:

$$\Pi_i(q_i, q_j, x_i^o, x_i^a) = p(q_i, q_j)q_i - q_i^2 - k^o\left(x_i^o\right)^2 - k^a\left(x_i^a\right)^2,$$

and its after taxes and subsidies profit by:

$$V_i(q_i, q_j, x_i^o, x_i^a, x_j^o) = \Pi_i - t_iE_i + r_i^o x_i^o + r_i^a x_i^a.$$

The regulator aims at maximizing the total social welfare, which is equal to the consumer surplus CS, minus damages and subsidies, plus taxes and the net profits of the firms, i.e.,

$$S(q_i, q_j, x_i^o, x_j^o, x_i^a, x_j^a) = CS - D_i - D_j + \Pi_i + \Pi_j. \tag{1}$$

The consumer surplus corresponding to the consumption of $Q = q_i + q_j$ is:

$$CS(q_i, q_j) = \int_0^{q_i+q_j} p(u)du - p(q_i, q_j)(q_i+q_j) = \frac{1}{2}(q_i+q_j)^2. \tag{2}$$

3 The socially optimal production and R&D levels

In terms of sequence of moves, the game is played as follows. In the first stage, the regulator announces its tax and subsidy rates, i.e., the triplet $\left(t_i, r_i^o, r_i^a\right), i = 1, 2$. In stage 2, the firms choose their investments in both types of R&D and in the last stage, their outputs. As usual, to obtain a subgame perfect Nash equilibrium, we solve the game in the reverse order.

The first-order conditions of the regulator's third stage are:

$$\frac{\partial S}{\partial q_i} = \frac{\partial S}{\partial q_j} = 0. \tag{3}$$

The resolution of system (3) gives:

$$\hat{q}_i = \frac{1}{8}\left(2a - \alpha\left[2 - \left(3 - \beta - lx_j^a\right)x_i^o + \left(1 - 3\beta - 3lx_i^a\right)x_j^o\right]\right). \tag{4}$$

The symmetric expression of (4) is:

$$\hat{q}_i = \frac{1}{4}\left[a - \alpha + \alpha\left(1 + \beta + lx_i^a\right)x_i^o\right]. \tag{5}$$

A sufficient condition for production quantities to be positive is

$$\alpha < a, \tag{6}$$

that is, the marginal damage cost is lower that the maximum willingness to pay. We assume from now on that this condition is fulfilled.

The first-order conditions of the regulator's second stage are:[2]

$$\begin{aligned}
\frac{dS}{dx_i^o} &= \frac{\partial \hat{q}_i}{\partial x_i^o}\frac{\partial S}{\partial q_i} + \frac{\partial \hat{q}_j}{\partial x_i^o}\frac{\partial S}{\partial q_j} + \frac{\partial S}{\partial x_i^o} = 0, &(7)\\
\frac{dS}{dx_i^a} &= \frac{\partial \hat{q}_i}{\partial x_i^a}\frac{\partial S}{\partial q_i} + \frac{\partial \hat{q}_j}{\partial x_i^a}\frac{\partial S}{\partial q_j} + \frac{\partial S}{\partial x_i^a} = 0, &(8)\\
\frac{dS}{dx_j^o} &= \frac{\partial \hat{q}_i}{\partial x_j^o}\frac{\partial S}{\partial q_i} + \frac{\partial \hat{q}_j}{\partial x_j^o}\frac{\partial S}{\partial q_j} + \frac{\partial S}{\partial x_j^o} = 0, &(9)\\
\frac{dS}{dx_j^a} &= \frac{\partial \hat{q}_i}{\partial x_j^a}\frac{\partial S}{\partial q_i} + \frac{\partial \hat{q}_j}{\partial x_j^a}\frac{\partial S}{\partial q_j} + \frac{\partial S}{\partial x_j^a} = 0. &(10)
\end{aligned}$$

At the equilibrium, equations (7)-(10) are simplified, and the symmetric solutions verify the following equations system:

$$\begin{aligned}
\alpha\left(1+\beta+lx_i^a\right)\hat{q}_i - 2k^o x_i^o &= 0, &(11)\\
\alpha l x_i^o \hat{q}_i - 2k^a x_i^a &= 0, &(12)
\end{aligned}$$

where $\hat{q}_i$ is given by (5), and (11) and (12) are equivalent to:

$$\begin{aligned}
\alpha\left(1+\beta+lx_i^a\right)\left[a-\alpha+\ \alpha\left(1+\beta+lx_i^a\right)x_i^o\right] - 8k^o x_i^o &= 0, &(13)\\
\alpha l x_i^o\left[a-\alpha+\ \alpha\left(1+\beta+lx_i^a\right)x_i^o\right] - 8k^a x_i^a &= 0. &(14)
\end{aligned}$$

The resolution of system (13)-(14) gives the socially optimal R&D levels $\hat{x}_i^o$ and $\hat{x}_i^a$. From (13), we have:

$$\hat{x}_i^o = \frac{\alpha(a-\alpha)(1+\beta+l\hat{x}_i^a)}{8k^o - \alpha^2\left(1+\beta+l\hat{x}_i^a\right)^2}. \tag{15}$$

From (14), we have:

$$\hat{x}_i^a = \frac{\alpha l\left[a-\alpha+\alpha(1+\beta)\hat{x}_i^o\right]\hat{x}_i^o}{8k^a - \alpha^2 l^2 \hat{x}_i^{o2}}. \tag{16}$$

Proposition 1 *There is a unique solution $\hat{x}_i^o > 0$ and $\hat{x}_i^a > 0$ that solves the equations system given by (13) and (14).*

Proof. See Appendix. ■

Conjecture 1 *We conjecture that*

$$\lim_{k^o,k^a\to+\infty}\hat{x}_i^o = \lim_{k^o,k^a\to+\infty}\hat{x}_i^a = 0. \tag{17}$$

[2] The second order conditions are verified in the appendix when k^0 and k^a are high enough.

This conjecture makes sense intuitively because when the investment cost parameters are very high, it's socially optimal to not invest in R&D. Condition (6) guarantees that the socially optimal levels of innovation are positive when k^o and k^a are high enough.

From (15) and (16), we can show that:

$$\lim_{k^o,k^a\to+\infty} k^o\hat{x}_i^o = \frac{1}{8}\alpha(1+\beta)(a-\alpha), \quad \lim_{k^o,k^a\to+\infty} k^a\hat{x}_i^a = 0. \tag{18}$$

From (11) and (12), we can show that:

$$\hat{x}_i^o = \sqrt{\left(\frac{k^a(1+\beta)}{k^o l} + \frac{k^a}{k^o}\hat{x}_i^a\right)\hat{x}_i^a}. \tag{19}$$

Proposition 2 *It holds that:*
i) If $k^a \geqslant k^o$, or if l is low enough, then $\hat{x}_i^o > \hat{x}_i^a$.
ii) If $k^a < k^o$ and l is high enough, then $\hat{x}_i^a > \hat{x}_i^o$.

Proof. See Appendix. ■

Proposition 2 shows that the socially optimal R&D level of original research is higher than the one of absorptive capacity when the learning parameter is low enough, or when the investment cost parameter of original research is lower than the one of absorptive capacity. The investment in absorptive capacity is higher only when the investment cost parameter of absorptive capacity is lower that the one of original research and when the learning parameter is high enough.

4 The socially optimal emissions tax and R&D subsidies

In this section, we determine the best response of the players to the regulator's announcement of the triplet (t_i, r_i^o, r_i^a), $i = 1,2$. As stated before, the regulator made its announcement in the first stage and the firms react by first determining their R&D investments (second stage), and next their outputs (third stage). Again, the game is solved backward.

In the third stage, the firms optimize their after taxes and subsidies profit given by:

$$V_i(q_i, q_j, x_i^o, x_i^a, x_j^o) = \Pi_i - t_iE_i + r_i^o x_i^o + r_i^a x_i^a.$$

Solving the first-order conditions for this stage

$$\frac{\partial V_i}{\partial q_i} = \frac{\partial V_j}{\partial q_j} = 0, \tag{20}$$

leads to

$$q_i^* = \frac{1}{15}\left(3a - 4t_i\left[1 - x_i^o - (\beta + lx_i^a)\,x_j^o\right] + t_j\left[1 - x_j^o - \left(\beta + lx_j^a\right)x_i^o\right]\right). \tag{21}$$

The partial derivatives set for the symmetric case are:

$$\frac{\partial q_i^*}{\partial x_i^o} = \frac{t_i}{15}(4-\beta-lx_i^a), \qquad \frac{\partial q_i^*}{\partial x_i^a} = \frac{4}{15}t_i l x_i^o,$$
$$\frac{\partial q_i^*}{\partial x_j^o} = \frac{t_i}{15}(4\left[\beta+lx_i^a\right]-1), \qquad \frac{\partial q_i^*}{\partial x_j^a} = -\frac{t_i}{15}lx_i^o.$$

Consider the case of a positive emissions tax. When a firm increases its level of original or absorptive research, its emissions/output ratio decreases enabling it to expand its production. When the competing firm increases its original research, this has two opposite effects on the production of the firm: because of R&D spillovers and absorptive capacity, the emissions ratio of the firm decreases enabling it to expand its production; the second effect is a negative one and obliges the firm to decrease its production because the competing one can increase its production due to the decrease of its emissions/output ratio. When β and/or l are high enough, the first positive effect dominates. When the competing firm increases its absorptive capacity, its emissions ratio decreases enabling it to expand its production which forces the firm to reduce its production.

The symmetric expression of (21) is:

$$q_i^* = \frac{1}{5}\left(a - t_i\left[1 - x_i^o - (\beta + lx_i^a)\, x_i^o\right]\right). \tag{22}$$

The first-order conditions of firm i's second stage are:[3]

$$\frac{dV_i}{dx_i^o} = \frac{\partial q_i^*}{\partial x_i^o}\frac{\partial V_i}{\partial q_i} + \frac{\partial q_j^*}{\partial x_i^o}\frac{\partial V_i}{\partial q_j} + \frac{\partial V_i}{\partial x_i^o} = 0, \tag{23}$$
$$\frac{dV_i}{dx_i^a} = \frac{\partial q_i^*}{\partial x_i^a}\frac{\partial V_i}{\partial q_i} + \frac{\partial q_j^*}{\partial x_i^a}\frac{\partial V_i}{\partial q_j} + \frac{\partial V_i}{\partial x_i^a} = 0. \tag{24}$$

At the equilibrium, (23)-(24) are simplified, and the following equations are satisfied for symmetric solution(s):

$$4t_i\,(4-\beta-lx_i^a)\, q_i^* - 30k^o x_i^o + 15r_i^o = 0, \tag{25}$$
$$16t_i l x_i^o q_i^* - 30k^a x_i^a + 15r_i^a = 0, \tag{26}$$

where q_i^* is given by (22).

System (25)-(26) contains two equations and two unknown variables which are x_i^o and x_i^a. Since the emissions taxes and R&D subsidies are set to push firms attaining the socially optimal production and R&D levels, then the optimal emissions tax and R&D subsidies should be chosen such that $\hat{x}_i^o$ and $\hat{x}_i^a$ are the solution of equations system (25)-(26).

Therefore, from (22) we have:

$$t_i = \frac{a - 5\hat{q}_i}{1-(1+\beta+l\hat{x}_i^a)\hat{x}_i^o}, \tag{27}$$

[3] The second order conditions are verified in the appendix when k^0 and k^a are high enough.

and

$$\lim_{k^o,k^a\to+\infty} t_i = \frac{1}{4}(5\alpha - a). \tag{28}$$

Note that

$$\lim_{k^o,k^a\to+\infty} t_i < 0 \Leftrightarrow \alpha < a/5.$$

Therefore, when the marginal damage of pollution is low enough, the regulator actually subsidizes pollution (or production) to deal with the duopoly distortion. Further, from (5), we have

$$\lim_{k^o,k^a\to+\infty} \hat{q}_i = \frac{1}{4}(a-\alpha) > 0. \tag{29}$$

From (25)-(26), we have:

$$\begin{aligned} r_i^o &= \frac{1}{15}\left(30k^o\hat{x}_i^o - 4t_i\left[4-\beta-l\hat{x}_i^a\right]\hat{q}_i\right), && (30)\\ r_i^a &= \frac{1}{15}(30k^a\hat{x}_i^a - 16t_il\hat{x}_i^o\hat{q}_i) && (31)\end{aligned}$$

From (30) and (31), we deduce:

$$\begin{aligned} \lim_{k^o,k^a\to+\infty} r_i^o &= \frac{1}{60}\left[5(4\beta-1)\alpha + (4-\beta)a\right](a-\alpha), && (32)\\ \lim_{k^o,k^a\to+\infty} r_i^a &= 0. && (33)\end{aligned}$$

The following proposition compares the subsidy rates of efforts in original and absorptive capacity R&D.

Proposition 3 *When k^o and k^a are high enough:*

i) The R&D subsidy for original research is always higher than the one for absorptive capacity when $\beta \geq 1/4$;

ii) The R&D subsidy for absorptive capacity is higher when $\beta < 1/19$ and α is high enough.

Proof. See Appendix. ■

The above proposition shows that the regulator gives a greater support to original research when the free R&D spillovers are important. However, when the free R&D spillovers are not important and consumers are very sensitive to the protection of the environment, he gives a greater support to absorptive research.

5 Conclusion

We considered in this paper a duopoly competing in quantities and where firms can invest in original and absorptive R&D to control their emissions. We have shown that a regulator can reach the social optimal outcome by implementing tax and subsidy schemes. The regulator subsidizes at a higher rate the absorptive capacity research than original research when the free spillovers are low and the marginal disutility of pollution is high, and the contrary occurs when the free spillovers are high. When the cost of absorptive capacity is lower than the one of original research and the learning parameter is high, then the socially optimal level of absorptive capacity is higher than the one of original research. We have the opposite result when the cost of original research is lower than the one of absorptive research, or when the learning parameter is low.

Although we have adopted simple functional forms for demand, costs and emissions to output ratio, we were not able to obtain explicit values for the socially optimal R&D levels. If we were able to do so, then we would have compared the socially optimal level of original research in the presence and absence of absorptive capacity. This comparison is worth considering in a future investigation since one reason evoked by the absorptive capacity literature is that absorptive capacity may increase the R&D level and sometimes plays a better role than RJVs (e.g., Leahy and Neary (2007)).

6 Appendix

A) Second-order conditions of the regulator's second stage

Consider the Hessian Matrix:

$$H = \begin{pmatrix} \frac{d^2S}{dx_i^{o2}} & \frac{d^2S}{dx_i^o dx_i^a} & \frac{d^2S}{dx_i^o dx_j^o} & \frac{d^2S}{dx_i^o dx_j^a} \\ \frac{d^2S}{dx_i^o dx_i^a} & \frac{d^2S}{dx_i^{a2}} & \frac{d^2S}{dx_i^a dx_j^o} & \frac{d^2S}{dx_i^a dx_j^a} \\ \frac{d^2S}{dx_i^o dx_j^o} & \frac{d^2S}{dx_i^a dx_j^o} & \frac{d^2S}{dx_j^{o2}} & \frac{d^2S}{dx_j^o dx_j^a} \\ \frac{d^2S}{dx_i^o dx_j^a} & \frac{d^2S}{dx_i^a dx_j^a} & \frac{d^2S}{dx_j^o dx_j^a} & \frac{d^2S}{dx_j^{a2}} \end{pmatrix}$$

By using the first-order conditions given by (7)-(10), we can compute the second derivatives constituting matrix H which can be written as:

$$H = \begin{pmatrix} f_1 - 2k^o & f_2 & f_3 & f_4 \\ f_2 & f_5 - 2k^a & f_6 & f_7 \\ f_3 & f_6 & f_8 - 2k^o & f_9 \\ f_4 & f_7 & f_9 & f_{10} - 2k^a \end{pmatrix},$$

where f_i, $i = 1, ...10$, are polynomial functions in x_i^o and x_i^a (symmetric case). Since

$$\lim_{k^o, k^a \to +\infty} \hat{x}_i^o = \lim_{k^o, k^a \to +\infty} \hat{x}_i^a = 0,$$

then f_i take finite values when k^o and k^a tend to $+\infty$.

Therefore:

i) $\Delta_1 = f_1 - 2k^o < 0$ when k^o and k^a are high enough.

ii) $\Delta_2 = \begin{vmatrix} f_1 - 2k^o & f_2 \\ f_2 & f_5 - 2k^a \end{vmatrix} > 0$ when k^o and k^a are high enough.

iii) $\Delta_3 = \begin{vmatrix} f_1 - 2k^o & f_2 & f_3 \\ f_2 & f_5 - 2k^a & f_6 \\ f_3 & f_6 & f_8 - 2k^o \end{vmatrix}$;

We have $\lim_{k^o, k^a \to +\infty} \Delta_3 = \lim_{k^o, k^a \to +\infty} \frac{-8k^{o2}k^a}{k^{o2}k^a} = -8$. Thus, $\Delta_3 < 0$ when k^o and k^a are sufficiently high.

iv) $\Delta_4 = \begin{vmatrix} f_1 - 2k^o & f_2 & f_3 & f_4 \\ f_2 & f_5 - 2k^a & f_6 & f_7 \\ f_3 & f_6 & f_8 - 2k^o & f_9 \\ f_4 & f_7 & f_9 & f_{10} - 2k^a \end{vmatrix}$;

We have

$$\lim_{k^o, k^a \to +\infty} \Delta_4 = \lim_{k^o, k^a \to +\infty} \frac{16k^{o2}k^{a2}}{k^{o2}k^{a2}} = 16.$$

Thus, $\Delta_4 > 0$ for k^o and k^a sufficiently high.

Therefore, we have a maximum.

B) second-order conditions of firms second stage

By using the first-order conditions given by (23)-(24), we can show that:

i) $\frac{d^2V_i}{dx_i^{o2}} = g_1(t_i, x_i^a) - 2k^o$, where g_1 is a polynomial function in t_i and x_i^a (symmetric case). Since $\lim_{k^o, k^a \to +\infty} x_i^a$ and $\lim_{k^o, k^a \to +\infty} t_i$ are finite numbers, then g_1 takes a finite value when $k^o, k^a \to +\infty$. Thus, $\frac{d^2V_i}{dx_i^{o2}} < 0$ when k^o and k^a are sufficiently high.

ii) $\frac{d^2V_i}{dx_i^{a2}} = g_2(t_i, x_i^o) - 2k^a$, where g_2 is a polynomial function in t_i and x_i^o (symmetric case). Since $\lim_{k^o, k^a \to +\infty} x_i^o$ and $\lim_{k^o, k^a \to +\infty} t_i$ are finite numbers, then g_2 takes a finite value when $k^o, k^a \to +\infty$. Thus, $\frac{d^2V_i}{dx_i^{a2}} < 0$ when $k^o$and k^a are sufficiently high.

iii) $\frac{d^2V_i}{dx_i^o dx_i^a} = g_3(t_i, x_i^o, x_i^a)$, where g_3 is a polynomial function in t_i, x_i^o,and x_i^a (symmetric case). Since $\lim_{k^o, k^a \to +\infty} x_i^o$, $\lim_{k^o, k^a \to +\infty} x_i^a$ and $\lim_{k^o, k^a \to +\infty} t_i$ are finite numbers, then g_3 takes a finite value when $k^o, k^a \to +\infty$.

When $k^o$and k^a are high enough, we can say that:

$\cdot \frac{d^2V_i}{dx_i^{o2}} < 0$ and $\frac{d^2V_i}{dx_i^{a2}} < 0$, and

$\cdot \begin{vmatrix} \frac{d^2V_i}{dx_i^{o2}} & \frac{d^2V_i}{dx_i^o dx_i^a} \\ \frac{d^2V_i}{dx_i^o dx_i^a} & \frac{d^2V_i}{dx_i^{a2}} \end{vmatrix} = [g_1(t_i, x_i^a) - 2k^o]\,[g_2(t_i, x_i^o) - 2k^a] - [g_3(t_i, x_i^o, x_i^a)]^2 > 0.$

Therefore, the second-order conditions of the firms second stage are verified.

C) Proof of Proposition 1

Expression (13) can be developed as:

$$\alpha(1+\beta)(a-\alpha)+\alpha^2(1+\beta)^2x_i^o+\alpha l\left[a-\alpha+2\alpha(1+\beta)x_i^o\right]x_i^a+\alpha^2l^2x_i^o\left(x_i^a\right)^2-8k^ox_i^o=0 \tag{34}$$

By using the expression of x_i^a given by (16) in (34) and then multiplying by $\left(8k^a-\alpha^2l^2x_i^{o2}\right)^2$, we get a polynomial function of degree 5 in x_i^o:$P(x_i^o)=0$.

The coefficient of $(x_i^o)^5$ is $-8\alpha^4l^4k^o$, and the constant term is $64\alpha(1+\beta)(a-\alpha)\left(k^a\right)^2$.

Since $P(0)>0$ and $\lim_{x_i^o\to+\infty}P(x_i^o)=-\infty$, then $P(x_i^o)$ admits at least one real and positive root. We know that a polynomial of degree 5 can have at a maximum five roots in IR. However, since we have shown that every critical couple of points (x_i^o,x_i^a) is a maximum when k^o and k^a are sufficiently high, then we have a unique solution which maximizes the social welfare. This unique solution $(\hat{x}_i^o,\hat{x}_i^a)$ verifies $\hat{x}_i^o>0$ and $\hat{x}_i^a>0$ because of (6) and (17) and when k^0 and k^a are high enough.

D) Proof of Proposition 2

From expression (19), we deduce the following:

i) if $k^0\leq k^a$, then $\hat{x}_i^o>\hat{x}_i^a$.

ii) if $k^a<k^0$, then

$$\hat{x}_i^o<\hat{x}_i^a\Leftrightarrow\frac{k^a\left(1+\beta+l\hat{x}_i^a\right)}{k^0l}<\hat{x}_i^a\Leftrightarrow\hat{x}_i^a>\frac{k^a\left(1+\beta\right)}{\left(k^0-k^a\right)l}.$$

If l is high enough, then $\hat{x}_i^o<\hat{x}_i^a$. If l is low enough, then it is the other way around ($\hat{x}_i^o>\hat{x}_i^a$).

E) Proof of Proposition 3

From (32) and (33):

$$\lim_{k^o,k^a\to+\infty}r_i^o>\lim_{k^o,k^a\to+\infty}r_i^a\Leftrightarrow 5(4\beta-1)\alpha+(4-\beta)a>0.$$

i) If $\beta\geqslant 1/4$, the above inequality is always satisfied.

ii) If $\beta<1/4$, $\lim_{k^o,k^a\to+\infty}r_i^o<\lim_{k^o,k^a\to+\infty}r_i^a\Leftrightarrow\alpha>\frac{(4-\beta)a}{5(1-4\beta)}$. This last inequality is not in contradiction with (6) iff $\beta<1/19$.

References

[1] Ben Youssef, S, 2009, "Transboundary Pollution, R&D Spillovers and International Trade", *The Annals of Regional Science*, 43, 235-250.

[2] Cohen, W.M. and D.A. Levinthal, 1989, "Innovation and Learning: The Two Faces of R&D", *The Economic Journal*, 99, 569-596.

[3] Conrad, K, 1993, "Taxes and Subsidies for Pollution-Intensive Industries as Trade Policy", *Journal of Environmental Economics and Management*, 25, 121-135.

[4] D'Aspremont, C., and A. Jacquemin, 1988, "Cooperative and Noncooperative R&D in Duopoly with Spillovers", *The American Economic Review*, 78, 1133-1137.

[5] D'Aspremont, C., and A. Jacquemin, 1990, "Cooperative and Noncooperative R&D in Duopoly with Spillovers:Erratum", *The American Economic Review*, 80, 641-642.

[6] Dosi, C. and M. Moretto, 1997, "Pollution Accumulation and Firm Incentives to Promote Irreversible Technological Change under Uncertain Private Benefits", *Environmental & Resource Economics*, 10, 285-300.

[7] Farzin, Y.H. and P.M. Kort, 2000, "Pollution Abatement Investment when Environmental Regulation is Uncertain", *Journal of Public Economic Theory*, 2, 183-212.

[8] Fischer, C. and R.G. Newell, 2008, "Environmental and Technology Policies for Climate Mitigation", *Journal of Environmental Economics and Management*, 55, 142–162.

[9] Grünfeld, L.A, 2003, "Meet me Halfway But don't Rush: Absorptive Capacity and strategic R&D Investment Revisited", *International Journal of Industrial Organization*, 21, 1091-1109.

[10] Hammerschmidt, A, 2006, "A Strategic Investment Game with Endogenous Absorptive Capacity", Vienna University of Economics & B.A, Working Paper No. 92.

[11] Jung, C., K. Krutilla and R. Boyd, 1996, "Incentives for Advanced Pollution Abatement Technology at the Industry Level: an Evaluation of Policy Alternatives", *Journal of Environmental Economics and Management*, 30, 95-111.

[12] Kamien, M.I. and I. Zang, 2000, "Meet me Halfway: Research Joint Ventures and Absorptive Capacity", *International Journal of Industrial Organization*, 18, 995–1012.

[13] Leahy, D. and J.P. Neary, 2007, "Absorptive Capacity, R&D Spillovers, and Public Policy", *International Journal of Industrial Organization*, 25, 1089-1108.

[14] Milliman, S.R. and R. Prince, 1989, "Firm Incentives to Promote Technological Change in Pollution Control", *Journal of Environmental Economics and Management*, 17, 247-265.

[15] Milliou, C, 2009, "Endogenous Protection of R&D Investments", *Canadian Journal of Economics*, 42, 184-205.

[16] Poyago-Theotoky, J, 1999, "A Note on Endogenous Spillovers in a Non-Tournament R&D Duopoly", *Review of Industrial Organization*, 15, 253-262.

[17] Requate, T. and W. Unold, 2003, "Environmental Policy Incentives to Adopt Advanced Abatement Technology: Will the True Ranking Please Stand Up?", *European Economic Review*, 47, 125 – 146.

[18] Spencer, B.J and J.A. Brander, 1983, "International R&D Rivalry and Industrial Strategy", *Review of Economic Studies*, 50, 707-722.

[19] Stranlund, J.K., 1997, "Public Technological Aid to Support Compliance to Environmental Standards", *Journal of Environmental Economics and Management*, 34, 228-239.

[20] Ulph, A, 1996, "Environmental Policy and International Trade when Governments and Producers Act Strategically", *Journal of Environmental Economics and Management*, 30, 265-281.

[21] Wiethaus, L, 2005, "Absorptive Capacity and Connectedness:Why Competing Firms Also Adopt Identical R&D Approaches", *International Journal of Industrial Organization*, 23, 467-481.