Environmental Regulation in Oligopoly: On licensing and diffusion of clean technology*

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Preliminary Version

Abstract

We investigate the impact of environmental regulation on the licensing and the diffusion of a patented clean technology when the potential licensees are product market competitors in an oligopolistic industry. We show that polluters' willingness to pay for a clean technology, and thereby, the innovator's incentives to disseminate that technology depend not only on the environmental regulation stringency but also on the strategic interactions between the potential licensees and on the patentee's licensing policy. We consider a quantity policy (auctions) and a price policy (uniform fixed fees) and show that the former should be preferred to the latter by the patentee only if rationing (i.e. precluding some polluters from obtaining a license) is privately optimal. Focusing on pollution taxation within Cournot oligopoly, we further find that rationing is optimal only whenever two conditions are simultaneously met: the patented technology is significantly advanced and the environmental regulation is sufficiently stringent. In fact, as the perceived cost of polluting increases, so do the patentee's incentives to sell fewer licenses so as to extract higher rents from its licensees. Therefore, more stringent regulations need not result in more diffusion of clean technology. This suggests that the dynamic efficiency of an environmental regulation depends also on the competitive environments (i.e market and technological structure, demand elasticities, market conduct) of *all* the firms involved in the process of induced environmental innovation.

Key Words: Environmental regulation, Clean Technology, Licensing, Oligopoly
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1 Introduction

Pollution is a pervasive by-product of firms' activities in many highly concentrated industries. For example, emissions of green house gases like CO_2 is characteristic of notably oligopolistic industries such as chemicals, cement, petroleum or electricity generation to name a few. To cope with that, many governments have come to rely on environmental policies such as pollution taxes or permits trading systems.[1] Faced with such kind of environmental regulations, polluters typically come up with compliance strategies consisting in weighted combinations of output reduction, pollution charges payment and resort to environmentally sounder ways of pursuing activity. In fact, the strategy of each polluter reflects its endeavor to minimize the costs (in terms of profit losses) of complying with the environmental regulation. Hence, by providing new opportunities to improve environmental performance the development and the diffusion of cost-effective environmental advances known as *clean technologies* could help reduce private as well as social costs of achieving environmental objectives (see e.g [20], [23], [12], [3]).

Clean technologies, however, are often developed and patented by specialized firms in a separate (upstream) industry and licensed to (downstream) polluters subject to environmental regulation. The willingness to pay for clean technology of the latter determines the prospect of licensing revenues and, thereby, the former's research and development incentives. Hence, to be efficient overall should environmental policies not only provide polluters with adequate incentives to implement cleaner technologies into their production processes but also adequately rewards private efforts aimed at developing these technologies.

This paper analyzes the impact of environmental regulation on the licensing and the diffusion of a patented clean technology when the potential licensees are product market competitors in an oligopolistic industry. Thus, our contribution to the environmental economics literature is twofold. First, whereas previous theoretical literature essentially focus on *end-of-pipe* pollution abatement technologies (i.e. which do not affect the marginal conditions of polluters) or simply assume away strategic interactions in the polluting industry, we investigate the case of process-integrated environmental innovations affecting both marginal and infra-marginal conditions (see e.g [8] and [1]).[2] In doing so, we emphasize how strategic interactions among polluters might influence their decisions on investment in clean technology. Second, we examine strategic considerations in the licensing of patented clean technologies. We show that polluters' willingness to pay for a clean technology, and thereby, the innovator's incentives to develop that technology depend not only on the environmental regulation stringency but also on the strategic interactions between the potential licensees and on the patentee's licensing policy. Throughout, we mostly consider simple *ex ante* incentives-based regulations (such as pollution taxation), the stringency of which is set *once and for all* before environmental innovation occurs. Thereby, we assume away

[1] Leading examples includes the European Union multi-sectoral emissions trading scheme (EU-ETS) and the US Regional Greenhouse Gas Initiative (RGGI) whose aim is to reduce CO_2 emissions from the power sector.

[2] For an insightful discussion on the theoretical implications of the distinction between end-of-pipe abatement technology and process-integrated environmental innovations see Amir et al. [1].

potential time-inconsistency or commitment problems the regulator could be faced with (see e.g [18], [26] or [22]). Nevertheless, this modeling choice is motivated by the practical prevalence of such *ex ante* commitment in existing regulations.

Broadly considered, the process of *induced environmental innovation* by which technological change is connected to environmental regulation has sparked a wide body of theoretical and empirical literature. For instance, patent data have been extensively used to estimate clean technology suppliers' innovation responsiveness to environmental regulation (patents counts [4]) or to analyze the diffusion of environmental innovations (patents citations e.g. [13]).[3] In theory also, various frameworks have been used to investigate the impact of environmental regulation on polluters' incentives to adopt "advanced abatement technologies" (e.g. [8], [20], [3], [27]) or on firms' incentives to undertake environmental R&D (e.g. [18], [21], [10], [26], [22]). Thus far, while much emphasis has been placed on the impact the design of environmental policies might have on their so-called *dynamic efficiency*, that is, the extent to which they foster the development and the diffusion of environmentally sounder technologies, the role of strategic interactions *within and across* the industries involved in that process -central to our analysis- has, by contrast, received only a limited attention.[4]

Among the few papers emphasizing the strategic role of investment in environmental R&D in oligopoly ([14], [2], [21]), the closest in spirit to our paper is Montero [21] who examines Cournot duopolists' incentives to invest in environmental R&D before competing in a polluting industry subject to environmental regulation. There also, however, the extent of strategic interaction is somehow limited since the analysis is mostly restricted to *symmetric* investment decisions. Yet, as we argue below, even when polluters are symmetric at the outset, *asymmetric* investment patterns might arise in equilibrium. That ex ante identical firms might eventually take different investment decisions or end up implementing distinct technologies is not specific to our model (see e.g. [3],[9]). Nor is the fact that the licensing strategy employed to sell a patented advanced technology will influence its development and diffusion (see e.g [16], [17]). The key difference lies in the fact that, with environmental (induced) innovation, the investment decisions and the licensing strategies are driven by environmental regulation.

Although less normative in scope, the present paper also relates to a growing body of work analyzing the impact of market power in the *abatement goods and services industry*[5] (e.g. [6], [5], [7], [24]) on the optimal environmental policy design, since by definition a patent protection provides its owner with some monopoly power. However, our work contrasts with this series of papers too, since there, as in the aforementioned literature, strategic interactions in one of the underlying industries are still downplayed.[6] In investigating the impact of environmental taxation within a Cournot oligopoy on the

[3]For an overview of this literature, see for instance [15] and the references therein.

[4]See [25] for a survey on the dynamic efficiency in theoretical literature.

[5]This industry is sometimes referred to as the *eco-industry* in the literature and could include for instance waste and water management firms as well as electric equipment manufacturers.

[6]Canton et al. [5] consider Cournot competition in both the polluting industry and the eco-industry. However, since they focus on end-of-pipe abatement, strategic interactions in the polluters' output market do not directly affect their demand for abatement.

diffusion of clean technology, this paper draws on some developments in oligopoly theory (see e.g. [19], [30], [11]). Moreover, in analyzing the licensing of clean technology, we build upon a generic literature on contracting in presence of multilateral externalities (see [28] and the reference therein). In particular, the licensing strategies of cost-reducing innovations in oligopoly have been well studied in the industrial organization literature (see e.g. [29] for a survey).

Closely related to our interest, Katz and Shapiro [17] compare licensing by means of a quantity policy (auctions) and by means of a price policy (equavilent to fixed fees) and show that the former yields at least as high returns to the patentee than does the latter, and thereby provides it with more incentives to develop and patent the new technology. However, despite the theoretical higher profitability of (sophisticated) licenses auctions, most patented innovations are still commercialized by means of licenses fees (or equivalent basic auction mechanisms).

Our analysis helps understanding the prominant use of such basic licensing strategies in monetizing environment-related patents. Indeed, considering auctions and uniform fixed fees, we show that the former should be preferred to the latter by the patentee only if *rationing* (i.e. precluding some polluters from obtaining a license) is privately optimal. Furthermore, focusing on pollution taxation within Cournot oligopoly, we find this is the case only whenever two conditions are simultaneously met: the patented technology is significantly advanced and the environmental regulation is sufficiently stringent. When the environmental regulation is lax or the environmental advance of the clean technology is not significant enough, polluters are reluctant to pay significant license fees. Hence, the patentee, which cannot expect to extract much rents from each of its potential licensees, has strong incentives to widely disseminate its innovation instead of using a rationing licensing strategy i.e. complete diffusion is privatley optimal from its point of view. If on the contrary, the clean technology is sufficiently clean, as the perceived cost of polluting increases, so do the patentee's incentives to sell fewer licenses so as to extract higher rents from its licensees. Therefore, more stringent regulations need not result in more diffusion of clean technology. This suggests that the dynamic efficiency of an environmental regulation depends also on the competitive environments (i.e market and technological structure, demand elasticity and curvature, market conduct) of *all* the firms involved in the process of induced environmental innovation.

The remainder of the paper is organized as follows. In Section 2 we lay out the model. In Section 3 we focus on pollution taxation within Cournot oligopoly and derive some comparative statics results on private valuations for clean technology in a general case. We examine the optimal licensing policy for the case of linear demand in Section 4 and offer some concluding remarks in Section 5.

2 The Model

The polluting industry. We consider n initially symmetric firms using a conventional constant return-to-scale production technology. The linear cost function is $C(q) = cq$ with $c \geq 0$ and the production process generates pollution as byproduct emissions of an harmful effluent. We normalize to one the *emission rate* (i.e the emissions to output ratio) of the conventional production process. Hence, when producing q units of output a *conventional* firm generates q units of emissions. We refer to an environmental innovation altering the conventional production process in a way that reduces the emission rate from 1 to $(1-\beta)$ with $\beta \in (0,1]$ as the *clean* technology β. Hence, when implementing such a technology, an *innovative* firm generates $(1-\beta)$ units of emissions only per unit of output. Thus, the parameter β captures the cleanliness of the technology (the higher β, the cleaner the production process).

The clean technology industry. The clean technology is developed in a separate (upstream) industry. Following previous literature, for simplicity we consider a pure monopoly in that industry.[7] Throughout, we shall refer to the upstream monopolist as the *innovator* or as the *patentee*.

Environmental Regulation. At the outset, the environmental regulator credibly commits to an emission tax level τ to be levied on each pollution unit released during the compliance period. This provides polluters with incentives to seek for cleaner production technologies, and thereby, provides the innovator with incentives to undertake environmental R&D aimed at developing such technologies.

Timing and Solution Concept. The timing of our basic model reads as follows. First, the environmental regulator announces the emission tax level. Then, the patentee chooses how to license the clean technology it has developed. Then, polluters independently and publicly decide whether to buy or not a license from the patentee. Finally, each polluter produces its optimal output and incurs its environmental compliance costs (i.e. pays its environmental taxes). For each regulation stringency level τ we solve the game for a subgame perfect Nash equilibrium consisting in a number k^* of licenses to the technology sold by the patentee.

Notations. For further reference, let $q^{\emptyset}$, $e^{\emptyset}$ and $\pi^{\emptyset}$ respectively denote the equilibrium output, the corresponding emissions level and profit of each firm in the *laisser-faire* regime, that is, absent any environmental regulation. For a given instrument $r \in \{\tau, \sigma\}$ and $\gamma \in \{0, \beta\}$, let $q_{\gamma}(k, \beta, \tau)$, $e_{\gamma}(k, \beta, \tau) = (1-\gamma) q_{\gamma}(k, \beta, \tau)$ and $\pi_{\gamma}(k, \beta, \tau)$ denote respectively the equilibrium output, the corresponding emissions level and profit of a firm operating with technology γ conditional on k firm(s) having adopted the technology β. Moreover, let $Q(k, \beta, \tau)$ and $E(k, \beta, \tau)$ denote the corresponding equilibrium aggregate output and emissions level, respectively.

To analyze the impacts of environmental regulation on the overall process of induced environmental innovation, we need first to understand how a given policy provides polluters with incentives to adopt any given clean technology β. But, as we shall see below, polluters' valuation for the technology β may also depends on the patentee's licensing policy. Therefore, we start by describing the licensing options left to our patentee.

[7] See for instance [18], [25] or [22].

2.1 The patentee's licensing policies

In this paper we consider the following licensing policies: a price policy under which the patentee set a fixed and non-discriminatory license fee F and a quantity policy taking the form of a k-license auction under which the patentee set the number k of licenses for sell subject to a reservation price (i.e a minimum bid). Note however, that following [17] we could as well think of both licensing strategies as auction. Indeed, in our complete information framework setting the number of licenses *offered* at the auction place equal to (or greater than) the number of polluters along with a single positive minimum bid equal to F is equivalent to a our pure price policy. Throughout, it might be worth also distinguishing between rationing and non-rationing licensing strategies. We shall say that the patentee licensing strategy is *rationing* if the equilibrium number of license(s) sold under this strategy is *strictly lower* than the number of polluters active in the industry under consideration.

2.2 Polluters' valuation for clean technology

When all firms use the conventional technology, each firm's costs of complying with the emission tax τ, can be measured as the difference between the profit it would have gained under *laisser-faire* and that actually realized at the end of the compliance period and are thus given by $\pi^{\emptyset} - \pi_0(0, r) \geq 0$. Similarly, when the technology β has been adopted by $0 < k \leq n$ firm(s) the polluting industry is potentially composed of two types of firms: $n - k$ conventional firm(s) and k innovative one(s). Each firm's total compliance costs, might then depend on the industry's technological structure. Indeed, for a conventional firm those costs would be given by $\pi^{\emptyset} - \pi_0(k, \beta, \tau)$, whereas for an innovative one they would amount to $\pi^{\emptyset} - \pi_\beta(k, \beta, \tau)$.

Now, suppose the technology β has been licensed to $k - 1$ polluter(s). By acquiring a license, an unlicensed polluter would save on compliance costs an amount given by

$$\delta(k, \beta, \tau) = \pi_\beta(k, \beta, \tau) - \pi_0(k - 1, \beta, \tau)$$

Thus, as mentioned above, -because of strategic interactions in their product market- the polluters' incentives to switch to the technology β depends not only on the environmental regulation stringency (i.e the emission tax level τ), but also on the market structure (as captured by the number k of licensees). Notwithstanding this, the polluters' willingness to pay for a license to the clean technology should not be deduced too quickly from these compliance costs savings as such. Indeed, as we argue below, it could also depends on the patentee's licensing policy. To see this, let us rewrite the compliance costs saving as

$$\delta(k, \beta, \tau) = \underbrace{\pi_\beta(k, \beta, \tau) - \pi_0(k, \beta, \tau)}_{\Delta(k,\beta,\tau)} + \underbrace{\pi_0(k, \beta, \tau) - \pi_0(k - 1, \beta, \tau)}_{\lambda_0(k,\beta,\tau)} \tag{1}$$

Thus, the compliance costs savings can be decomposed into two distinct parts. First, $\Delta(k, \beta, \tau) = \pi_\beta(k, \beta, \tau) - \pi_0(k, \beta, \tau)$ represents the advantage of being one of the k licensees. Second $\lambda_0(k, \beta, \tau) =$

$\pi_0(k,\beta,\tau)-\pi_0(k-1,\beta,\tau)$ measures impact of the last license sold on a conventional firm's profit. Then, consider the k-license auction policy to begin with, and notice that once the emission tax level has been set, the private benefits of implementing a clean technology are similar to those of implementing a cost-reducing innovation. Therefore, the following lemma can be seen as an application of a result presented in Katz and Shapiro [17].

Lemma 1 *Given the emission tax level τ, when the patentee uses a k-license auction with $k<n$, each polluter would bid up to $\Delta(k,\beta,\tau)$. In a n-license auction, each polluter would bid $\delta(n,\beta,\tau)$*

Proof. Consider the k-license auction strategy. First, note that if $k<n$ (resp. $k=n$) then in any bidding equilibrium all polluters who purchase licenses pay the same price to implement the technology β. If not, the winning firm making the highest bid could lower its offer slightly and still receive a license. Then, observe that no polluters would bid strictly above $\Delta(k,\beta,\tau)$ (resp. $\delta(k,\beta,\tau)$) since in such a case, winning one of k license(s) would make it strictly worse-off than submitting a losing bid. Finally, if the lowest winning bid $\underline{b}$ were strictly below $\Delta(k,\beta,\tau)$ (resp. $\delta(k,\beta,\tau)$) then a losing bidder could be strictly better-off by bidding slightly above $\underline{b}$ and winning a license. ■

Turning to the license fees policy, let $F\geq 0$ denote the licensing fee charged by the patentee. Then, simple comparisons yield the following lemma.

Lemma 2 *Given the emission tax level τ, $\delta(k,\beta,\tau)\geq F>\delta(k+1,\beta,\tau)$, then an outcome where $0\leq k<n$ firm(s) buy(s) a license to the technology β is a Nash equilibrium of the licensing subgame.*

Proof. Consider any candidate equilibrium number of innovative firm(s) $0\leq k<n$ such that $\delta(k,\beta,\tau)\geq F>\delta(k+1,\beta,\tau)$. Then, it is easy to see that there is no strictly profitable unilateral deviation. Indeed, by deviating a conventional firm would be strictly worse-off since $\pi_\beta(k+1,\beta,\tau)-F<\pi_0(k,\beta,\tau)$. Likewise, by deviating an innovative firm would not be better-off since $\pi_\beta(k,\beta,\tau)-F\geq\pi_0(k-1,r)$ ■

Remark 1 *A direct implication of this lemma is that* no diffusion *(resp.* complete diffusion*) is the unique Nash equilibrium outcome of the diffusion subgame if and only if $\forall k\in\{1,2,...,n\}$, $\delta(k,\beta,\tau)<F$. (resp. $\delta(k,\beta,\tau)>F$).*

Indeed, no firm would switch to the technology β if the licensing fee were to outweigh the resulting benefits. Likewise, all firms would implement the clean technology β if the resulting individual costs savings were to outweigh the license fee.

2.3 Licensing revenues

Given the emission tax level τ, the maximal revenue the patentee can earn under a k-license auction is given by

$$R(k,\beta,\tau)=\begin{cases} k\Delta(k,\beta,\tau) & \text{if} \quad k<n \\ n\delta(n,\beta,\tau) & \text{otherwise.}\end{cases}$$

Next, define $\bar{k}(F,\beta,\tau) \doteq \max\{k \leq n-1 : \delta(k,\beta,\tau) \geq F > \delta(k+1,\beta,\tau)\}$. Then, it follows directly from Lemma 2 and 3 that the maximal revenue the patentee can derive by charging a licensing fee equal to F is

$$R(F,\beta,\tau) = \begin{cases} \bar{k}(F,\beta,\tau)F & \text{if} \quad \delta(n,\beta,\tau) < F \\ n\delta(n,\beta,\tau) & \quad \text{otherwise.} \end{cases}$$

At this point, except that the maximal revenue under both licensing policies coincide when the licensing strategy is non rationing, because of the too weak structural assumptions regarding our polluting industry, little can be said about the patentees' optimal licensing strategy . The next section provides a first step towards a more thorough investigation of the overall process of induced environmental innovation by analyzing polluters' willingness to pay for clean technology and licensing revenues in a Cournot oligopoly.

3 The value of clean technology in Cournot oligopoly

In this section we analyze the willingness to pay for clean technology of polluters competing à la Cournot and facing a (inverse) demand curve given by $P(Q)$ where Q denote the industry aggregate output. We assume (merely for technical reasons) that $P(Q)$ is well-behaved in the sense that $P(\cdot)$ is thrice continuously differentiable with $P'(Q) < 0$ for all $Q > 0$ and satisfies the following assumption.

Assumption 1 $\Theta(Q) \equiv P''(Q)Q/P'(Q) > -2$ *for all* $Q > 0$.

This assumption ensures the existence and uniqueness of a Cournot equilibrium in an asymmetric oligopoly.[8] We further assume that the environmental regulation is not too stringent so that the following assumption holds.

Assumption 2 $\tau < \hat{\tau} \doteq \min\{\tau : \textit{such that} \quad q_0(n-1,1,\hat{\tau}) = 0\}$

This assumption allows us to restrict our attention on interior equilibria of the product market subgame. Indeed, the worst situation for a conventional polluter faced with a given emission tax level τ, is when all of its product market competitors operating with the cleanest technology (i.e when $k = n-1$ and $\beta = 1$ so that advanced technology is perfectly clean.) Therefore, as long as the emission tax level is such that even in such a situation the former would continue to produce a strictly positive quantity in equilibrium, Assumption 2 ensures that in equilibrium each firm produces a strictly positive quantity regardless the industry's technological profile (i.e. for all k and for all β).

Now, observe that for a given emission tax level τ, if the technology β is implemented by $k \leq n$ polluter(s), a firm operating with the technology $\gamma \in \{0,\beta\}$ would *perceive* a constant marginal cost given by $c + (1-\gamma)\tau$ and therefore would act as is facing the following problem:

$$\max_q \pi_\gamma(q, |k,\tau) = (P(Q) - c - (1-\gamma)\tau)q$$

Indeed, in our framework, each polluter's *perceived* marginal cost encompasses the constant marginal cost c to which is added the *marginal compliance cost* associated with the emission rate of its production

[8] See for instance Février and Linnemer [11] from which we borrow the notation $\Theta(Q)$.

process. Let $\bar{\gamma}(k,\beta) = (n-k\beta)/n$ denote the *average emission rate* when the technology β is implemented by k polluter(s). Then, the following lemma simply establishes that for a given emission tax level τ, when the technology β is implemented by k polluter(s), the equilibrium outputs are those of a n-firm Cournot oligopoly with $n-k$ firm(s) operating at the constant marginal cost $c+\tau$ and k firm(s) operating at the constant marginal cost $c+(1-\beta)\tau$.

Lemma 3 *Under Assumptions 1 and 2, the aggregate equilibrium output $Q(k,\beta,\tau)$ obtains as the solution in Q to the following (aggregate) first-order condition:*

$$\frac{Q}{n} = -\frac{P(Q) - c - \bar{\gamma}(k,\beta)\tau}{P'(Q)} \tag{2}$$

The equilibrium output of each firm operating with the technology β is given by

$$q_\beta(k,\beta,\tau) = \frac{Q(k,\beta,\tau)}{n} + \frac{n-k}{n}\frac{\beta\tau}{-P'(Q(k,\beta,\tau))} \tag{3}$$

whereas the equilibrium output of each firm operating with the conventional technology is given by

$$q_0(k,\beta,\tau) = \frac{Q(k,\beta,\tau)}{n} - \frac{k}{n}\frac{\beta\tau}{-P'(Q(k,\beta,\tau))} \tag{4}$$

The aggregate emissions level is thus given by

$$E(k,\beta,\tau) = \bar{\gamma}(k,\beta)Q(k,\beta,\tau) - \frac{k(n-k)}{n}\frac{\beta^2\tau}{-P'(Q(k,\beta,\tau))} \tag{5}$$

Proof. See Appendix. ■

Lemma 3 allows us to derive some comparative statics results about private and social values of clean technology. First, the following proposition indicates how the development and the dissemination of clean technology is likely to affect social or aggregate outcomes.

Proposition 1 *i) For a given emission tax level τ and a given k, the aggregate equilibrium output (emission level) is increasing (may increase or decrease) in β. ii) For a given emission tax level τ and a given β, the aggregate equilibrium output (emission level) is increasing (may increase or decrease) in k. iii) For a given β and a given k, the aggregate equilibrium output and emission level are decreasing in τ.*

Proof. See Appendix. ■

Proposition 1 highlights a key difference between cost-reducing and environmental innovations. Typically, the diffusion of a cost-reducing innovation within a Cournot oligopoly unambiguously enhances welfare. In contrast, in our case, while aggregate output and thus increase consumers surplus increase as more polluters implement the clean technology (i.e as k increases), it is also true that such an increase is likely to cause more environmental damage if the reduction of the unit emission rate of the k licensees is not significant enough (i.e if β to compensate for the increase in their individual outputs.

3.1 Polluters' valuation for clean technology

First, note that strategic interactions in the product market affect polluting firms' incentives to implement the clean technology through the negative impact that every additional license sold by the patentee has on each polluter's profit. In fact, as stated in the following proposition each polluter adopting the technology β imposes a *negative externality* on the others.

Proposition 2 *Each licensee imposes a negative externality on its competitors. Moreover, the magnitude of this negative impact on the polluters' individual profits depends on* β *and* τ *and is stronger for licensees than for conventional polluters.*

Proof. See Appendix. ■

Proposition 2 conveys an intuitive grasp of how strategic considerations relative to the polluters' output market is likely to affect the diffusion of clean technology. Indeed, notice that under the licensing schemes we focus on the patentee receives payment only from those polluters actualling buying a license. Hence, the former incentives to more or less disseminate its technology result from the following trade-off. On the one hand, selling additional licenses at a given price yields additional revenues. However, each additional license sold deprives each licensee of some competitive advantage -since it means sharing the perceived cost-leadership with a larger number of equally efficient rivals. Although, from an unlicensed polluter's points of view facing more licensees also means competiting with fewer equally inefficient rivals, the forgone profit associated to each additional license sold by the patentee is greater for a licensee than for a conventional polluter. Consequently, regardless of its licensing policy, the more licenses it sells, the lower the price the patenntee could expect receiving for each.

Naturally, the magnitude of the negative externality each licensee imposes on its competitors, depends not only on the total number of licensees, but also on the cleanliness of the technology and the emission tax level altogether. The following proposition indicates how the polluters' valuation for the clean technology depends on those variables.

Proposition 3 *When the patentee uses a k-license auction to sell the technology* β*, then: i) for a given* β *and a given* k*, the highest winning bid is strictly increasing in* τ*. ii) For a given emission tax level* τ *and a given* k*, the highest winning bid is strictly increasing in* β*. iii) For a given emission tax level* τ *and a given* β*, the highest winning bid is (strictly) decreasing in* k *(if* $k < n$*).*

Proof. See Appendix. ■

Proposition 3 has an intuitive interpretation. The higher the emission tax level, the more each polluter is willing to pay to obtain one of the k licenses. Likewise, for any given emission tax level, the cleaner the technology β the more it allows to save on compliance costs and, thus, the more each polluter is likely to bid for a license. More interestingly, the lower the number of licenses for sale, the higher the polluters' valuation of the clean technology.

Proposition 4 *Given the emission tax level* τ*, i) there exists a threshold* $\underline{F}(\beta,\tau) > 0$ *(resp.* $\bar{F}(\beta,\tau)$*) for the license fee such that for all* $F < \underline{F}(\beta,\tau)$ *(resp.* $F > \bar{F}(\beta,\tau)$*) all polluters (resp. no polluters)* *buy a license for the technology β. ii) For all F such that $\underline{F}(\beta,\tau) < F < \bar{F}(\beta,\tau)$ there exists a unique equilibrium number $k(F,\beta,\tau)$ of firm(s) adopting the clean technology. Moreover, $k(F,\beta,\tau)$ is a weakly decreasing in F and weakly increasing in τ and β.*

Proof. See Appendix. ■

Proposition 4 contrasts with the received literature abatement technology adoption where strategic interactions in the downstream market are not considered. For instance, in [20], [10] or [27], if faced with an emission tax a polluter finds it profitable to implement an abatement technology, so should do all polluters. [9] In our context however, from a polluter's point of view, the value of implementing the clean technology depends not only upon the tax level set by the regulator, but also on the number of its licensed rivals, as it would be the case for a cost-reducing process innovation. In fact, in a Cournot oligopoly, for given emission tax level, the value of implementing the clean technology obeys the logic of purchasing a license to cost-reducing process innovation. Thus, as put by Katz and Shapiro ([17], p.575): "Essentially, the value of a license to a [environmental] process innovation is proportional to the licensee's output. This output, in turn, is lower if the licensee's rivals produce more output themselves, as they will if more of them own licenses."

3.2 Licensing strategies

Given the emission tax level τ, it is immediate to see that when patentee uses the the license fee policy, its profit-maximization problem can be looked at as follows:

$$\max_{k} \pi^{f}(k,\beta,\tau) = k\delta(k,\beta,\tau)$$

Indeed, by setting a license fee equal to $\delta(k,\beta,\tau)$ for technology β, the patentee would face a demand for k licenses from the polluters. Therefore, when the former has a comprehensive understanding of the strategic interactions among the latter, but cannot contractibly commit on the number of licenses for sale, choosing the license fee amounts to choose the number of licenses to be sold. When in uses the (rationing) k-license auction strategy ($k < n$), for a given emission tax level τ its profit is

$$\pi^{a}(k,\beta,\tau) = \begin{cases} k\Delta(k,\beta,\tau) & \text{if} \quad k < n \\ n\delta(n,\beta,\tau) & \text{otherwise.} \end{cases}$$

Hence, since for all $k < n$ we have $\delta(k,\beta,\tau) < k\Delta(k,\beta,\tau)$, we see that the k-license auction policy strictly dominates the license fee policy if it is optimal for the patentee to ration the licenses. Hereafter, we shall maintain the assumption in case the profit-maximizing licensing strategy is non rationing, the patentee prefers the (simpler) licensing fee policy.

[9] Indeed, since these authors exclusively focus on the direct effect $\delta(k,\beta,\tau)$ once the regulator has set the unit emission tax level τ, the value of implementing the technology β, does not depends on the number of other polluters doing so (i.e. $\delta(k,\beta,\tau)$ does not depends on k).

4 Induced environmental innovation

In this section we investigate the overall impact of environmental regulation on the diffusion of clean technology in a Cournot oligopoly. For simplicity, we consider a linear demand.

Assumption 3 *$P(Q) = a - bQ$, with $a > 0$ and $b > 0$.*

Assumption 1 holds trivially for linear demand functions for which $\Theta(Q) = 0$ for all $Q > 0$. Assumption 2, in turn, can be more readily expressed as

Assumption 4 *$\tau < \hat{\tau} \doteq (a - c)/n$.*

4.1 Private dissemination of clean technology

In this section we derive the patentee's optimal licensing strategies for a given technology β under both licensing procedures. We assume that the costs of developing the technology β have been sunk and that licensing the clean technology to the polluters is costless.

4.1.1 Optimal licensing strategies

We can show that under both licensing policy, for a given emission tax level τ and a given β, the patentee's profit-maximizing number of licensee(s) is unique. Let us respectively denote by $k^f(\beta, \tau)$ and $k^a(\beta, \tau)$ the optimal number of licensee(s) under the fee policy and the auction policy. The following proposition indicates how the polluters' market demand and market structure affect the patentee's dissemination incentives.

Proposition 5 *Under Assumptions 3 and 4, for a given emission tax level τ we have: i) $\partial k^f(\beta, \tau)/\partial a \geq 0$ and $\partial k^a(\beta, \tau)/\partial a \geq 0$, ii) $\partial k^f(\beta, \tau)/\partial n \geq 0$ and $\partial k^a(\beta, \tau)/\partial n \geq 0$, iii) $\partial k^f(\beta, \tau)/\partial \beta \leq 0$ and $\partial k^a(\beta, \tau)/\partial \beta \leq 0$, and iv) $k^f(\beta, \tau) - k^a(\beta, \tau) \geq 0$. Moreover, for a given β we have: v) $\partial k^f(\beta, \tau)/\partial \tau \leq 0$ and $\partial k^a(\beta, \tau)/\partial \tau \leq 0$.*

Proof. See Appendix. ■

In words, Proposition 5 says that under both licensing policies for a given emission tax level τ, the number of license(s) to the technology β sold by the patentee: i) weakly increases with the size (as captured by the parameter a) of the polluters' market, ii) weakly increases with the number of polluters, iii) weakly decreases as the cleanliness parameter β increases and iv) the number of license(s) sold by the patentee is at least as high under the licence fee policy than under the auction policy. Moreover, v) for a given β, the number of license(s) sold by the patentee weakly decreases as the emission tax level increases. Assertions iv) and v) order some comments. Indeed, first, iv) suggests that *ceteris paribus* the cleaner the technology β, the less the patentee finds it optimal to disseminate it which is certainly a bad news for the industry environmental performance. Second, v) indicates that contrary to conventional wisdom, more stringent regulations (here, higher emission tax levels) need not induce more dissemination of clean technology. The following proposition analyzes in more detail the patentee's incentives to fully disseminate the clean technology.

Proposition 6 *Define* $\underline{\tau}^f(\beta)$ *such that* $k^f(\beta, \underline{\tau}^f(\beta)) = n - 1$*, then for all* $\tau \in (\underline{\tau}^f(\beta), \hat{\tau})$*, it is optimal for the patentee to partially disseminate the technology* β *with a rationing license fee if and only if* $\beta \geq \beta^f \doteq \frac{2(n-1)}{3(n-2)}$*. Similarly, define* $\underline{\tau}^a(\beta)$ *such that* $k^a(\beta, \underline{\tau}^f(\beta)) = n - 1$*, then for all* $\tau \in (\underline{\tau}^a(\beta), \hat{\tau})$*, it is optimal for the patentee to partially disseminate the technology* β *with a rationing k-license auction if and only if* $\beta \geq \beta^a \doteq \frac{2(n-1)}{3n-5}$.

Proof. See Appendix. ∎

Proposition 6 shows that under either licensing policy, it is privately optimal for the patentee to use a rationing strategy only whenever two conditions are simultaneously met. First, the environmental advance of the technology β should be significant enough and, second, emission tax level should be high enough. Whenever one of these conditions is not met, the patentee prefers having all polluters buying a license and implementing the clan technology rather than artificially limiting the diffusion of its innovation to exploit the strategic interactions among the potential licensees.

5 Concluding Remarks

We have investigated the effect of environmental regulation stringency on the diffusion of a patented clean technology when the potential licensees are product market competitors in an oligopolistic industry. We have shown that in general, polluters willingness to pay for clean technology, and thereby, the innovators incentives to disseminate its clean technology depends not only on the environmental regulation stringency but also on the strategic interactions between potential licensees and on the patentee's licensing policy. Considering two licensing policies: a quantity policy (auctions) and price policy (uniform license fees) we have found that a licenses auction guarantees higher profits to the patentee than does a uniform fee only if rationing, that is, precluding some polluters from obtaining a license is privately optimal. Moreover, focusing on pollution taxation within Cournot oligopoly, we have seen that rationing is optimal only whenever two conditions are simultaneously met: the patented technology is significantly advanced and the environmental regulation is stringent enough. Consequently, contrary to conventional wisdom, more stringent regulations need not result in more diffusion of clean technology. Thus, our results suggest that the dynamic efficiency of an environmental regulation depends not only on its stringency but also on the competitive environments (i.e market and technological structure, demand elasticities, market conduct) of all the firms involved in the process of induced environmental innovation. Including endogenous innovation in this framework is in our agenda. Further research could extend the present analysis to other types of environmental regulation and to other market structures.

A Omitted proofs

Proof of Lemma 3 When the technologyβ is implemented by k licensees, the first-order condition for a firm operating with the technology $\gamma \in \{0, \beta\}$ can be written as

$$P'(Q)q_{\beta}(k, \beta, \tau) + P(Q) = c + (1 - \beta)\tau \tag{6}$$

where omitting arguments, Q denote the equilibrium equilibrium aggregate output. Summing over the n first-order conditions gives

$$P'(Q)Q + nP(Q) = nc + (n - k\beta)\tau \tag{7}$$

Dividing both sides of equation (7) by $nP'(Q)$ and rearranging terms yields equation (2). Hence, the solution in Q to equation (2) is the equilibrium aggregate output. Moreover, taking $\gamma = \beta$ in equation (6) and subtracting it from equation (7) gives expression (3) after rearranging terms. Similarly, taking $\gamma = 0$ in equation (6) and subtracting it from equation (7) gives expression (4). Finally, multiplying expression (3) by $k(1 - \beta)$ and expression (4) by $(n - k)$ and summing yields

$$E(k, \beta, \tau) = \frac{Q}{n}\left[k(1 - \beta) + n - k\right] - \frac{\beta\tau}{nP'(Q)}\left[k(1 - \beta)(n - k) - k(n - k)\right] \tag{8}$$

which is equivalent to expression (5) ■

Proof of Proposition 1 Totally differentiating equation(7) w.r.t β yields

$$P'(Q)\frac{\partial Q(k, \beta, \tau)}{\partial \beta}\left[\frac{P''(Q)Q}{P'(Q)} + n + 1\right] = -k\tau \tag{9}$$

rearranging gives

$$\frac{\partial Q(k, \beta, \tau)}{\partial \beta} = \frac{-k\tau}{(\Theta + n + 1)P'(Q)} > 0 \tag{10}$$

for all $\beta < 1$. Likewise, we have

$$\frac{\partial Q(k, \beta, \tau)}{\partial \tau} = \frac{n - k\beta}{(\Theta + n + 1)P'(Q)} \leq 0 \tag{11}$$

with equality if $k = n$ and $\beta = 1$. Proceeding analogously we obtain

$$\frac{\partial Q(k, \beta, \tau)}{\partial k} = \frac{-\beta\tau}{(\Theta + n + 1)P'(Q)} > 0. \tag{12}$$

for all $k < n$.

The indeterminacy of the comparative statics results on the aggregate emission level follows obviously after observing that the signs of $\partial E(k, \beta, \tau)/\partial \beta$ and $\partial E(k, \beta, \tau)/\partial k$ are in general indeterminate since those of the derivative of $\bar{\gamma}(k, \beta)Q(k, \beta, \tau)$ with respect to k and with respect to β are so. However, since we have $(1-\beta)Q(k, \beta, \tau) \leq E(k, \beta, \tau) \leq Q(k, \beta, \tau)$ and $\partial Q(k, \beta, \tau)/\partial \tau < 0$ we have $\partial E(k, \beta, \tau)/\partial \tau < 0$ ■

Proof of Proposition 2 Let $s_\gamma(k,\beta,\tau) = q_\beta(k,\beta,\tau)/Q(k,\beta,\tau)$ denote the equilibrium market share of a firm operating with the technology $\gamma \in \{0,\beta\}$ when the technology β is implemented by k licensees. First, observe that the equilibrium profit of a firm operating with the technology γ can be written as

$$\pi_\gamma(k,\beta,\tau) = -P'(Q(k,\beta,\tau))q_\gamma^2(k,\beta,\tau) \tag{13}$$

Then, totally differentiating equation (13) w.r.t k yields

$$\frac{\partial \pi_\gamma(k,\beta,\tau)}{\partial k} = -2P'(Q)\frac{\partial q_\gamma}{\partial k}q_\gamma - \frac{\partial Q}{\partial k}P''(Q)q_\gamma^2$$

which, after making use of expression (12) and rearranging terms can be written as

$$\frac{\partial \pi_\gamma(k,\beta,\tau)}{\partial k} = -q_\gamma\left[2P'(Q)\frac{\partial q_\gamma}{\partial k} - \frac{\beta\tau}{\Theta+n+1}\Theta s_\gamma\right] \tag{14}$$

Totally differentiating equation (6) w.r.t k and rearranging terms yields

$$-P'(Q)\frac{\partial q_\gamma}{\partial k} = -\beta\tau\left[\frac{\Theta s_\gamma + 1}{\Theta+n+1}\right] \tag{15}$$

Using equation (15) and manipulating equation (14) we obtain

$$\frac{\partial \pi_\gamma(k,\beta,\tau)}{\partial k} = -\beta\tau q_\gamma\left[\frac{\Theta s_\gamma + 2}{\Theta+n+1}\right] < 0 \tag{16}$$

where the inequality follows from Assumptions 1 and 2.

Next, recalling that $\lambda_\gamma(k,\beta,\tau) \equiv \pi_\gamma(k,\beta,\tau) - \pi_\gamma(k-1,\beta,\tau)$, it remains to show that $\lambda_\beta(k,\beta,\tau) < \lambda_0(k,\beta,\tau)$. Hence, showing that for $k < n$, $\Delta(k,\beta,\tau) \equiv \pi_\beta(k,\beta,\tau) - \pi_0(k,\beta,\tau)$ strictly decreases in k would complete the proof since we have $\lambda_\beta(k,\beta,\tau) < \lambda_0(k,\beta,\tau) \iff \Delta(k,\beta,\tau) < \Delta(k-1,\beta,\tau)$. But, we know from expressions (3) and (4) that $s_\beta - s_0 = -\beta\tau/P'(Q)Q > 0$. Thus, we have

$$\frac{\partial \Delta(k,\beta,\tau)}{\partial k} = P'(Q)\frac{\beta^2\tau^2}{\Theta+n+1}\left[\Theta(s_\beta+s_0)+2\right] < 0 \tag{17}$$

since Assumptions 1 and 2 ensure that $\Theta(s_\beta + s_0) > -2$. ■

Proof of Proposition 3 Totally differentiating equation (13) w.r.t β yields

$$\frac{\partial \pi_\gamma(k,\beta,\tau)}{\partial \beta} = -2P'(Q)\frac{\partial q_\gamma}{\partial \beta}q_\gamma - \frac{\partial Q}{\partial \beta}P''(Q)q_\gamma^2$$

which, using expression (10) and rearranging terms becomes

$$\frac{\partial \pi_\gamma(k,\beta,\tau)}{\partial \beta} = -q_\gamma\left[2P'(Q)\frac{\partial q_\gamma}{\partial \beta} - \frac{k\tau}{\Theta+n+1}\Theta s_\gamma\right] \tag{18}$$

Then, taking $\gamma = \beta$ and totally differentiating equation (6) w.r.t β yields

$$\frac{\partial Q}{\partial \beta}\left[P''(Q)q_\beta + P'(Q)\right] + P'(Q)\frac{\partial q_\beta}{\partial \beta} = -\tau$$

which, making use of expression (10) yields, after some manipulations

$$-P'(Q)\frac{\partial q_\beta}{\partial \beta} = \tau\left[\frac{\Theta(1-ks_\beta)+n+1-k}{\Theta+n+1}\right] > 0 \tag{19}$$

since Assumption 2 ensures that $s_\beta < 1/k$.

Likewise, taking $\gamma = 0$ and totally differentiating equation (6) w.r.t β yields after some manipulations

$$-P'(Q)\frac{\partial q_0}{\partial \beta} = -k\tau\left[\frac{\Theta s_0 + 1}{\Theta + n + 1}\right] < 0 \tag{20}$$

Next, using respectively equations (19) and (20) in expression (18) and rearranging terms we obtain respectively

$$\frac{\partial \pi_\beta(k,\beta,\tau)}{\partial \beta} = -q_\beta \tau \left[\frac{\Theta(3ks_\beta - 2) + 2(n-k+1)}{\Theta + n + 1}\right] > 0 \tag{21}$$

and

$$\frac{\partial \pi_0(k,\beta,\tau)}{\partial \beta} = -q_0 k\tau \left[\frac{\Theta s_0 + 2}{\Theta + n + 1}\right] < 0 \tag{22}$$

Finally, noticing that $\frac{\partial \Delta}{\partial \beta} = \frac{\partial \pi_\beta}{\partial \beta} - \frac{\partial \pi_0}{\partial \beta} > 0$ yields the result.

We proceed similarly to prove *ii)* and obtain

$$\frac{\partial \pi_\beta(k,\beta,\tau)}{\partial \tau} = -q_\beta \tau \left[\frac{\Theta(3ks_\beta - 2) + 2(n-k+1)}{\Theta + n + 1}\right] > 0 \tag{23}$$

and

$$\frac{\partial \pi_0(k,\beta,\tau)}{\partial \tau} = -q_0 k\tau \left[\frac{\Theta s_0 + 2}{\Theta + n + 1}\right] < 0 \tag{24}$$

Assertion *iii)* has already been demonstrate in the proof of Proposition 2 (see equation (17).

Proof of Proposition 3 The proof which is similar to the proof of Proposition 2 is omitted.

Proof of Proposition 4 First, the patentee's profit-maximization problem under the license fee policy is given by

$$\max_{k \leq n} k\delta(k,\beta,\tau) = k\beta\tau\left[\frac{2(a-c-\tau) + (n-2k+2)\beta\tau}{b(1+n)^2}\right] \tag{25}$$

Solving (25) for k yields

$$k^f(\beta,\tau) = \min\{n, Int\left(\frac{2(a-c-\tau) + (n+2)\beta\tau}{4\beta\tau}\right)\} \tag{26}$$

where $Int\,(x)$ denote integer part of x i.e the larger integer lower than x.
Next, the patentee's profit-maximization problem under the k-license auction policy is given by

$$\max_{k \leq n} k\Delta(k,\beta,\tau) = k\beta\tau\left[\frac{2(a-c-\tau) + (n-2k+1)\beta\tau}{b(1+n)^2}\right] \tag{27}$$

Solving (27) for k yields

$$k^a(\beta,\tau) = \min\{n, Int\left(\frac{2(a-c-\tau) + (n+1)\beta\tau}{4\beta\tau}\right)\} \tag{28}$$

Hence, as long as the optimal strategies are rationing, we have $i)$ $\partial k^f(\beta,\tau)/\partial a = \partial k^a(\beta,\tau)/\partial a = 1/2\beta\tau > 0$, $ii)$ $\partial k^f(\beta,\tau)/\partial n \geq 0 = \partial k^a(\beta,\tau)/\partial n = 1/4 > 0$, $iii)$ $\partial k^f(\beta,\tau)/\partial\beta = \partial k^a(\beta,\tau)/\partial\beta = -(a-c-\tau)/2\beta^2\tau < 0$, and $iv)$ $k^f(\beta,\tau) - k^a(\beta,\tau) \in \{0,1\}$. Moreover, for a given β we have: $v)$ $\partial k^f(\beta,\tau)/\partial\tau = \partial k^a(\beta,\tau)/\partial\tau = -2(a-c)/\beta\tau^2 < 0$. ■

Proof of Proposition 5 For a given τ, consider the following rationing conditions

$$\frac{2(a-c-\tau)+(n+2)\beta\tau}{4\beta\tau} = n-1 \tag{29}$$

and

$$\frac{2(a-c-\tau)+(n+2)\beta\tau}{4\beta\tau} = n-1 \tag{30}$$

Solving equations (29) and (30) for τ yields the lower bounds on the emission tax levels that induce the patentee to use a licensing strategy precluding at least one firm from implementing the technology β:

$$\tau^f(\beta) = \frac{2(a-c)}{(5n-6)\beta+2} \tag{31}$$

and

$$\tau^a(\beta) = \frac{2(a-c)}{5(n-1)\beta+2} \tag{32}$$

Then, solving $\tau^f(\beta) = \hat{t}$ and $\tau^a(\beta) = \hat{t}$ (where $\hat{\tau} \doteq (a-c)/n$ as defined in Assumption 4) for β and using assertions $iv)$ and $v)$ of Proposition 6 yields the results. ■

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