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Revisiting the optimal patent policy tradeoff for environmental technologies

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Abstract

The invention and the diffusion of environmental process of production and consumption goods are impeded by two market failures: the first on environment and the second on knowledge. The question arises whether the instruments aiming at correcting these market failures should be jointly designed or not. We investigate this question for a major instrument of support to innovation: the patent system. We demonstrate that a patent system and a discriminating environmental taxation that are jointly defined provide for a greater efficiency. We conclude that the two externalities interact with each other through the patent system.

1 Introduction

Environmental technologies will be called to play a major role in the transition toward sustainable societies. A growing concern among economist asks whether or not environmental technologies should be supported through dedicated policies, in opposition to neutral policies that equally support all inventions independently of their environmental features (Rennings, 2000, [17]; Jaffe et al., 2005, [6]; Weyant, 2011, [18]; Nordhaus, 2011, [13]). In this paper we focus on a major instrument of support to innovation: the patent system. Our analysis explores the optimal patent system for environmental

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process inventions defined as process inventions that reduce the environmental damage associated with the production of a consumption good.

Letting apart the market failure on the environment, when a patent system is established to support regular inventions the design of an optimal patent system deals with the tradeoff between the dead weight loss associated with the patent system and the welfare improvement from new knowledge. By regular, we qualify inventions that do not generate any environmental benefits.

When a market failure on the environment is included in the problem of designing an optimal patent policy, both the design of the patent system and the level of environmental taxation can be chosen by the regulator. The interest of such exercise is to know whether or not environmental technologies are efficiently supported by an environmentally neutral patent system, i.e. a patent system that does not discriminate environmental from regular inventions. To answer this question we build a bridge between the literature on optimal patent policy and the literature on optimal environmental taxation. Assuming that the regulator can choose both the patent policy and the environmental taxation we conclude that the two market failures interact with each other through the patent system. Indeed, the distortive effect induced by the patent system impacts the optimal environmental taxation that in turn influences the strength of the protection that the regulator have to concede to the private sector to foster investment in knowledge creation. More precisely the environmental taxation is influenced by the patent protection that modifies the competition regime. In turn, the environmental taxation policy, adjusted to the competition regime, impacts the profit of the patentee and changes the incentive to innovate making the optimal patent policy different for environmental technologies, compared to regular inventions. We conclude that policymakers should implement a patent system for environmental technologies coupled with a discriminating environmental taxation, i.e. different for the patentee and its competitors.

This paper is constructed as follows. Section 2 provides for the theoretical context. Section 3 presents a model of optimal environmental patent policy. First, the general principles of the environmental patent problem are detailed and it is demonstrated that the patent policy and the environmental taxation interact with each other (3.2). Then, two illustrations of the general principles are given in subsections 3.3 and 3.4. Finally, section 4 discusses our results and concludes.

2 Environmental innovation and the double externality

Two strategies can be adopted by policymakers to stimulate environmental innovation. A first strategy is to correct the negative externalities on the environment on one hand and to provide for an environmentally neutral support to innovation on the other hand. A second strategy is to implement an innovation policy that targets environmental technologies by discriminating the inventions generating environmental benefits. In subsection 2.1, we present the arguments that support the first strategy. In subsection 2.2 we demonstrate that it is inconsistent with a patent system, laying the ground for a patent policy dedicated to environmental technologies.

2.1 *Price fundamentalism* theory, Pigovian taxation and perfect competition

According to Nordhaus (2011, [13]), when negative externalities on the environment are internalized, for instance with a tax or a quota market, environmental technologies are put on a leveled playing fields with regular technologies. In addition to the environmental policy, the regulator must implement neutral innovation support policies aiming at increasing the private rate of return from an invention in order to spur investments in new technologies. The rationale for this support to innovation lies in the public good feature of knowledge, discussed in the next subsection. Following this logic, it is sufficient to price the negative externalities on environment to support environmental innovation, if innovative activities in general are efficiently bolstered. Nordhaus calls this theory the *price fundamentalism* and states that it can serve as a blueprint for policymakers who are committing to support environmental innovation. As Nordhaus acknowledges, it holds true under several conditions among which the perfect internalization of all product and market externalities that constitutes the most important one.

In our view the reason why this condition is the most important lies in the nexus between environmental taxation and market structure. Take, for example, one of the favorite tool of economists to correct environmental externalities: the Pigovian taxation (Pigou, 1932, [15]). The goal of a Pigovian tax is to equalize the marginal private cost of production with the marginal social cost that includes the impact of the environmental damage of production on social welfare. To achieve this the level of the tax must be equal to the Marginal Environmental Damage (MED) of production and consequently the market price will reflect the marginal social cost of production. Hence, Pigovian taxation corrects the environmental externality and market forces can then achieve the social optimum. This reasoning holds under the assumption that the polluting good market is perfectly competitive. As producers are price takers the tax is perfectly passed through the price. When it comes to innovation this assumption of perfect competition might not hold because of innovation policies and it questions the relevancy of using *price fundamentalism* to guide environmental innovation policies. Indeed, the early paper of Buchanan has emphasized the influence of market structure on the optimal environmental taxation (Buchanan, 1969, [3]; see also Lee, 1975, [8] and Barnett, 1980, [2]).

2.2 The limits of *price fundamentalism* in a patent system

As evoked above, implementing an innovation policy might create competition distorsions. Innovation results from the accumulation of knowledge which is a public good: it is non-rival (the consumption of knowledge by an agent does not reduce the consumption available to other agents) and non-exclusive (it is too costly to prevent someone from consuming knowledge). Therefore, the socially optimal level of knowledge price is equal to zero because the non-rivalry implies a marginal cost of reproduction of knowledge that is nill, if transmission cost excluded. In other words, society's welfare is maximized when knowledge diffusion is the largest. This corresponds, as Arrow wrote (1962, [1]), to

> an ideal socialist economy, [where] the reward of the invention would be completely separated from any charge to the users of the information.

In a free market economy however a substantial part of research activities is undertaken by profit-maximizing firms. In the absence of a public intervention the market leads to an underinvestment in knowledge creation compared to its socially optimal level. In this extent innovation policies must increase the private yield the firms can expect from an invention. For this purpose, the regulator could either reduce the cost of R&D or increase the payoff from an invention. The latter lever mainly relies on Intellectual Property Rules (IPR) aiming at increasing the appropriability of an invention defined as the share of the new knowledge the inventor can internalized. In this paper we focus on one of the most used IPR instruments: the patent system. A patent system is an incentive mechanism that gives the inventor a temporary ownership right over the patented invention that prevents, or at least inhibits, other agents to produce, use or sell the invention during the period of protection. The duration of the patent is its length and the degree of exclusivity over the invention with respect to competitors is its breadth. Thus, a patent system increases the incentive to innovate and contributes to common knowledge growth because of the requirement to disclose knowledge once the patent is granted. The downside of a patent is that it gives a temporary dominant market position to the patent owner and therefore generates a dead weight loss. The dominant position of the patent holder invalidates the assumption of perfect competition on which relies *price fundamentalism* theory.

It should be noted that alternative theories on environmental innovation has been proposed by several authors. Weyant (2011, [18]) recommends a stronger government R&D budget dedicated to environmental technologies. Its argumentation is based on the existence of several barriers that stifle environmental innovation: the underpricing of environmental damages, the important role of not-for-profit research that does not respond to price signals and the difficult appropriation of energy technologies. Another critic can be found in Jaffe et al. (2005, [6]). They state that the two types of externalities, on the knowledge and on the environment, interact with each other making the implementation of support instruments dedicated to environmental technologies an efficient strategy. To justify this, they also discuss the issue of an imperfect internalization of environmental damages that limits investment in environmental technologies.

To our view, the perfect internalization of environmental damages is not a sufficient condition to spur efficiently environmental innovation. We do not propose an environmental patent theory based on an imperfect internalization of the externality on the environment. Our focus is on the nexus of the patent system and the environmental taxation. We investigate this issue in a model of optimal patent policy for environmental inventions. It is demonstrated that the optimal taxation of a patent holder depends on the social cost of the patent system. To this extent, the regulator intervenes efficiently when the environmental taxation and the patent system are jointly designed. We conclude that environmental technologies should be promoted through a dedicated patent system.

3 The model.

3.1 The Race for the Patent

Our modeling of the patent race is based to a large extent on Loury (1979, [10]) and Lee and Wilde (1980, [9]). To our best knowledge their approaches, initially applied to invention races, were extended for the first time to optimal patent policy design by Denicolò (1996, [4]). Representing the patent race is necessary to deduce the incentive constraint the regulator has to take into account when she aims at inducing the socially optimal level of R&D expenses. Considering n identical firms that are all seeking to achieve the same discovery: a new production process reducing the MED associated with the consumption good they produce. Hence, we consider a 'purely' environmental invention that does impact the production cost. The first racer that discovers the invention wins the patent and the remaining payoff for its competitors is reduced, if not annihilated depending on the breadth of the patent. Each firm i, with $i = 1, ..., n$, engages a level of R&D expenses denoted x_i that will be paid at each period until the invention is discovered by one of the n firm. The choice of x_i is based on the probability to win the patent race that depends both on the intrinsic uncertainty of a R&D project (technological uncertainty) and on the probability that a competitor discovers the invention (market uncertainty).

Technological uncertainty relates to the probability to discover the invention. A firm i knows that independently of its competitors the probability to discover the invention at a given period of time, denoted τ_i, increases both with the R&D expenses x_i and with the time t that has passed since the beginning of the research period . The probability law of the discovery time τ_i is

$$Pr(\tau_i \leq t) = 1 - e^{-h(x_i)t}.$$

It is assumed that there are decreasing returns on R&D, thus $h(.)$ is a strictly increasing and concave function. In the absence of any competitors the probability to win the race would obviously reduce to the probability to discover the invention and the firm would determine the optimal amount of R&D with respect to technological uncertainty only. However, a second factor influences the probability to win the race: market uncertainty. Because winning a patent means to be the first to discover an invention, a firm will take into account the probability that one of the competitors first discovers the invention. We denote $\overline{\tau}_i$ the earliest date at which one of the competitors of i discovers the invention, hence we have $\overline{\tau}_i = Min(\tau_j, \forall j \neq i)$. Because firms are homogeneous, they all face the same technological uncertainty and the probability law of $\overline{\tau}_i$ is

$$Pr(\overline{\tau}_i \leq t) = 1 - Pr(\tau_j > t, \forall j \neq i).$$

Denoting $H_i = \sum_{j \neq i} h(x_j)$, it can be rewritten

$$Pr(\overline{\tau}_i \leq t) = 1 - e^{-H_i t}.$$

A firm takes into account these two sources of uncertainty. We assume the firm knows both the distributions of τ_i and $\overline{\tau}_i$. The probability to win the patent race becomes the probability to discover the invention before the discovery is realized by a competitor. Under the assumptions of risk neutrality and perfect foresight the expected profit of firm i is the discounted value of the prize from winning the patent, denoted B, to which we will return later, weighted by the probability to win the patent race minored by the discounted R&D cost paid until the discovery is realized. It is written

$$E(\Pi_i) = \int_0^{\infty} \left\{ \int_0^t Pr(\tau_i = s) B e^{-s\rho} \mathrm{d}s \right\} \mathrm{Pr}(\overline{\tau}_i = t) dt - \int_0^{\infty} \left\{ \int_0^t x_i e^{-s\rho} \mathrm{d}s \right\} Pr(\overline{\tau}_i = t \text{ or } \tau_i = t) \mathrm{d}t,$$

with ρ the discount rate. Integrating this expression gives

$$E(\Pi_i) = \frac{h(x_i)B - x_i}{H_i + h(x_i) + \rho}. \tag{1}$$

The inventor maximizes (1) w.r.t x_i so that we can write

$$(H_i + \rho)(h'B - 1) - \Big(h(x_i) - x_i h'\Big) = 0$$

with h' the first derivative of h and x_i being now the private optimum of R&D expenses. Considering now the private decisions from the regulator's point of view. Assuming that she knows the socially optimal amount of R&D expenses. Since the searching firms are homogeneous it is equivalent to know the socially optimal level of individual R&D expenses, denoted x^*. As noted by Denicolò, knowing x^* implies that the regulator knows the optimal discovery time (Denicolò, 1996, [4]). Inserting x^* in the previous expression and rearranging to isolate the term B, we have the following equality

$$B = \frac{h'(n - x^*) + \rho}{h'[(n-1)h + \rho]}. \tag{2}$$

This expression represents the link between the prize obtained from winning the patent (B) and the socially optimal level of R&D expenses of inventors (x^*). As the latter is considered as known the r.h.s of equation (2) is a constant. What interests us is the influence of the patent policy and the environmental taxation on the value of B that must be set to induce the socially optimal level of R&D. Firms expect the winner's prize B to be composed of two parts: the profit raised during the period of patent protection, denoted Π, and the profit raised after the patent has expired, denoted $\overline{\Pi}$. Hence we have

$$B = \int_0^T \Pi e^{-t\rho} \mathrm{d}t + \int_T^\infty \overline{\Pi} e^{-t\rho} \mathrm{d}t,$$

where T denotes the patent's length. Incorporating the developed form of B in equality (2) gives

$$\frac{\phi}{\rho}(\Pi - \overline{\Pi}) = K, \tag{3}$$

where $K = \frac{nh' - x^* h' + \rho}{h'[(n-1)h + \rho]} - \frac{\overline{\Pi}}{\rho}$ and $\phi = 1 - e^{-\rho T}$. The L.H.S of equation (3) depends from the strength of the patent protection (its breadth that influences Π and its length embodied in ϕ) and from the environmental taxes raised during the patent period that influences Π. They are chosen by the regulator to determine the value of the patent prize that induces the socially optimal level of R&D expenses. Since the latter is assumed to be known the incentive constraint (3) is an equality. The R.H.S of equation (3) is a constant that includes the profit realized after the patent period. This profit is considered to be exogenous as it does not depend from the patent system. After the patent has expired the remaining environmental externality is nonetheless assumed to be corrected by the first best environmental tax.

3.2 General principles of the environmental patent policy

In this subsection we derive from the environmental patent problem several principles before presenting two applications in subsections 3.3 and 3.4 that explore two types of competition regime faced by the patentee.

The purpose of the public intervention is to induce the socially optimal level of R&D expenses engaged by competing firms while minimizing the temporary dead weight loss resulting from the dominant market position of the patentee. Hence, she maximizes the social welfare subject to the condition (3). The regulator's intervention relies on four policy instruments:

- The patent's length T, embodied in ϕ, that has a positive influence on the patentee's reward. The value of ϕ weights the social welfare during the patent and the social welfare after it has expired in the total welfare taken into account by the regulator. Obviously, both the temporary dead weight loss resulting from the patent and the incentive to innovate increase with T.

- The patent breadth, denoted α, represents the strength of the protection guaranteed to the patent holder with respect to its competitors during the period of validity of the patent. The broader is the patent the harder it is for the competitors to use the new technology at its full potential. In this extent when the breadth is minimum the new technology is in free access. At the other extreme of the protection spectrum, when α is maximum, they are no spillovers and the competitors are constrained to use the old technology.

- The environmental tax paid by the patentee per unit of produced output denoted t_p. Because having a patent identifies the firm as enjoying a technological advantage over its competitors the regulator is able to adjust the environmental tax paid by the patent holder.

- The environmental tax paid by its competitors per unit of produced output t_c.

The problem of the regulator is written

$$\underset{\phi,\alpha,t_p,t_c}{Max} \quad \frac{\phi}{\rho}W(\alpha,t_p,t_c) + \frac{(1-\phi)}{\rho}\overline{W}$$

$$s.t.c \quad \frac{\phi}{\rho}(\Pi(\alpha,t_p,t_c) - \overline{\Pi}) = K,$$

where the social welfare expressions are the sum of the consumers and producers surpluses minus the environmental damage. W denotes the level of social welfare during the patent protection, and $\overline{W}$ after it expires. Both $\overline{\Pi}$ and $\overline{W}$ are constants because after the patent expires the regulator corrects the environmental externality business-as-usual by deriving the first best tax paid by firms. Substituting the constraint in the objective function and neglecting the constants K and $\frac{\overline{W}}{\rho}$, we can rewrite and simplify the regulator's program as a minimization problem

$$\underset{\alpha,t_p,t_c}{Min} \; \frac{\overline{W} - W(\alpha, t_p, t_c)}{\Pi(\alpha, t_p, t_c) - \overline{\Pi}}. \tag{4}$$

The length of the patent, on which ϕ depends, vanishes from the regulator's problem. Deriving the FOCs gives

$$W'_{t_p}(\Pi - \overline{\Pi}) + \Big(\overline{W} - W(\alpha, t_p, t_c)\Big)\Pi'_{t_p} = 0, \tag{5}$$

$$W'_{t_c}(\Pi - \overline{\Pi}) + \Big(\overline{W} - W(\alpha, t_p, t_c)\Big)\Pi'_{t_c} = 0 \tag{6}$$

and

$$W'_{\alpha}(\Pi - \overline{\Pi}) + \Big(\overline{W} - W(\alpha, t_p, t_c)\Big)\Pi'_{\alpha} = 0. \tag{7}$$

The novelty of our paper lies in the fact that the environmental feature of the patented invention puts forward a link between environmental taxation and patent policies.

To solve analytically this problem we must know the social welfare expression and it implies specifying the competition regime, the demand function and the production cost functions. This is done in the two applications presented in subsection 3.3 and 3.4. Nonetheless, this is not necessary if we want to derive several general principles that only rely on two realistic assumptions: $(\Pi - \overline{\Pi})$ and Π'_{t_p} are respectively non-negative and non-positive. The first proposition stipulates that the level of profit of the patentee is higher during the patent protection than after. This is a trivial assumption as the goal of a patent system is to guarantee an extra-profit that the inventor would not earn without a patent protection. The second one means that the patentee's profit cannot increases with the tax she must pay; a straightforward intuition. When these two assumptions hold, two cases may arise from equation (5):

- First case: the dominant market position of the patent holder creates a dead weight loss during the patent period. Hence, all other things being equal, the social welfare is lower during the period of patent protection and we have $\overline{W} - W(\alpha, t_p, t_c) > 0$. Considering the benchmark case of the first best environmental taxation, where $W'_{t_p} = 0$, denoted t^*. We can deduce from (5) that $W'_{t_p} > 0$ which implies that the optimal taxation paid by the patentee differs from the first best solution that would have prevailed in the absence of any patent system. Moreover, assuming that the social welfare is a strictly concave function of t_p and has an unique maximum t^* we conclude that the optimal level of environmental taxation of the patentee during the patent protection should be below t^*. The patent system influences the environmental taxation policy, and we can expect this effect to be reciprocal because the reward from winning the patent depends from the tax paid by the patent holder.

- Second case: the patent system implies no dead weight loss during the patent period, hence $\overline{W} - W(\alpha, t_p, t_c)$ is nill. In this case, through the combined effect of the patent system and the environmental taxation the regulator is able to annihilate the temporary dead weight loss resulting from the dominant market position of the patentee. This case contrasts with the usual feature that a patent system, as a second best instrument, creates a temporary dead weight loss. The corollary result is that the tax paid by the patentee that should be implemented maximizes the social welfare during the patent such that $W'_{t_p} = 0$. Here, implementing the optimal taxation annihilates the social cost of patent protection.

To resume, the double externality impacts the environmental patent policy in both cases. In the first case it prevents the regulator from deriving the environmental taxation paid by the patentee *as if* there was no patent system, that is by maximizing the welfare w.r.t the tax. In the second one, the double externality leads to an unusual situation where the patent system is not socially costly during its validity. Both situations are illustrated in the two following subsections.

3.3 Application 1: Patent length and environmental taxation with infinite breadth

This first application investigates a simple case that considers *ex ante* that the patent breadth is maximum. The advantage of such assumption is to isolate the interaction between the environmental taxation of the patent holder and a patent system reduced to the period of protection. Moreover, it offers the possibility for a straight comparison of our results with those of Nordhaus (1967, [12]) as this application is an extension to environmental inventions of his model of optimal patent length. As said before, the patented invention reduces the MED of production. This less polluting process of production generates a MED denoted e. A patent protection with a maximum breadth excludes any potential competitors to use the new process. As a result the patent holder enjoys a monopoly situation over the new technology.

Considering that the new technology is used to produce a polluting good and denoting the produced quantity Q. The demand for this good is assumed to be linear and represented by the function

$Q = a - dP$ where P is the price of the good. The marginal cost of production of the good is c. For simplicity, we assume that e and c are both constant. Once the patent expires all firms can use the patented invention and the market becomes perfectly competitive. The remaining externality on environment is internalized with a Pigovian tax denoted t and equal to e. It has two consequences. First, the social welfare after the patent has expired $\overline{W}$ is maximized and written $\overline{W} = \frac{1}{2d}\big(a-(c+e)\big)^2$. Second, the profit realized by the patent holder after the patent system has expired vanishes in the incentive constraint (3) that can be written

$$\frac{\phi}{\rho}\Pi = K. \tag{8}$$

Substituting (8) in the regulator's program gives the following problem

$$\underset{t_p}{Min} \ \frac{\overline{W} - W(t_p)}{\Pi}.$$

Where $W = (1/2d)Q_p^2 + P_pQ_p - (c+e)Q_p$, with Q_p and P_p denoting respectively the quantity of output produced by the patentee and the corresponding price [1]. They both depend on the environmental tax t_p chosen by the regulator and paid by the patent holder. Differentiating w.r.t t_p, we have the following condition

$$W'_{t_p}\Pi = \Pi'_{t_p}(W - \overline{W}). \tag{9}$$

Replacing $\overline{W}$ by its expression in (9) and solving for t_p we derive the optimal tax paid by the patent holder denoted t_p^*:

$$t_p^* = e - \frac{1}{d}\left(a - d(c+e)\right). \tag{10}$$

The optimal level of environmental taxation kills two birds with one stone. First, it internalizes the environmental damage. Second, it corrects the market distortion caused by the monopolistic position of the patentee. This result is consistent with the literature on the optimal taxation of a pollutant monopoly (see Buchanan, 1969, [3]; Lee, 1975, [8] and Barnett, 1980, [2]). The effect of the environmental taxation on the monopoly price and the resulting rent granted to the patent holder are represented on Figure 1. The rent is represented by the grey area.

The tax t_p^*, lower than the MED, makes the marginal production cost curve crosses the marginal revenue curve at a point that makes the monopoly price equals to the marginal social cost of production,

[1] Equalizing the marginal revenue and the marginal cost of the patent holder we obtain the usual expressions $Q_p = \frac{1}{2}(a - d(c+t_p))$ and $P_p = \frac{1}{2d}(a + d(c+t_p))$.

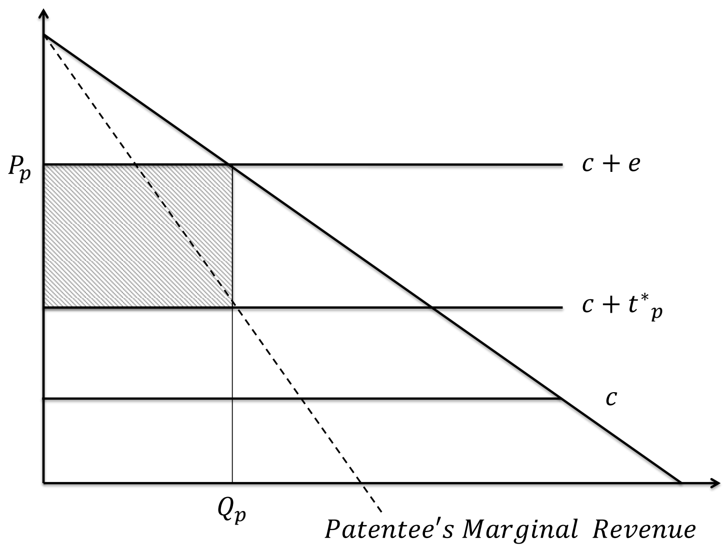

Figure 1: Optimal environmental taxation of the patent holder when breadth is infinite.

$c+e$. As a consequence the market equilibrium is the first best situation and the patent system generates no dead weight loss during the patent period. Considered apart from the patent policy question, this result would not provide for any novelty. However we can derive the implications of the environmental taxation t_p^* on the optimal patent length denoted T^*. Replacing the patentee's profit $\Pi(t_p^*)$ in the incentive constraint we obtain the optimal length

$$T^* = \frac{1}{\rho} ln(\frac{\Pi(t_p^*)}{\Pi(t_p^*) - \rho K}). \tag{11}$$

Several remarks must be made. First, compared to an invention that decreases the marginal cost of production c (a classic case widely covered by the literature; *e.g.* [12], [16] and [4]) the patent length for a environmental invention is shorter [2]. It comes from the fact that the environmental taxation t_p^*, lower than e, induces a higher profit for the patentee that allows the regulator to shorten the patent length. Second, in this setup the patent system does not induce any dead weight loss for society during the patent protection as the monopoly power of the patentee is corrected. Hence, coupling a lower environmental taxation with a dedicated patent system provides for a more efficient policy than to separately correct each externality with help of an environmentally neutral patent system and an environmental tax disconnected from the competition regime associated with the patent protection.

[2] This comparison holds *ceteris paribus* for two inventions (a decrease of the MED versus a decrease of the marginal cost of production) with equal social yields. See proof in Appendix A.

The application proposed in this subsection is an illustration of the second case evoked in subsection 3.2. However, it must be noted that the optimal tax t_p^* might become negative depending on the market conditions and it raises additional issues on the social acceptability and the funding of this subsidy.

3.4 Application 2: Optimal discriminatory taxation and patent policy in a Stackelberg competition

The question of patent breadth has been deliberately ignored in the previous application in order to put the accent on the link between environmental taxation and patent length. The previous application however suffers from a lack of realism as it is rare that a patent annihilates every competition faced by the patent holder; it may be the case only for breakthrough inventions. To include the influence of competitors we consider that the breadth of the patent is not set *ex ante* but chosen by the regulator and we modify the current competition regime during the patent period. The breadth of a patent characterizes the scope of the protection that depends from the claims made by the applicant(s). The content of the claims, and thus the protection scope of the patent, results from the negotiation between the applicant(s) and the patent examiner(s). In this extent the breadth can be regarded as the share of the new technology that is accessible to competitors without making them guilty of patent infringement. Drawing on this, we retain the following definition of the breadth: when the new invention allows for a decrease of the MED from e_0 to e with $e = e_0 - b$, the share of the technology that is lawfully accessible to patentee's competitors allows them to reduce the MED of their production to $e_0 - (1 - \alpha)b$. The breadth is obviously maximum when $\alpha = 1$ (no spillovers toward competitors) and minimum when $\alpha = 0$ (full spillovers toward competitors).

In this second application we assume that a patent gives to its owner a Stackelberg leadership that competes in quantity with a competitive fringe of m firms. Producers, both the leader and the followers, have the same production cost function : $C(q) = \frac{1}{2}q^2$ with q the quantity produced by a firm. Because competitors must assess the share of the new technology they can copy without infringing the patent, additional research must be carried out and it generates a sunk cost denoted S paid before entering the market. The quantity of output produced by the leader and the environmental tax she pays are respectively denoted q_l and t_l. The subscript f indicates the equivalents for each follower of the competitive fringe. Apart from these changes we retain the same notations and demand function as in the previous subsection.

In this market setup the expression of the social welfare during the patent period is

$$W(\alpha, t_l, t_f) = \frac{1}{2d}Q^2 + (P - t_l - \frac{1}{2}q_l)q_l + m(P - t_f - \frac{1}{2}q_f)q_f - mS - eq_l - m(e_0 - (1-\alpha)b)q_f,$$

where $Q = q_l + mq_f$ the total quantity of produced output. Similarly, the social welfare after the patent expires is equal to $\overline{W} = \frac{1}{2d}(a - de)^2$, as the patent holder loses the Stackelberg leadership and the market becomes perfectly competitive [3].

Subject to the incentive constraint, the regulator minimizes the temporary dead weight loss associated with the patent w.r.t. environmental taxes t_l and t_p and patent's breadth α. We can derive the F.O.Cs

$$W'_{t_l}\Pi + (W(\alpha, t_l, t_f) - \overline{W})\Pi'_{t_l} = 0, \tag{12}$$

$$W'_{t_f}\Pi + (W(\alpha, t_l, t_f) - \overline{W})\Pi'_{t_f} = 0 \tag{13}$$

and a corner solution is easily deduced for the optimal breadth which is minimum (the marginal loss in terms of welfare from increasing the patent breadth is positive and equal to mbq_f). Incorporating $\alpha = 0$ and combining (12) and (13), we obtain the following equality

$$W'_{t_f}\Pi'_{t_l} = W'_{t_l}\Pi'_{t_f}.$$

Developing and rewriting this expression gives the optimal price $P = q_f + e$. As the firms of the competitive fringe are price takers they produce until their marginal cost of production $(q_f + t_f)$ equals the market price and consequently the optimal tax paid by the competitive fringe denoted t_f^* is a Pigovian tax: $t_f^* = e$. Inserting it into (12) reveals the link between the temporary dead weight loss from the patent and the quantity of produced output:

$$(q_l - q_f)\frac{q_l}{2} = \overline{W} - W(t_l). \tag{14}$$

We can simplify this expression to

$$\frac{1}{2d}(a - de)Q - m(\frac{q_f^2}{2}) = \frac{1}{2d}(a - de)^2.$$

[3]It should be kept in mind that under perfect competition firms enter the market until their profits fall to zero. This situation corresponds to a theoretically infinite division of production between producers since there are no fixed cost after the patent expires. Each firm will produce an infinitesimally small quantity and the marginal social cost of production (being the equilibrium price) will tend to e as the externality is corrected with a Pigovian taxation.

Noting that $m(\frac{q_f^2}{2})$ represents the total revenue earn by the competitive fringe that compensates the total sunk cost mS. Therefore, the difference between the level of produced output during the patent period, Q, and afterward, $(a - de)$, depends on the total amount of sunk cost. At this point we can derive the optimal level of tax t_l^* and obtain

$$t_l^* = e - (\frac{d+m+1}{d+m})(a-de) - (\frac{d+m+2}{d+m})Z \tag{15}$$

with $Z = \frac{mS}{(1/2d)(a-de)}$. The market price[4] can be deduced from the two environmental taxes and gives $P = e - (Z/d)$. As Z is positive this price is low enough to exclude the competitive fringe from the market since their profits are negative for every level of production. Hence, the expression t_l^* can be simplified to $t_l^* = e - (\frac{d+1}{d})(a - de)$. As in the previous subsection the optimal tax is lower than the MED in order to mitigate the patentee's market power. However, the major difference compared to the previous case of application is the temporary loss in terms of social welfare measured by the difference between W and $\overline{W}$. As q_f is nill, the equality (14) can be rewritten as

$$W = \overline{W} - \frac{q_l^2}{2}.$$

The temporary dead weight loss of the patent is the result of delegating the whole production to the same firm, being the patentee, generated by the convexity of the cost function. The existence of a temporary dead weight loss provides for an illustration of the first case presented in subsection 3.2. In this extent the patentee must pay an environmental tax during the patent period that is lower than the level that would maximize the social welfare.

Finally, the optimal length of the patent is derived as in (11) and is adjusted from the level of profit. Hence we have

$$T^* = \frac{1}{\rho} ln(\frac{\Pi}{\Pi - \rho K}). \tag{16}$$

4 Discussion and concluding remarks

This paper serves two purposes. The first is to detail the impact of the interactions between the two market failures on the environmental innovation within a patent system and to derive its general principles. The second is to provide for a narrower scope by investigating the optimal policies in two applications.

[4]The pricing equation resulting from the competition regime is $P = \frac{(d+m+1)(a+mt_f)+(d+m)t_l}{(d+m)(d+m+2)}$.

The first level of analysis can be called general as it includes as few assumptions as possible. They are mainly contained in the innovation race that generates the incentive constraint of the regulator' s problem. The value added of taking into account the patent race is to understand the determinants of the prize from winning the patent that the regulator have to equalize to a constant K if she aims at inducing the socially optimal level of R&D expenses, assumed to be known. Another modeling strategy is to let this prize unknown as in Klemperer (1990, [7]). The incentive constraint allows to formulate the problem of the regulator : to minimize the temporary dead weight loss generated by the patent system subject to the constraint that the private sector undertakes the socially optimal level of R&D. Deriving the FOCs of the problem we can deduce the general principles of the environmental patent problem by making two realistic assumptions. First, the level of the patentee' s profit is higher during the patent protection period than after it has expired. It is consistent with the principle of a patent system. Second, the profit of the patentee decreases with the environmental tax she pays as can be expected in reality. These assumptions are sufficient to demonstrate the existence of an interaction between a patent system and an environmental taxation policy. Two cases may arise:

- First, the optimal patent system has a social cost during the patent period. The condition of optimality (5) stipulates that the sign of the derivative of the social welfare during the patent period with respect to the environmental tax paid by the patentee should be positive. If the two externalities do not interact within the patent system the environmental tax paid by the patent holder would maximize the social welfare. Assuming that the social welfare is a concave function of the environmental tax paid by the patentee, we can conclude that the level of the tax paid by the patent holder is lower than the one that would have prevailed in the absence of a patent system.

- Another case may arise when the optimal patent system does not generate a dead weight loss during its validity. In this setting, the environmental tax paid by the patentee maximizes the social welfare during the patent period. Again, the introduction of an environmental externality in the patent system influences the optimal policy. Indeed, the regulator could jointly implement a patent system and an environmental taxation policy that are not socially costly during the patent period. This conclusion strongly contrasts with the literature on optimal patent policy built on the tradeoff between the temporary dead weight loss resulting from the market power of the patentee and the increase of welfare from knowledge creation.

The second level of analysis presents two applications of the environmental patent problem. An abundant literature on patent policy has demonstrated the high sensitivity of the optimal policy to the competition regime in place during the protection period, a feature explained by Denicolò (1996, [4]). Then, our two applications do not pretend to give systematic guidelines to policymakers but rather to illustrate the general principles derived from the first level of analysis.

The first application puts the accent on the articulation between patent length and environmental taxation. To do so, it is assumed that the breadth is maximum and that the patentee is in monopoly situation. In this setting the patentee sets its quantity by equalizing its marginal revenue and its marginal cost of production. The dead weight loss resulting from the monopoly position during the patent period can be suppressed by implementing a *low* environmental tax that makes the monopoly price equals to the marginal social cost of production. Here, the term *low* refers to an environmental tax smaller than the level of MED of production. Hence, the welfare during the patent period is at its first best level. The taxation of a pollutant monopoly is a question that has been investigated by Buchanan (1969, [3]), Lee (1975, [8]) and Barnett (1980, [2]). What interests us here is the opportunity for the regulator to suppress the temporary dead weight loss of the patent by adjusting the tax paid by the patent holder. Simultaneously, the patent's length is adjusted to the particular taxation conditions enjoyed by the patentee and it is shortened, compared to the optimal length of a patent protecting a regular invention. Despite the attractiveness of this solution it suffers however from a lack of realism. We assume that the regulator has perfect information about the market structure and is able to fully *control* the monopoly with the sole tool of the environmental tax. In reality, this control would need to rely on a complete regulation rather than one tax. Second, the tax could be negative for some values of the parameters, especially when the new invention allows a low level of MED. It would be relevant to investigate the funding of this subsidy as well as its social acceptability.

The second application provides for a richer representation as the breadth is not considered *ex ante* as maximum. Consequently, there are market opportunities for a competitive fringe. It appears nonetheless that the optimal strategy for the regulator is to exclude the competitors by setting the environmental tax they pay equal to the level of MED and a lower tax for the patent holder. This lower tax makes the market price equals to the MED and it prevents the competitive fringe to enter the market. Since an increasing marginal cost of production is considered, the temporary dead weight loss of the patent, compared to perfect competition, arises from the fact that the patentee carries the totality of the production. In comparison of the post patent period, there is an additional cost due to the concentration of the production in a single firm. Despite the differences between the two applications in terms of competition regimes the optimal policies follow the same principle: the market power of the patentee is counterbalanced by a low environmental tax that reduces, and possibly annihilates, the temporary social burden of the patent system. It has another consequence: the low environmental tax has a positive impact on the patentee's profit and it makes the patent's length shorter.

We can summarize the main idea of this paper as follows. Considering a regular process invention that decreases the marginal cost of production without changing the environmental damage of the production. The profit of the inventor will depend on the cost savings allowed by the new process. These cost savings are exogenous and consequently outside the scope of the regulator's intervention. For an environmental invention the situation is different. In fact, the *translation* of the environmental gains into private gains is made through the environmental taxation defined by the regulator. Contrary to the regular case, environmental taxation comes in addition to the two dimensions of the patent system, the breadth and the length. This provides for broader possibilities to the regulator who can differentiate the private reward from the environmental gains between the patentee and its competitors. Hence, the role of the breadth is rendered obsolete when coupling the patent system with a discriminatory environmental taxation. Indeed, in a regular patent system the breadth will delimit the access of the competitors to the new technology. When the regulator chooses the breadth of the patent, she knows it will induce the difference of the production cost between the patentee and its competitors and indirectly the difference of profits. In the environmental patent problem the breadth does not raise the same issues: the breadth of the patent will have a social impact through the level of environmental damage. The difference of production cost between the patentee and its competitors will be endorsed by the discriminating environmental taxation.

To conclude, the goal of this model is to demonstrate that patent policy and environmental taxation should be jointly designed by the regulator. The interaction between the two policies advocates for a patent system dedicated to environmental technologies and jointly implemented with an *ad hoc* environmental taxation of the patent holder. However, our results remain very theoretical and must be tested against real world. In this extent, several issues arise. First, environmental damages are underpriced in our economies. A cautious optimism suggests that it will evolve in the next years but for the moment it limits our purpose. Second, different institutions are responsible of patent and environmental policies. The representation of a unique regulator is too simplistic. Finally, our paper focuses only on patent policy but the same issues should be investigated for different instruments of support to knowledge creation, such as R&D subsidies.

A Appendix

We give proof that the optimal patent length defined in equation (11) is, *ceteris paribus*, shorter than the optimal length for a regular invention in a context where there is no market failure on environment.

We consider that the regular invention induces a decrease of the marginal cost of production from c_0 to c and the green invention a decrease of the MED from e_0 to e. Since we consider two inventions with the same social value we have $e_0 - e = c_0 - c$. The first inventor (regular inventor) produces a non polluting good and the second producer (environmental inventor) a polluting good at a zero cost, tax excluded. Computing the optimal patent length using the incentive constraint, it appears that if the profit of the environmental innovator (Π_{green}) is higher than the profit of the regular innovator ($\Pi_{regular}$), then the optimal length is shorter for the former. The two inventor's profits are:

$$\begin{cases} \Pi_{green} = \dfrac{1}{d}(a - de)^2 \\ \Pi_{regular} = \dfrac{1}{4d}(a - dc)^2 \end{cases}$$

As $e = c$, the environmental patent is shorter.

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