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Abstract

Spontaneous adoption of cleaner technologies can be slowed down by various sources of inertia. Investment irreversibility, uncertainty about the actual private benefits, and the expectation of declining adoption costs due to the diffusion of environmental innovation, may involve a timing of technological migration incompatible with avoidance of excessive pollutant accumulation. In this paper we examine the implications of the sources of inertia on the design of public incentives aimed at accelerating abandonment of polluting technologies when the policy-maker faces incomplete information about the private switching costs.

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1 Introduction

The classical case for policy intervention, addressed in environmental literature, arises when market failures impede internalisation of the social costs (benefits) of pollution (abatement), and, consequentely, voluntary adoption of cleaner technologies.

However, a case for policy intervention may also arise when firms face a different value of waiting before adopting potentially profitable "green" technologies than does society as a whole. For instance, even in the presence of market conditions (e.g. consumers' willingness-to-pay for green products) which are potentially able to drive voluntary abandonment of polluting technologies (Porter and Van der Lind,1995), regulation is still required as long as firms' expectations do not involve spontaneous timing of environmental innovation consistent with avoidance of a socially undesirable level of pollutant accumulation. However, to bridge the gap between the private switching time and the socially desirable one, regulators, rather than assuming the existence of a trade-off between social benefits and private costs of environmental innovation, should focus on the sources of "technological inertia" so as to increase the private opportunity cost of postponing potentially profitable environmental innovations (Dosi and Moretto, 1997).

Two potential sources of inertia are addressed in this paper. The first one is uncertainty about the evolutionary pattern of private benefits. The second one is the expectation of declining adoption costs, due to the diffusion of environmental innovation throughout the industry.

Our analysis builds upon two distinct streams of literature. The first one deals with the role of the option value to delay an irreversible investment involving stochastic benefits (Dixit and Pindyck, 1994). The second one relates to innovation and standardisation, by emphasizing the impacts of network externalities implying lack of co-ordination and excess inertia in technological change (Farrell and Saloner, 1985; Katz and Shapiro, 1985).

The aim of this paper is twofold. First, we provide a unified framework of analysis of technological migration when investment irreversibility and lack of co-ordination operate simultaneously within an industry. Secondly, we explore the implications of these sources of inertia from a regulatory point of view.

The paper is structured as follows. In the following paragraph we identify the optimal private time pattern of technological migration. In Section 3 we consider the policy-maker's problem. By assuming that the regulator has pre-identified the date before which the entire industry under consideration should abandon the polluting technology and adopt the green one, and s/he is unable (or unwilling) to adopt mandatory regulation, we identify public incentives required to bridge the gap between the private time of technological change and the socially desirable one. In particular, we will examine the properties of a first-price auction, where firms are required to declare their optimal expected private switching time and the subsidy is granted to the agent who announces the lowest one.

2 The firms' problem

2.1 Basic setup and assumptions

Two firms ($i = 1, 2$) belonging to the same industry are given the opportunity of abandoning their present ("polluting") production process, and to adopt a new ("green") one, by affording a *sunk switching cost* C_i.

The technological change under consideration is expected to increase net operating benefits; however, firms face uncertainty about the benefits per unit of time, x_t. We assume that the state variable x_t is described by a geometric Brownian motion:

$$dx_t = \alpha x_t dt + \sigma x_t dB_t \qquad \text{with } \alpha, \sigma > 0 \text{ and } x_0 = x. \tag{1}$$

where dB_t is the increment of a standard Wiener process and both the expected rate of growth and the instantaneous variance of x are constant over time.[1]

While the evolutionary pattern of the technological change's net operating benefits (henceforth "the private benefits") is independent of the number of agents who have abandoned the polluting technology[2], we assume that the

[1] Following the literature on voluntary environmental innovation (for a review see Brau and Carraro, 1999), the variable x can be seen as a function of the additional revenues due to consumers' willingness to pay for "green outputs", and/or reduction of variable costs, and/or 'regulatory gains'.

[2] This assumption allows us to focus on when, rather than whether, the environmental innovation takes place. However, the model could be easly expanded to include the impacts of the "green" industry size on the innovation timing. If private decrease with the number of "green firms", it becomes convenient for the first innovator not to be followed. The more rivals delay the technological switch, the greater the gain for the firm which abandons the

firm's investment cost depends on the number of firms who have already adopted the green technology:

$$C_i(\theta, n) = \theta_i k(n), \qquad i = 1, 2 \quad \text{and } n = 1, 2$$

where $k(n)$ stands for the pure capital cost and θ_i is a valuation parameter reflecting agent i's private perception of forgone potentially more valuable investment opportunities in the future. If both firms adopt simultaneously the green technology or one "joins the network", the per-capita investment cost is $\theta_i k(2)$. If, on the other hand, one agent switches alone ("goes first") s/he pays $\theta_i k(1)$. The difference $k(1)- \; k(2) > 0$ indicates that there is an advantage in co-ordinating or joining a network, and the higher the firm's opportunity cost of adopting the green technology under consideration, the greater the share value of the "network benefit" $k(1) - k(2)$.[3]

Whilst $k(2)$ and $k(1)$ are common knowledge, θ_i is private information, and takes values in $\Theta = [\underline{\theta}, \bar{\theta}] \subseteq R_+$ with cumulative distribution $G(\theta_i)$ and density $g(\theta_i)$, which are public knowledge. Types are independent between firms so they do not convey information about the other agent's private valuation parameter θ.

Based on these assumptions, firms' *option values* to migrate to the green technology can be defined as follows. By assuming risk-neutrality, if agent i "goes first", under (1) the option value, evaluated at time zero, can be expressed as:

$$V_i(x; 1) = \max \left[0, E_0 \left\{ \int_{T_i}^{\infty} x_t e^{-rt} dt - \theta_i k(1) e^{-rT_i} \mid x_0 = x \right\} \right], \tag{2}$$

polluting technology first. Keeping the state variable x as the stochastic shift component of firms' private benefits, in our two-player framework, we may measure the preemptive effect by the flow of benefits per unit of time $D(n)$, where n is the number of agents that have already switched. That is:

$$D(n)x, \qquad n = 1, 2$$

with $D(1) > D(2)$ indicating that the operating premium when both agents adopt is lower than when only one adopts (see Moretto, 1996, 2000).

[3]It is not difficult to extend the model to include the case in which coordinate adoption by agents involves a greater spillover effect than that of participating in an existing network. A typical assumption in the literature on the adoption of technology is that the fixed cost of adoption declines over time as the potential users' experience with the technology accumulates. We leave this complication aside as it adds little additional insight on the network effect.

while for agent $j \neq i$ (who "goes second"):

$$V_j(x;2) = \max\left[0, E_0\left\{\int_{T_j}^{\infty} x_t e^{-rt}dt - \theta_j k(2)e^{-rT_j} \mid x_0 = x\right\}\right], \qquad (3)$$

where $r > \alpha$ is the nonstochastic discount rate, and $T_j \geq T_i$ stand for the stochastic stopping times at which firms will find it optimal to abandon the current technology and adopt the green one.

2.2 The waiting game

Firms' time pattern of technological migration is affected by two sources of inertia. On the one hand, since the investment expenditure cannot be recovered, adoption of the green technology is slowed down by uncertainty about the technological change's benefits (*irreversibility effect*). On the other hand, the technological change is decelerated by each agent's hope of gaining the network benefit $\theta[k(1) - k(2)]$. In particular, as far as the second source of inertia is concerned, the uncertainty about the other agent's investment opportunity cost makes it advisable to wait to see how things go for the other before switching (*war of attrition effect*). If this does not happen and the "rival" is reluctant to adopt the green technology, the agent may eventually decide to go first.

It is important to point out two features of the model. Firstly, at each time t firms observe the realization of the state variable x_t, and, depending on their private valuation parameter θ, decide whether to adopt the green technology. Secondly, there is a Bayesian learning process where agents learn by observing the rival's behavior. Therefore, a Nash equilibrium will be the solution of a pair of linked "stopping time problems", where each agent solves the switching problem by taking account of the rival's possible actions and learning about the rival's private valuation parameter from the fact that he has not switched up to that moment.

Specifically, each agent i will optimally select, depending on current information about the state x and the distribution G, an upper trigger level $\bar{x}_i^* \in X = [\bar{x}^l, \bar{x}^u] \subseteq R_+$. Thus, if at time t, $x_t \geq \bar{x}_i^*$ and the other firm has not yet switched, the agent will unilaterally abandon the polluting technology. Otherwise, if the other firm has switched at $x_t < \bar{x}_i^*$, agent i learns that he can adopt the green technology by paying $k(2)$.

Notice, however, that the certainty of being second does not imply switching immediately after the first has switched. As the opportunity cost of switching depends on θ, and x is assumed to be exogenous to the agents' actions (i.e. the benefits per unit of time do not depend on the number of adopters), a lower trigger level $\bar{x}_i^{**} < \bar{x}_i^*$ always exists, below which the only dominant strategy for the firm is to keep the option to abandon the polluting technology alive and wait longer before exercising it. Only when x_t crosses $\bar{x}_i^{**}$ does the agent consider the possibility of switching second.

As long as $\bar{x}_i^{**} < x_t < \bar{x}_i^*$ for $i = 1, 2$, each firm waits for the other to change technology first. During this period of *excess inertia* (Farrell and Saloner, 1985) each firm, while facing the opportunity cost of being stuck with the polluting technology, has an option value to wait, both because of the technological change's irreversibility and the hope of gaining the network benefit. In continuous time, this countervailing interest can be represented by the following *bandwagon strategy*:

$$a_i(x, G) = \begin{cases} (a) & if \quad 0 < x < \bar{x}_i^{**} \\ (b) & if \quad \bar{x}_i^{**} \leq x < \bar{x}_i^* \\ (c) & if \quad x \geq \bar{x}_i^* \end{cases} \quad \text{for } i = 1, 2. \tag{4}$$

where:

(a) never switch, regardless of the other agent's behavior;

(b) switch only if the other has already done so, i.e."jumping on the bandwagon";

(c) unilaterally switch, i.e. "initiating the bandwagon".

2.3 The optimal private trigger levels ($\bar{x}_i^*$ and $\bar{x}_i^{**}$)

The optimal choice by agent i of $\bar{x}_i^*$ and $\bar{x}_i^{**}$ must take account of the fact that as x moves randomly he updates his conditional distribution of the other firm's valuation parameter θ_j , and, consequently, of agent j's trigger values $\bar{x}_j^*$ and $\bar{x}_j^{**}$, $i \neq j$. However, since from the point of view of firm i, what matters to identify $\bar{x}_i^*$ and $\bar{x}_i^{**}$ is the joint distribution of firm j's type and actions, we can refer to the distributional strategy approach proposed by Milgrom and Weber (1985). In other words, by relying on the game's symmetry, we can place assumptions on the joint distribution of $(\theta, \bar{x}^*)$ on $\Theta \times X$, so that the marginal distribution with respect to Θ is the one specified by the prior beliefs G.

Let's define $F(\bar{x}_j^*; x)$ as the continuous distribution function, with density $f(\bar{x}_j^*; x)$, for agent j's trigger level conditional on the information available to agent i at time zero so that the hazard-rate is $h(\bar{x}_j^*) = \frac{f(\bar{x}_j^*;x)}{1-F(\bar{x}_j^*;x)}$. Let's also assume that $\lim_{\bar{x}_j \to x} f(\bar{x}_j^*; x) > 0$, thus $\bar{x}_j^*$ does not have any mass at x, but it does have positive density there, i.e. $\mathbf{\Lambda}_0 \in \left\{ \bar{x}_j^* \mid f(\bar{x}_j^*; x) > 0 \right\} \subseteq X = [\bar{x}^l, \bar{x}^u]$, is the set for which the density has positive support.

Agent i's option value at time zero to adopt the green technology at time T_i if agent j is still using the polluting technology and his strategy is T_j , is given by:

$$\begin{aligned} V_i(x; \bar{x}_i^*) &= E_{T_j} \left\{ E_0 \left\{ \int_{T_j}^{\infty} x_t e^{-rt} dt - \theta_i k(2) e^{-rT_j} \right\} \mid T_i \geq T_j \right\} \qquad (5) \\ + \Pr(T_i &< T_j) E_0 \left\{ \int_{T_i}^{\infty} x_t e^{-rt} dt - \theta_i k(1) e^{-rT_i} \right\} \end{aligned}$$

In other words, agent i's option value to invest is given by the option value if he does not innovate till time T_j and then switches second at cost $\theta_i k(2)$, plus the option value of not innovating till time T_i and then going first. $T_i = \inf(t > 0 \mid x_t = \bar{x}_i^*)$ is the switching time at which agent i decides unilaterally to adopt the green technology (strategy c).

Each firm observes the realization of the state variable x, updates his conjectures on the other agent's threshold $F(\bar{x}_j^*; x)$, and instantaneously considers when adopting maximizing (5). Moreover, as time goes by and x_t hits new upper levels without the other agent switching, he learns that the probability of this happening in the near future may increase. The next proposition states that instantaneous responses and information on the rival's valuation parameter may be used to postpone the investment.

Proposition 1 *(i) If a threshold level* $\bar{x}_i^* \in X = [\bar{x}^l, \bar{x}^u]$ *exists, such that* $0 < \bar{x}_i^{**} < \bar{x}_i^*$, *then a perfect equilibrium involves each firm playing the following stationary strategy:*

$$a_i(F) = \begin{cases} \text{Strategy } (a) & if \quad 0 < x < \bar{x}_i^{**} \\ \text{Strategy } (b) & if \quad \bar{x}_i^{**} \leq x < \bar{x}_i^* \\ \text{Strategy } (c) & if \quad x \geq \bar{x}_i^* \end{cases} \qquad \text{for } i = 1, 2.$$

(ii) Where optimal trigger levels are given by:

$$\bar{x}_i^{**} = \frac{\beta}{\beta - 1}(r - \alpha)\theta_i k(2), \qquad (6)$$

$$\bar{x}_i^* = \frac{\beta}{\beta-1}(r-\alpha)\theta_i k(1) + \frac{\beta}{\beta-1}(r-\alpha)\theta_i (k(1)-k(2))\frac{\bar{x}_i^* h(\bar{x}_i^*)}{\beta}, \qquad (7)$$

(iii) And the option value to invest is given by:

$$V_i(x;\bar{x}_i^*) = A_i(\bar{x}_i^{**})F(\bar{x}_i^{**};x)x^{\beta} + A_i(\bar{x}_i^*)x^{\beta} + B_i(\bar{x}_i^*,x)x^{\beta} \equiv$$

$$\equiv \left(\frac{\bar{x}_i^{**}}{r-\alpha} - \theta_i k(2)\right)\left(\frac{x}{\bar{x}_i^{**}}\right)^{\beta} \int_x^{\bar{x}_i^{**}} dF(\bar{x}_j;x) + \left(\frac{\bar{x}_i^*}{r-\alpha} - \theta_i k(1)\right)\left(\frac{x}{\bar{x}_i^*}\right)^{\beta} +$$

$$+ \left[\int_{\bar{x}_i^{**}}^{\bar{x}_i^*} \left[\left(\frac{\bar{x}_j}{r-\alpha} - \theta_i k(2)\right)\left(\frac{\bar{x}_i^*}{\bar{x}_j}\right)^{\beta} - \left(\frac{\bar{x}_i^*}{r-\alpha} - \theta_i k(1)\right)\right] dF(\bar{x}_j;x)\right]\left(\frac{x}{\bar{x}_i^*}\right)^{\beta}$$

Proof. See Appendix.

The second term on the r.h.s. of (7) reflects the *war of attrition effect.* The war of attrition, which is driven by the expected "network benefit" $k(1)-k(2)$ and by each agent's uncertainty about the rival's valuation parameter θ, induces a postponement of the irreversible investment.[4]

Corollary 1 *(i) The higher θ, the later the agent(s) will adopt the green technology (monotonicity property of the trigger value(s)):*

$$\frac{d\bar{x}_i^*(\theta_i)}{d\theta_i} > 0, \;\; \textit{and}\; \bar{x}_i^*(\theta_i) \in X(\Theta) = [\bar{x}^l(\underline{\theta}), \bar{x}^u(\bar{\theta})], \quad \textit{for}\; i = 1,2.$$

(ii) The rate of delay of technological change increases with θ, that is:

$$\bar{x}_i^*(\theta_i') - \bar{x}_i^*(\theta_i) > \bar{x}_i^+(\theta_i') - \bar{x}_i^+(\theta_i) \qquad \textit{for}\; \theta_i' > \theta_i \quad \textit{for}\; i = 1,2.$$

Proof. See Appendix.

As the model is developed in continuous time (i.e. after an agent has switched the rival observes and responds immediately), the switching time of

[4]In the case of a single firm (or if firms would not expect a "network benefit", i.e. $k(1) = k(2)$), the firm's optimal trigger level would be lower and would only reflect the expected investment rentability $((r-\alpha)\theta_i k(1))$ weighted by the option multiplier $\frac{\beta}{\beta-1}$ which accounts for the *irreversibility effect,* i.e. $\bar{x}_i^+ = \frac{\beta}{\beta-1}(r-\alpha)\theta_i k(1)$ (Dosi and Moretto, 1997). On the other hand, if $k(1)-k(2) > 0$, in the case of complete information agents have no interest in going unilaterally; they will be better-off coordinating, and their optimal trigger levels will simply be $\bar{x}_i^{**}$ (Moretto,2000).

the two firms may be indistinguishable. However, even without making use of a discrete-time model we can also have sequential adoption depending on the wedge in the investment's opportunity cost between agents (see Simon and Stinchombe, 1989).

Corollary 2 *Sequential adoption exists if* $\bar{x}_j^{**}(\theta_j) > \bar{x}_i^*(\theta_i), \quad i \neq j \quad i,j = 1,2.$

3 The agency's problem

3.1 The policy objective

We assume that on the grounds of available information on the relevant ecosystem(s)'s response to the industry's emissions, and of estimated social costs of pollutant accumulation, public authorities ("the agency") have identified $\hat{T}$ as the date before which the entire industry under consideration should abandon the polluting technology and adopt the green one. Moreover, we assume that the agency is unable or unwilling to adopt mandatory regulations and, if necessary, intends to accelerate abandonment of the polluting technology by subsidizing the technological change.

Since the private switching time (T) is a stochastic variable, the agency has to identify a policy-rule referring to T's probability distribution. For the sake of simplicity, we assume the following environmental policy-objective:[5]

$$E(T) = \hat{T} \tag{8}$$

and subsidies will be granted only if the spontaneous time of abandonment of the polluting technology is expected to go beyond $\hat{T}$. By (1) and the definition of T , (8) may be reformulated in terms of the (per unit of time) private benefit x at which the technological change should take place to satisfy the agency's policy-objective. We denote with $\hat{x}$ the "social trigger value" such that $E[\inf(t > 0 \mid x_t = \hat{x})] = \hat{T}$.[6]

[5] The policy-rule can be made more stringent by giving different weights to different moments of the private switching time distribution (depending on different assumptions about the agency's risk aversion).

[6] As the net benefits are driven by (1), the switching time is a stochastic variable with first moment $E(T) = \frac{x_t - x}{\alpha}$, so that $\hat{x} = x + \alpha\hat{T}$ (Cox and Miller, 1965, p.221).

When considering the optimal subsidization policy, it is worth noting that while firms' hopes of gaining the network benefit $(k(1)-k(2))$ tend to decelerate the spontaneous technological change, the existence of spillover effects on the switching costs provides the agency with the opportunity to adopt a targeted policy, by subsidizing the firm with the lower private valuation parameter θ (henceforth, the "leader firm") rather than the entire industry. For instance, by targeting the subsidy to the leader firm, i.e. by anticipating "initiation of the bandwagon", the agency may accelerate technological change throughout the entire industry.

However, the agency does not know the private valuation parameters θ, to exploit the potential regulatory benefits resulting from network externalities, s/he has to identify an appropriate incentive mechanism such that the (unknown) leader firm will find it profitable to abandon the polluting technology the first time x, randomly fluctuating, hits the social trigger $\hat{x}$. Assuming the agency acts as an utilitarian regulator, and subsidies are financed through distortionary taxation, the optimal targeted incentive will emerge through maximization of the following ex-post social welfare function:

$$W-(1+\lambda)s(\hat{x})+U(\hat{x}) \tag{9}$$

where W is the (agency's) estimated social benefit brought about by accelerating the industry's technological change, $s(\hat{x})$ is the subsidy, $\lambda \geq 0$ is the shadow cost of public funds and $U(\hat{x})$ denotes the subsidized firm's utility level.

3.2 Auctioning investment grants

To find a feasible incentive mechanism, consistent with the policy-objective (8) and able to minimize private informational rents, we consider a "Bayesian auction" where the firms are required to simultaneously announce their private trigger levels $(\tilde{x}_1^*, \tilde{x}_2^*)$ and, by the monotonicity property, the subsidy is granted to the firm that announces the lowest one.

In this paragraph it will be shown that the subsidy under consideration is formed by the sum of a fixed payment function (individual rational transfer) - defined according to the difference between the announcement $\tilde{x}_i^*$ and the social trigger $\hat{x}$ - plus a linear sharing of overruns which depends on the announced trigger value. If this subsidy is incentive compatible it will be sufficient to induce the leader firm to adopt the green technology when

x, randomly fluctuating, hits the social trigger $\hat{x}$. Although, as shown in the next paragraph, granting a subsidy only to the leader firm may not be enough to achieve the policy objective - i.e. inducing technological change throughout the entire industry - by "creaming" the industry the incentive mechanism allows the agency to induce the other firm to switch (to "jump on the bandwagon") without paying informational rents.

Since the agency does not know the private valuation parameters θ, s/he is unable to identify the true optimal trigger values $\bar{x}_i^*(\theta_i)$. However, without loss of generality, we may assume that the agency knows the firms' conjectural distribution. Therefore, conditional on the information available at the time when the subsidization scheme is announced, the firms' optimal trigger levels are drawn independently from the same continuous distribution $F_t(\bar{x}_i^*; u_t)$, with density $f_t(\bar{x}_i^*; u_t)$, for $i = 1, 2$ and $u_t = \hat{x}$.[7] Moreover, we assume that the hazard-rate is monotone, i.e. $h(\bar{x}_i^*)$ is nondecreasing in $\bar{x}_i^*$, and $\int_{\hat{x}}^{\bar{x}^u} [1 - F_t(\tilde{x}_i; \hat{x})] d\tilde{x}_i < \infty$ for all $\hat{x}$.

Defining with $s_i(\tilde{x}_i^*; \tilde{x}_j^*)$ the subsidy per unit of time required to induce adoption of the green technology at $\hat{x}$, as a function of the announced trigger levels $\tilde{x}_i^*$, the firm i's expected net rental price can be expressed as:

$$U_i(\bar{x}_i^*, \tilde{x}_i^*; \hat{x}) = E_{\tilde{x}_j} \left\{ s_i(\tilde{x}_i^*; \tilde{x}_j^*) - y_i(\tilde{x}_i^*; \tilde{x}_j^*)(\bar{x}_i^* - \hat{x}) \right\}, \quad \text{for } i = 1, 2 \tag{10}$$

We refer to (10) as "firms' utility", and $y_i(\tilde{x}_i^*; \tilde{x}_j^*)$ is the probability that agent i is selected to receive the subsidy, with $\sum_{i=1}^{2} y_i(\tilde{x}_i^*; \tilde{x}_j^*) = 1$, for any $\tilde{x}_i^*$ and $\tilde{x}_j^*$.

While in the case of complete information the planner maximizes (9) by selecting the firm with the lowest trigger value $\bar{x}^*$ (and subsidizes only that firm), by the above arguments, in the case of incomplete information, the ex-ante maximand becomes:

$$\left(\sum_{i=1}^{2} y_i(\bar{x}_i^*; \bar{x}_j^*) \right) W - (1 + \lambda) \sum_{i=1}^{2} s_i(\bar{x}_i^*; \bar{x}_j^*) + \sum_{i=1}^{2} U_i(\bar{x}_i^*; \hat{x}) \tag{11}$$

which should be maximized with respect to y_i and U_i under a participation and an incentive constraint. The following proposition indicates the results of this Bayesian auction.

[7] We also maintain the assumption that $\lim_{\bar{x}_i \to \hat{x}} f_t(\bar{x}_i^*; \hat{x}) > 0$, and $\Lambda_t \in \{\bar{x}^* \mid f_t(\bar{x}_i^*; \hat{x}) > 0\} \subseteq [\, \bar{x}^l(\underline{\theta}), \bar{x}^u(\bar{\theta})]$.

Proposition 2 *In the case of two agents whose private trigger values are drawn independently from the same continuous distribution with monotone hazard-rate, an optimal Bayesian auction will give the subsidy to the "leader firm", i.e. to the firm with the lowest rental price. The optimal choice will be:*

$$y_i(\bar{x}_i^*;\bar{x}_j^*) = 1 \quad if \quad \bar{x}_i^* \leq \bar{x}_j^*$$
$$y_i(\bar{x}_i^*;\bar{x}_j^*) = 0 \quad if \quad \bar{x}_i^* > \bar{x}_j^*$$

and the expected transfer to the agent is:

$$E_{\bar{x}_j}\left\{s_i(\bar{x}_i^*;\bar{x}_j^*)\right\} = E_{\bar{x}_j}\left\{y_i(\bar{x}_i^*;\bar{x}_j^*)(\bar{x}_i^* - \hat{x})\right\} + \int_{\bar{x}_i^*}^{\bar{x}^u} E_{\bar{x}_j}\left\{y_i(\tilde{x}_i^*;\bar{x}_j^*)\right\} d\tilde{x}_i^*$$

Proof. See Appendix.

While maximization of (11) determines expected transfers, that is the firm's strategy is optimal on "average" given the other firm's strategy, if we consider a *first-price auction* the firms will bid an amount greater than their individual rational transfer $(\bar{x}_i^* - \hat{x})$.[8] As long as the probability of being the lowest bidder is $E_{\bar{x}_j}\left\{y_i(\bar{x}_i^*;\bar{x}_j^*)\right\} = 1 - F_t(\bar{x}_i^*;\hat{x})$, we get the following subsidy (annuity):[9]

$$s_i(\bar{x}_i^*;\hat{x}) = (\bar{x}_i^* - \hat{x}) + \int_{\bar{x}_i^*}^{\bar{x}^u} \frac{F(\tilde{x}_i^*;\hat{x})}{F(\bar{x}_i^*;\hat{x})} d\tilde{x}_i^*, \quad \text{for } i = 1, 2 \tag{13}$$

[8] For *first-price auction* we mean an auction where agents bid directly for the subsidy s_i and receive what they bid (Fudenberg and Tirole, 1991).

[9] Alternatively, it is always possible to construct a Vickrey type dominant strategy auction where each agent has a strategy that is optimal for any bids by his opponent. Since, for the Vickrey auction, revelation of the true trigger value $\bar{x}_i^*$ is a dominant strategy but it will be granted a subsidy that depends on the second bid (*second-price auction*), in our two-agents case this implies implementing a subsidisation scheme of the type:

$$\begin{aligned} \tilde{s}_i(\bar{x}_i^*;\hat{x}) &= (\bar{x}_i^* - \hat{x}) + (\bar{x}_j^* - \bar{x}_i^*) = (\bar{x}_j^* - \hat{x}), \quad \text{for } \bar{x}_i^* \leq \bar{x}_j^* \\ \tilde{s}_i(\bar{x}_i^*;\hat{x}) &= 0 \quad \text{otherwise} \end{aligned} \tag{12}$$

When agent i wins the auction, his subsidy is equal to the individually rational transfer $(\bar{x}_i^* - \hat{x})$ plus the rent he gets when the conjectural distribution is truncated at the rival's trigger value $\bar{x}_j^*$, that is $(\bar{x}_j^* - \bar{x}_i^*)$. As $E_{\bar{x}_j}\{\tilde{s}_i(\bar{x}_i^*;\hat{x})\} = s_i(\bar{x}_i^*;\hat{x})$, the dominant strategy auction gives the same expected transfer as the optimal Bayesian auction (Fudenberg and Tirole, 1991, p.288).

Alternatively, referring to 5, it is possible to compute the total lump-sum subsidy to be granted to the leader firm:

$$
\begin{aligned}
S_i(\bar{x}_i^*;\hat{x}) &= \int_{\hat{T}}^{\infty} \left[s_i(\bar{x}_i^*;\hat{x})\right] e^{-r(t-\hat{T})}dt, \quad \text{for } i=1,2 \qquad (14)\\
&= V_i(\hat{x};\bar{x}_i^*) - V_i^0(\hat{x}) + \frac{\int_{\bar{x}_i^*}^{\bar{x}^u} \frac{F(\tilde{x}_i^*;\hat{x})}{F(\bar{x}_i^*;\hat{x})} d\tilde{x}_i^*}{r}
\end{aligned}
$$

where the second term on the r.h.s. is the discounted flow of information rents, whilst $V_i(\hat{x};\bar{x}_i^*)-V_i^0(\hat{x})$ is the leader firm's opportunity cost of adopting the green technology at the social trigger $\hat{x}$, i.e. the difference between the firm's option value to postpone the technological change under consideration $(V_i(\hat{x};\bar{x}_i^*))$ and the net present value of the project $(V_i^0(\hat{x}))$:

$$
V_i(x;\bar{x}_i^*)-V_i^0(x) = \theta_i k(1)+A_i(\bar{x}_i^{**})F(\bar{x}_i^{**};\hat{x})\hat{x}^{\beta}+A_i(\bar{x}_i^*)\hat{x}^{\beta}+B_i(\bar{x}_i^*,\hat{x})\hat{x}^{\beta}-\frac{\hat{x}}{r-\alpha} \qquad (15)
$$

From (15) it is evident that, besides taking into account the net present cost of technological change, the subsidy granted to the firm should also account for the option values of giving up network benefits and more information about the investment profitability.

3.3 Two-sides regulation

In the previous paragraph we have considered the case where the network benefit $(k(1)-k(2))$ is such that adoption of the green technology by the (subsidized) firm is sufficient to induce the other agent to switch immediately afterwards.

However, as we have shown in corollary 2, we can have sequential adoption depending on the wedge in firms' opportunity cost (θ). In particular, we get sequential adoption if $\bar{x}_j^{**}(\theta_j) > \bar{x}_i^*(\theta_i), \quad i \neq j \quad i,j=1,2$.

In this case, granting a subsidy to the leader firm is not enough to induce technological change throughout the industry: in other words, a subsidy should also be granted to the other firm. However, under our assumptions, on the basis of the announcement received from the leader firm, this second subsidy does not involve payment of an informational rent and it will be calculated referring to $\bar{x}_j^{**}$. Equation (13) should therefore be modified as follows:

$$
\begin{aligned}
s_i(\bar{x}_i^*;\hat{x}) &= (\bar{x}_i^* - \hat{x}) + \int_{\bar{x}_i^*}^{\bar{x}^u} \frac{F(\tilde{x}_i^*;\hat{x})}{F(\bar{x}_i^*;\hat{x})} d\tilde{x}_i^*, \quad \text{for } \bar{x}_i^* \leq \bar{x}_j^* \\
s_i(\bar{x}_i^{**};\hat{x}) &= \bar{x}_i^{**} - \hat{x} \quad \text{otherwise}
\end{aligned}
$$

4 Final remarks

Even when firms have discovered theoretically profitable opportunities from environmental innovation, various sources of inertia may involve a timing of abandonment of polluting technologies incompatible with avoidance of undesired levels of pollutant accumulation.

It has been shown that, when switching costs are expected to decline over time - as other firms have already adopted a green technology - each firm tends to further delay an irreversible environmental innovation, in order to exploit network benefits. Although network externalities tend to decelerate spontaneous environmental innovations, they provide the policy-maker with the opportunity of targeting public subsidies to the agent(s) with lower switching cost. In fact, by accelerating initiation of technological change, the regulator may induce the whole industry to switch.

However, this policy strategy requires knowledge of the private adoption costs. Otherwise, appropriate incentive mechanisms are required to minimize agents' informational rents. To find a cost-effective "creaming mechanism", we have examined a Bayesian auction, where each firm is required to announce its optimal trigger value, and a subsidy is granted to the firm which announces the lowest one, i.e. to the firm with the lowest technological change opportunity cost. Besides informational rents and the net direct investment cost, the subsidy under consideration must include the firm's opportunity value of waiting for more information on the intrinsic profitability of the project as well as on the industry's time pattern of technological change.

A Appendix

A.1 proof of proposition 1

We shall now prove the proposition for agent 1 (by symmetry this holds for agent 2 as well). The first part of the proof consists in identifying the optimal choice of the pure strategies' trigger levels for both players as a function of the state variable x and of the conjectural distribution F, and then looking for the stationary Nash equilibrium strategies.

Let us begin with strategy (b). As net benefits do not depend on the size of the market, agent 1 does not need to know his rival's valuation parameter θ_2 to follow strategy (b). He will consider switching only if $x_t \geq \bar{x}_1^{**}$ which is obtained by maximizing (3). By standard arguments, the solution for $V_1(x;2)$ can be obtained by transforming (3) into a differential equation and imposing some suitable set of boundary conditions. To do so, firstly we can equal over a time interval dt the total expected return on the investment opportunity with its expected rate of capital appreciation to obtain the following Bellman equation: $rV_1(x)dt = E\left[dV_1(x)\right]$. Then, expanding the term $E\left[dV_1(x)\right]$ by using Itô's Lemma, dividing by dt and taking the limit as dt tends to zero, yields the following differential equation (see Dixit 1993, p.14-15):

$$\frac{1}{2}\sigma^2 x^2 V_1''(x) + \alpha x V_1'(x) - rV_1(x) = 0 \ , \tag{16}$$

where V_1' and V_1'' indicate the first and second derivatives of V_1 with respect to x. In view of the fact that when x goes to zero the option value must go to zero, the general solution of (16) takes the form:

$$V_1(x) = A_1 x^{\beta} \quad , \tag{17}$$

where A_1 is a constant to be determined and $\beta > 1$ is the positive root of the quadratic equation $\Phi(\beta) \equiv \frac{1}{2}\sigma^2\beta(\beta-1) + \alpha\beta - r = 0$. To identify the trigger values we need to impose the following matching value condition:

$$V_1(\bar{x}_1^{**}) = \frac{\bar{x}_1^{**}}{r-\alpha} - \theta_1 k(2), \tag{18}$$

which states that at the switch the user must be indifferent to keeping the option alive or exercising it. The r.h.s. of expression (18) describes the net (of cost) present value of the innovative investment once investment is made. This must hold when one agent goes second. Whilst the upper value $\bar{x}_1^{**}$ makes the user indifferent to adopting as second, the following smooth pasting conditions determine optimality ruling out arbitrary exercise of the option to switch at different points (Dixit 1993, p.32):

$$V_1'(\bar{x}_1^{**}) = \frac{1}{r-\alpha}, \tag{19}$$

Substituting (18) in (17), we get:

$$V_1(x; \bar{x}_1^{**}, 2) = A_1(\bar{x}_1^{**})x^{\beta} \equiv (\frac{\bar{x}_1^{**}}{r-\alpha} - \theta_1 k(2)) \left(\frac{x}{\bar{x}_1^{**}}\right)^{\beta}. \tag{20}$$

Finally, taking the derivative of the above expression with respect to $\bar{x}_1^{**}$ and solving it, we obtain (6). Let's continue with strategy (c). If agent 1 decides to go unilaterally, taking account of the probability of being anticipated, the value at time t of investing in the green technology is given by (5). Using Bayes' rule, the relationship between $F(\bar{x}_2^*; x)$ and $F_t(\bar{x}_2^*; x_t)$ for $t > 0$ can be described by:

$$F_t(\bar{x}_2^*; u_t) = \frac{F(\bar{x}_2^*; x) - F(u_t; x)}{1 - F(u_t; x)} \qquad \text{where } u_t = \sup_{0<s<t}(x_t). \tag{21}$$

Indicating $h(\bar{x}_2^*)$ as the current value of the hazard-rate, it can be easily seen that it is independent of u_t, that is:

$$h(\bar{x}_2^*) = \frac{f_t(\bar{x}_2^*; u_t)}{1 - F_t(\bar{x}_2^*; u_t)} = \frac{f(\bar{x}_2^*; x)}{1 - F(\bar{x}_2^*; x)} \tag{22}$$

Therefore, making use of (20) and (21), the option value (5) can be rewritten as:

$$V_1(x_t; \bar{x}_1^*) = \left(\frac{\bar{x}_1^{**}}{r-\alpha} - \theta_1 k(2)\right)\left(\frac{x_t}{\bar{x}_1^{**}}\right)^{\beta} \int_{u_t}^{\bar{x}_1^{**}} dF_t(\bar{x}_2; u_t) + \left(\frac{\bar{x}_1^*}{r-\alpha} - \theta_1 k(1)\right)\left(\frac{x_t}{\bar{x}_1^*}\right)^{\beta} +$$

$$+ \left[\int_{\bar{x}_1^{**}}^{\bar{x}_1^*} \left[\left(\frac{\bar{x}_2}{r-\alpha} - \theta_1 k(2)\right)\left(\frac{\bar{x}_1^*}{\bar{x}_2}\right)^{\beta} - \left(\frac{\bar{x}_1^*}{r-\alpha} - \theta_1 k(1)\right)\right] dF_t(\bar{x}_2; u_t)\right]\left(\frac{x_t}{\bar{x}_1^*}\right)^{\beta} \tag{23}$$

or equivalently:

$$V_1(x_t;\bar{x}_1^*) = A_1(\bar{x}_1^{**})F_t(\bar{x}_1^{**};u_t)x_t^{\beta} + A_1(\bar{x}_1^*)x_t^{\beta} + B_1(\bar{x}_1^*,u_t)x_t^{\beta}.$$

The first term accounts for the case in which $u_t < \bar{x}_1^{**}$. In this case, the agent does not adopt even if he knows that he will pay $k(2)$. The second term is the usual option value of a single firm, and finally the third term is the expected gain by fighting before adopting. Agent 1's optimal choice of $\bar{x}_1^*$ can be obtained by simply maximizing $A_1(\bar{x}_1^*)+B_1(\bar{x}_1^*,u_t)$. The first order condition requires:

$$\frac{\partial V_1(x_t;\bar{x}_1^*)}{\partial \bar{x}_1^*} = \frac{1-\beta}{(r-\alpha)\bar{x}_1^*}\left(\frac{x_t}{\bar{x}_1^*}\right)^{\beta}(1-F_t(\bar{x}_1^*;u_t))\times \tag{24}$$

$$\left[\left(\bar{x}_1^* - \bar{x}_1^+\right) - (\bar{x}_1^+ - \bar{x}_1^{**})\frac{\bar{x}_1^* f_t(\bar{x}_1^*;u_t)}{\beta(1-F_t(\bar{x}_1^*;u_t))}\right] = 0.$$

where $\bar{x}_1^+ = \frac{\beta}{\beta-1}(r-\alpha)\theta_1 k(1)$ is the trigger value of going first without strategic behavior (or if firms would not expect a "network benefit", i.e. $k(1) = k(2)$). Looking for a maximum of $V_1(x_t;\bar{x}_1^*)$ also requires the square-bracketed term below to be positive:

$$\frac{\partial^2 V_1(x_t;\bar{x}_1^*)}{\partial(\bar{x}_1^*)^2} = \frac{(1-\beta)}{\beta(r-\alpha)\bar{x}_1^*}\left(\frac{x_t}{\bar{x}_1^*}\right)^{\beta}(1-F_t(\bar{x}_1^*;u_t))\times \tag{25}$$

$$\left[\beta - (\bar{x}_1^+ - \bar{x}_1^{**})h(\bar{x}_1^*) - (\bar{x}_1^+ - \bar{x}_1^{**})\bar{x}_1^*\frac{dh(\bar{x}_1^*)}{d\bar{x}_1^*}\right] < 0$$

Assuming that the second order condition holds and rearranging, we obtain the following implicit form for the trigger level $\bar{x}_1^*$:

$$\bar{x}_1^* = \bar{x}_1^+ + (\bar{x}_1^+ - \bar{x}_1^{**})\frac{\bar{x}_1^* f_t(\bar{x}_1^*;u_t)}{\beta(1-F_t(\bar{x}_1^*;u_t))}. \tag{26}$$

Although $\bar{x}_1^*$ is invariant to the current value of the state variable x it is in general not so with respect to u. The agent cannot credibly commit himself to the trigger level $\frac{\bar{x}_1^*}{\theta_1}$ as x_t increases, and the bandwagon optimal rule $a_1(u_t,F_t)$ defined in (4) and (26) is a contingent plan of how to play each time t for possible realization of the state x, which summarizes the entire history of the game up to that point. However, as the hazard-rate (22) is independent of u_t the trigger value also becomes independent from the information variable u_t. This makes the optimal operating rule $a_1(F)$ stationary.

A.2 Proof of corollary 1

From (7), the first part of the corollary is straightforward. Applying the implicit function theorem we get:

$$\frac{d\bar{x}_i^*}{d\theta_i} = \frac{\left(\bar{x}_i^+ + (\bar{x}_i^+ - \bar{x}_i^{**})\bar{x}_i^* h(\bar{x}_i^*)\right)^2}{\theta_i \left(\bar{x}_i^+ - (\bar{x}_i^+ - \bar{x}_i^{**})(\bar{x}_i^*)^2 \frac{dh(\bar{x}_i^*)}{d\bar{x}_i^*}\right)} > 0$$

Positivity of the above expression is guaranteed by the second order condition for a maximum (25). For the second part, it is easy to see that:

$$\frac{d\bar{x}_i^*}{d\theta_i}_{\rceil k_1 - k_2 > 0} > \frac{d\bar{x}_i^*}{d\theta_i}_{\rceil k_1 - k_2 = 0} = \frac{\bar{x}_i^+}{\theta_i}$$

A.3 Proof of proposition 2

We look for an incentive compatible mechanism $[s_i(.), y_i(.)]$ that induces a truth-telling Bayesian Nash equilibrium. First of all, a necessary condition for truth-telling is that the derivatives of "firms' utility" with respect to the agent i's announcement $\tilde{x}_i^*$, and evaluated at the true trigger value, i.e. $\tilde{x}_i^* = \bar{x}_i^*$, is nul.

$$\frac{\partial U_i}{\partial \tilde{x}_i^*} = E_{\bar{x}_j} \left\{ \frac{\partial s_i}{\partial \tilde{x}_i^*} - \frac{\partial y_i}{\partial \tilde{x}_i^*} (\bar{x}_i^* - \hat{x}) \right\} = 0, \quad \text{for } i = 1, 2. \tag{27}$$

Secondly, letting $U_i(\bar{x}_i^*; \hat{x})$ be the agent i's utility level when telling the truth, by the envelope theorem, (10) and (27) we obtain:

$$\frac{dU_i(\bar{x}_i^*; \hat{x})}{d\bar{x}_i^*} = -E_{\bar{x}_j} \left\{ y_i(\bar{x}_i^*; \bar{x}_j^*) \right\} < 0, \quad \text{for } i = 1, 2. \tag{28}$$

That is, at the optimum the utility is nonincreasing in $\bar{x}_i^*$. So the agent i's individual rationality (participation constraint) is satisfied if it is satisfied at $x = \bar{x}^u$. Finally, by using (10) and (27) to integrate (28), we obtain:

$$U_i(\bar{x}_i^*; \hat{x}) = U_i(\bar{x}^u; \hat{x}) + \int_{\bar{x}_i^*}^{\bar{x}^u} E_{\bar{x}_j} \left\{ y_i(\tilde{x}_i^*; \bar{x}_j^*) \right\} d\tilde{x}_i^*, \quad \text{for } i = 1, 2, \tag{29}$$

and the sufficient condition for truth-telling requires (Fudenberg and Tirole 1991, theorem 7.2 p.260):

$$E_{\bar{x}_j}\left\{\frac{\partial y_i}{\partial \bar{x}_i^*}\right\} \leq 0, \quad \text{for } i = 1, 2. \tag{30}$$

From (11) and the above arguments, the ex-ante agency's objective function can be expressed as:

$$\left(\sum_{i=1}^{2} y_i(\bar{x}_i^*; \bar{x}_j^*)\right) W + (1+\lambda)\sum_{i=1}^{2} y_i(\bar{x}_i^*; \bar{x}_j^*)(\bar{x}_i^* - \hat{x}) - \lambda \sum_{i=1}^{2} U_i(\bar{x}_i^*; \hat{x}) \tag{31}$$

Since the agency's objective function is decreasing in U_i and from (28) the utility level is decreasing in $\bar{x}_i^*$, the individual participation constraint will be tight at the highest trigger value $\bar{x}^u$. That is, assuming that, outside the relationship with the regulator, each agent has opportunities normalized to zero, we get: $U_i(\bar{x}^u; \hat{x}) = 0$, for $i = 1, 2$.

The agency's optimization problem under incomplete information can be stated as:

$$\max_{y_i, U_i} E_{\bar{x}_i, \bar{x}_j}\left\{\left(\sum_{i=1}^{2} y_i(\bar{x}_i^*; \bar{x}_j^*)\right) W + (1+\lambda)\sum_{i=1}^{2} y_i(\bar{x}_i^*; \bar{x}_j^*)(\bar{x}_i^* - \hat{x}) - \lambda \sum_{i=1}^{2} U_i(\bar{x}_i^*; \hat{x})\right\} \tag{32}$$

subject to:

$\frac{dU_i(\bar{x}_i^*;\hat{x})}{d\bar{x}_i^*} = -E_{\bar{x}_j}\left\{y_i(\bar{x}_i^*; \bar{x}_j^*)\right\} < 0, \quad \text{for } i = 1, 2$ Incentive Constraint

$U_i(\bar{x}^u; \hat{x}) = 0, \quad \text{for } i = 1, 2.$ Participation Constraint

$E_{\bar{x}_j}\left\{\frac{\partial y_i}{\partial \bar{x}_i^*}\right\} \leq 0, \quad \text{for } i = 1, 2$ Sufficient Condition

$\sum_{i=1}^{2} y_i(\bar{x}_i^*; \bar{x}_j^*) = 1, \quad \text{for any } \bar{x}_i^* \text{ and } \bar{x}_j^*.$

As is usual in the regulation mechanism with asymmetry of information we first ignore the second-order condition to check later that it is indeed satisfied at the optimum. As U_i is considered the state variable in the above maximization, we can substitute (29) in the agency's objective function and solve for the optimal y_i. Integrating by parts (32) for given $\bar{x}_j^*$, we rewrite the objective function in the following form:

$$E_{\bar{x}_i, \bar{x}_j}\left\{\sum_{i=1}^{2} y_i(\bar{x}_i^*; \bar{x}_j^*)\left[W - (1+\lambda)(\bar{x}_i^* - \hat{x}) - \lambda\frac{F_t(\bar{x}_i^*; \hat{x})}{f_t(\bar{x}_i^*; \hat{x})}\right]\right\}$$

Recalling the learning process (21), we simplify the agency's objective function as:

$$E_{\bar{x}_i,\bar{x}_j}\left\{\sum_{i=1}^{2} y_i(\bar{x}_i^*;\bar{x}_j^*)R(\bar{x}_i^*,\hat{x};x,\lambda)\right\} \tag{33}$$

where:

$$R(\bar{x}_i^*,\hat{x};x,\lambda)=\left[W-(1+\lambda)\left((\bar{x}_i^*-\hat{x})+\frac{\lambda}{1+\lambda}\frac{F(\bar{x}_i^*;x)-F(\hat{x};x)}{f(\bar{x}_i^*;x)}\right)\right]$$

By the monotone hazard rate assumption the term $R(\bar{x}_i^*,\hat{x};x,\lambda)$ is nonincreasing in $\bar{x}_i^*$, therefore the optimal choice by the regulator would be:

$$\begin{array}{l} y_i(\bar{x}_i^*;\bar{x}_j^*)=1 \quad if \quad \bar{x}_i^*\leq\bar{x}_j^* \\ y_i(\bar{x}_i^*;\bar{x}_j^*)=0 \quad if \quad \bar{x}_i^*>\bar{x}_j^* \end{array}$$

Hence $E_{\bar{x}_j}\left\{y_i(\bar{x}_i^*;\bar{x}_j^*)\right\}$ is nonincreasing almost everywhere which implies that the second order condition (30) is always satisfied. Finally, from (10), (28) and (29), the optimal Bayesian auction's system of transfers is such that:

$$\begin{aligned} E_{\bar{x}_j}\left\{s_i(\bar{x}_i^*;\bar{x}_j^*)\right\} &= U_i(\bar{x}_i^*;\hat{x})+E_{\bar{x}_j}\left\{y_i(\bar{x}_i^*;\bar{x}_j^*)(\bar{x}_i^*-\hat{x})\right\} \\ &= E_{\bar{x}_j}\left\{y_i(\bar{x}_i^*;\bar{x}_j^*)(\bar{x}_i^*-\hat{x})\right\}+\int_{\bar{x}_i^*}^{\bar{x}^u} E_{\bar{x}_j}\left\{y_i(\tilde{x}_i^*;\bar{x}_j^*)\right\}d\tilde{x}_i^*\ , \end{aligned}$$

This conclude the proof.

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