Switching to Green: the Timing of Socially Responsible Innovation

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Abstract

We develop a timing game for adopting a product technology that features a public good. We investigate the effects of the degree of product market competition, product differentiation, the private benefits from contributing to the public good, and firm asymmetries on the timing of adoption. We then examine the effects of consumer subsidies on equilibrium timings and the proliferation of the public good.

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1 Introduction

Adoption of new technologies is a key determinant of the pace of economic growth and the rate of change of productivity. The literature on the timing of adoption of new technologies is extensive.[1] In this paper we contribute to this literature by considering the adoption of "green" technologies, by which we mean technologies that in consumption provide a public good. Understanding the green technology adoption process is important because there is substantial pressure on policy makers around the globe to address environmental concerns. To identify the key trade-offs faced by private firms in developing, adopting, and marketing green technologies is essential to evaluate whether government intervention is beneficial and, if required, to design and assess policies that induce private industries to accelerate the adoption of such technologies.

We develop a model of a game of timing for the adoption of "green" technologies that in consumption generate public good benefits. In the environmental case, that public good is an absence of pollution, which is of benefit to all consumers. Our modeling approach follows Bagnoli and Watts (2003) and Besley and Ghatak (2007), who formulate a static model of private provision of a public good whereby a segment of consumers obtains private value from consuming the public good and are willing to pay more for it. Even if, in practice, there may be disagreements on the public good benefits of green products, our model assumes that "green" technologies produce goods that everyone agrees are public goods.

We study how the private benefits from contributing to the public good affect which firm adopts the green technology and the timing of such an adoption. We analyze this model under different degrees of product market competition (Bertrand or Cournot), different levels of firm asymmetry, and different policy regimes, resulting in three key theoretical findings. First, we find that when firms have similar cost structures, tougher product market competition (Bertrand) leads to earlier adoption of the green technology. Second, we find that when

[1] See, for example Milliou and Petrakis (2010), Dutta, Lach, and Rustichini (1995), Quirmbach (1986), Reinganum (1981), Jensen (1982, 1983), Riordan (1992), Stenbacka and Tombak (1994), and especially Fudenberg and Tirole (1985) and Katz and Shapiro (1987). For good surveys of the literature, see Reinganum (1989) and, more recently, Hoppe (2002).

firms are asymmetric, the identity of the innovating firm depends on the private benefits from contributing to the public good. If these benefits are small (large), the small (large) firm will adopt the green technology.

Finally, we look at the impact on social welfare of subsidies to consumers of green products. Our analysis shows that in some environments these subsidies may not be welfare enhancing and that equilibrium adoption time may be sooner than the socially optimal adoption time. This may occur because adoption relaxes product market competition by generating product differentiation and the rent seeking incentives generated by this "green differentiation" induce firms to adopt too early.

In our analysis Corporate Social Responsibility (CSR) arises from strategic behavior motivated by self-interest and profit maximization. There are many alternative explanations for such CRS which we do not examine here. For example, there may be shareholder preferences for investing in firms which exhibit CSR behavior and there may be different relative efficiencies of corporate versus private donations (Baron, 2007). We also do not consider the existence of activist-induced social pressure (as in Baron, 2009) albeit that may well be a mechanism for affecting the private benefits from contributing that are in our model. Furthermore, there are many other instruments available to policy makers which we do not investigate here. For instance, governments may use technology standards (as in Calveras, Ganuza and Llobet, 2007).

We organize our study as follows. First, we develop the model of a game of timing, we describe the profit functions of the firms and then the utility functions of the consumers who purchase the products of those firms. We then analyze the timing outcomes under different forms of product market competition (Bertrand and Cournot). Subsequently, we examine the equilibrium timing when firms are asymmetric in their production costs. In Section 5, we study the effectiveness of consumer subsidies in accelerating adoption of new technology and their impact on dynamic social welfare. We examine extensions in Section 6. In the final section, we summarize and discuss the results. The Appendix contains the proofs of all the results stated in the text.

2 Model

We develop a simple model that captures technology adoption to provide a socially responsible product under rivalry between two firms. Our model extends the technology adoption games of Fudenberg and Tirole (1985), Katz and Shapiro (1987) and Riordan (1992) by introducing the private provision of public goods as modeled in Bagnoli and Watts (2003) and Besley and Ghatak (2007).

Firms

We index two firms by $i = 1, 2$. At time zero, each firm sells a *standard product* and at each point in time has the option to switch to a *green product*. The green product differs from the standard product because it has a public good component (e.g., it is environmentally friendly or involves a socially responsible activity). When both firms sell the standard product, each of them obtains duopoly profits equal to π_i^0, $i = 1, 2$. If the green product is never produced, then firm i earns a profit of π_i^0/r where $r > 0$ is the interest rate. Switching decisions are made at discrete dates spaced δ apart: at each $t = 0, \delta, 2\delta, ...$, each firm decides whether to start selling the green product. As in Fudenberg and Tirole (1985) and Katz and Shapiro (1987), we focus on the limiting case in which $\delta \rightarrow 0$.[2]

To develop and market the green product firms adopt a *green technology.* We denote with $K(t)$ the present value of the cost of bringing the green technology online at time t. Following Fudenberg and Tirole (1985) and Katz and Shapiro (1987), we assume that $e^{rt}K(t)$ decreases in t and that $d^2\left(e^{rt}K(t)\right)/dt^2 > 0$.[3] We also assume that as $t \rightarrow \infty$, the cost $K(t)$ tends to zero. As in Katz and Shapiro (1987), we assume that once a firm offers the green product, the firms have no further opportunities to change their technologies, i.e., the green technology is an absorptive state. In Section 6, we remove this assumption. If firm i sells the green product, profits are π_i^G for the green technology adopter and π_j^{NG} with $j \neq i$ for

[2] This time structure follows Fudenberg and Tirole (1985) and Katz and Shapiro (1987). Fudenberg and Tirole (1985) show that there may be a loss of information (some equilibria cannot be represented) in the continuous time version of timing games.

[3] Quirmbach (1986) discusses the significance of the assumptions of the form of the cost function in more detail.

the non-adopter.

If firm i adopts the green technology at time T, it enjoys a flow of profits of π_i^0 for $t < T$ and profits equal to π_i^G for $t \geq T$ as well as incurs the cost $K(T)$. We indicate its profits as:

$$L_i(T) = \int_0^T \pi_i^0 e^{-rt} dt + \int_T^\infty \pi_i^G e^{-rt} dt - K(T) = \frac{1 - e^{-rT}}{r} \pi_i^0 + \frac{e^{-rT}}{r} \pi_i^G - K(T).$$

Firm $j \neq i$ obtains:

$$F_j(T) = \int_0^T \pi_j^0 e^{-rt} dt + \int_T^\infty \pi_j^{NG} e^{-rt} dt = \frac{1 - e^{-rT}}{r} \pi_j^0 + \frac{e^{-rT}}{r} \pi_j^{NG}.$$

In the case in which both firms choose to offer the product simultaneously, each will prevail with probability 0.5 so that firm i earns $\left(L_i(T) + F_i(T)\right)/2$.[4]

We normalize the marginal cost of production of the standard product of Firm 1 to be equal to zero. We indicate the marginal cost of production for Firm 2 with $c \geq 0$.[5] When a firm adopts the the green technology, its marginal cost becomes equal to $\varepsilon > 0$. In order to more fully characterize these profit functions, we need to specify the demand functions for the two products.

Consumers

We follow Bagnoli and Watts (2003) and consider a continuum of consumers indexed by i uniformly distributed on the measure 1 interval $[0, 1]$. In each period, each consumer buys

[4] This assumption is consistent with the idea of a patentable green technology; in the case of a joint patent application, the patent is assigned to each firm with probability 1/2. Katz and Shapiro (1987) show that the outcome of the game is not affected if in the case of simultaneous move both firms incur the development cost.

[5] There are many possible rationales for cost asymmetries (see Roller and Desgagne, 1996 for an enumeration and description). Some of them, for example, managerial competence, would be persistent across technologies. Others, such as an advantageous contract for sourcing of materials, may be eliminated in a shift to a different technology. In a previous version, we analyzed the case where the cost difference, c, is persistent. Here, thanks to a suggestion by a referee, we examine the case where the cost difference changes from c to ε when switching technologies. This gives us sharper predictions in Proposition 5 and in the welfare analysis.

at most one unit of the product and chooses whether to buy the standard product, the green product (if available), or neither. We indicate consumer i's utility function as:

$$U(x, Y; i) = \begin{cases} I + b(i, Y) & \text{if } \; x = 0 \\ I + \alpha - i + a - i + b(i, Y) & \text{if } \; x = G \\ I + a - i + b(i, Y) & \text{if } \; x = NG \end{cases}$$

where I is the consumer's income, $x = 0$ indicates no consumption, and $x = G, NG$ indicates the consumption of green and standard products, respectively. The following assumptions state the differential impact of the green and the standard product on consumers.

Assumption 1: aggregate consumption Y of the green good G is a public good with benefit $b(i, Y) \geq 0$ for each consumer i with $b_Y > 0$, and $b_{YY} < 0$.

Assumption 2: good G generates an additional private benefit $\alpha - i$ in comparison to good NG, with $\alpha \leq 1$.

The term $b(i, Y)$ is a measure of the value to consumer i of having Y units of green product consumed in the economy. The term $\alpha - i$, with $\alpha \leq 1$, indicates the extra value that the particular consumer gets from buying the green version of the product. As α increases, the private benefits from contributing to the public good increase.[6] The term $a - i$ captures the value to consumer i for purchasing the standard version of the good. We assume that $a > 1$ so that each consumer is willing to purchase the standard version at zero price.

Consider now the case in which both versions of the product are offered, and prices are p_G for the green product and p_{NG} for the standard product. Consumer i buys the standard version if $I + a - i + b(i, Y) - p_{NG} > I + b(i, Y)$ and $I + a - i + b(i, Y) - p_{NG} > I + \alpha - i + a - i - p_G + b(i, Y)$. Similarly, consumer i buys the green product only if $I + \alpha - i + a - i - p_G + b(i, Y) > I + b(i, Y)$ and $I + a - i + b(i, Y) - p_{NG} < I + \alpha - i + a - i - p_G + b(i, Y)$. Exploiting these inequalities, it is possible to identify two marginal consumers: i_G, who is indifferent between

[6] Because $\alpha \leq 1$ we can interpret α as the proportion of *caring* consumers. The model in Besley and Ghatak (2007) has a similar parameter. Following Bagnoli and Watts (2003) we assume that consumers that are willing to pay more for the non-green good are also willing to pay more for the green product. This assumption greatly simplifies the analysis and ensures that demands are linear in prices.

buying the green product and the standard product and i_{NG}, who is indifferent between buying the standard version and not buying the product at all.[7]

If the following condition is satisfied:

$$\alpha - a - p_G + 2p_{NG} < 0 \tag{1}$$

the marginal consumers are interior to the unit interval, i.e., $1 > i_{NG} > i_G > 0$. Once we characterize the marginal consumers, it is possible to derive the demand functions for the two products:

$$\begin{aligned} Q_G(p_G, p_{NG}) &= i_G = \alpha - p_G + p_{NG} \quad (2) \\ Q_{NG}(p_G, p_{NG}) &= i_{NG} - i_G = a - \alpha - 2p_{NG} + p_G. \quad (3) \end{aligned}$$

Finally, we assume that $a + \alpha > c + \varepsilon$ and $a > 2c$ to ensure that marginal costs are small enough so that some consumers' willingness to pay for either version exceeds its marginal cost. Note that this characterization of the demand differs substantially from that in much of the literature of new technology adoption. In that literature, scholars consider new technologies as either "drastic" new technologies or incremental developments in technology. A drastic new technology is one where the new technology supersedes the old and the market for the old technology disappears with the adoption of a new technology. An incremental new technology as often modelled as one similar to the old but with a lower cost of production such that nonadopting rivals can still survive in the marketplace (Reinganum, 1989). In our case, a green technology bestows certain benefits to consumers but at an *additional* cost to the producer. We now describe how the producers interact in the product market.

3 Product Market Competition and Green Technology Adoption

In this section we focus on the case in which there is no cost asymmetry ($c = 0$) and study the impact of product market competition on the time of green technology adoption. To this

[7] Specifically, $i_G = \alpha - p_G + p_{NG}$ and $i_{NG} = a - p_{NG}$.

end we compare an environment in which firms compete à la Bertrand with an environment in which they compete à la Cournot.

To compute the adoption time we follow Katz and Shapiro (1987) and assume that $K(t) = K_0 e^{-\lambda t}$ with $\lambda > r$. The parameter λ captures the rate of technological progress: i.e. the speed at which the adoption cost declines over time. Following Fudenberg and Tirole (1985) and Katz and Shapiro (1987), we define:

$$\begin{aligned} \widehat{T} &= \frac{1}{\lambda - r} \log \frac{\lambda K_0}{\pi^G - \pi^0} \\ \widetilde{T} &= \frac{1}{\lambda - r} \log \frac{r K_0}{\pi^G - \pi^{NG}}. \end{aligned} \tag{4}$$

Intuitively, if firm j never develops and firm i chooses to develop at T, i's payoff is $L(T)$. $\widehat{T}$ is the date that maximizes $L(T)$; we will refer to this date as the *stand-alone date* of development. We define $\widetilde{T}$ by $L(\widetilde{T}) = F(\widetilde{T})$ and will refer to this date as the *preemption date.*

Consider a setting in which $\pi^G < \pi^0$. In this case, no firm has an incentive to adopt and the green product will not be offered. If $\pi^G > \pi^0$ and $\pi^G < \pi^{NG}$, each firm will not adopt the green technology if it expects the other firm to adopt it. In this case in equilibrium one firm adopts at $\widehat{T}$ and the other never adopts. If $\pi^G > \pi^0$ and $\pi^G > \pi^{NG}$, Katz and Shapiro (1987) show that in equilibrium adoption occurs at the earlier of $\widehat{T}$ and $\widetilde{T}$.

Bertrand Competition

We now analyze the case in which the two firms compete by setting prices. We start by deriving the profits in the absence of adoption. In this case, the two firms will offer an identical product and undercut each others prices. This means that in equilibrium profits are equal to $\pi^0 = 0$.[8] If one firm adopts the green technology, the profits for the adopter and non-adopter are respectively:

$$\begin{aligned} \pi^G(p_G, p_{NG}) &= (p_G - \varepsilon) Q_G(p_G, p_{NG}) \\ \pi^{NG}(p_G, p_{NG}) &= p_{NG} Q_{NG}(p_G, p_{NG}). \end{aligned}$$

[8] This feature, together with the assumptions that $a + \alpha > c + \varepsilon$ and that the cost of adoption of the green technology $K(t)$ tends to zero, guarantees an adoption will take place under Bertrand competition.

In the following proposition, we characterize the equilibrium adoption time in this setting.

Proposition 1 *With Bertrand competition, there exists an* $\widetilde{\alpha}$ *such that if* $\alpha \leq \widetilde{\alpha}$*, adoption occurs at* $\widehat{T}$*, and if* $\alpha > \widetilde{\alpha}$*, adoption occurs at the minimum between* $\widehat{T}$ *and* $\widetilde{T}$*.*

We need to note three things from the above proposition. First, with Bertrand competition, adoption occurs for every value of α. Intuitively, competition is so intense that each firm has an incentive to differentiate itself from the competitor and adopt the green technology (i.e., $\pi^G, \pi^{NG} > \pi^0 = 0$). Secondly, if the private benefits are not too large ($\alpha \leq \widetilde{\alpha}$), the adopting firm chooses its time of adoption without considering the presence of the rival firm. In this case, profits for the adopter are low such that each firm prefers the other firm to adopt and adoption then occurs at the stand-alone date $\widehat{T}$. Thirdly, if $\alpha > \widetilde{\alpha}$, then adoption time depends on the rate of technological progress. Specifically, adoption time will be $\widehat{T}$ ($\widetilde{T}$) if:

$$\frac{\lambda}{r} \leq (>) \ \frac{\pi^G - \pi^0}{\pi^G - \pi^{NG}} \tag{5}$$

so that preemption incentives are taken into account only if technological progress is fast enough. When the rate of technological progress is high (λ is large and (5) does not hold), the marginal benefit of waiting is high, the stand-alone time tends to be large and preemption leads to adoption before $\widehat{T}$.

Cournot Competition

We now analyze the case in which the two firms compete in the product market by setting quantities. This is generally thought of as a less stringent form of competition than Bertrand. As in the Bertrand case, we start by characterizing the profits in the absence of adoption. In this case, the two firms offer an identical product and face a demand function equal to $P(q_1, q_2) = a - q_1 - q_2$. This means that in equilibrium each firm earns $\pi^0 = a^2/9$. Similarly, if one firms adopts the green technology, we obtain the demand functions that the firms face by inverting (2) and (3), which are equal to:

$$\begin{aligned} P_G(q_G, q_{NG}) &= a + \alpha - q_{NG} - 2q_G \\ P_{NG}(q_G, q_{NG}) &= a - q_{NG} - q_G. \end{aligned}$$

Therefore adoption profits are

$$\begin{aligned}\pi^G(p_G, p_{NG}) &= (P_G(q_G, q_{NG}) - \varepsilon)q_G \\ \pi^{NG}(p_G, p_{NG}) &= P_{NG}(q_G, q_{NG})q_{NG}.\end{aligned}$$

In the next proposition, we characterize the equilibrium adoption time under Cournot competition.

Proposition 2 *With Cournot competition, there exists an α^* such that there is no adoption if $\alpha < \alpha^*$. In addition, there is an $\widetilde{\alpha}$ such that if $\alpha^* \leq \alpha \leq \widetilde{\alpha}$, adoption occurs at $\widehat{T}$, and if $\alpha > \widetilde{\alpha}$, adoption occurs at the minimum between $\widehat{T}$ and $\widetilde{T}$.*

The proposition shows that adoption is not guaranteed with Cournot competition. If private benefits are not large enough, firms may find it unprofitable to switch and provide the socially responsible product. As in the previous proposition, preemption incentives matter only if $\alpha > \widetilde{\alpha}$ and technological progress is fast enough. Interestingly, the cutoff-value $\widetilde{\alpha}$ is identical to the one with Bertrand competition.

Comparison of the Two Regimes

We now compare Bertrand and Cournot adoption times. The next proposition shows that adoption occurs earlier with Bertrand competition.

Proposition 3 *Adoption time with Bertrand competition is lower or equal than adoption time with Cournot competition.*

The first thing to notice is that for $\alpha \leq \alpha^*$, adoption occurs with Bertrand competition but not with Cournot competition. This implies that adoption is not guaranteed when product market competition is relaxed. When $\alpha > \alpha^*$ and there is low technological progress, i.e., (5) holds, adoption time occurs at $\widehat{T}$. In the proof of the proposition we show that the value of $\widehat{T}$ with Bertrand competition, $\widehat{T}^B$, does not exceed the $\widehat{T}^C$, its value with Cournot competition. When (5) does not hold adoption occurs at $\widetilde{T}$. Interestingly, the difference $\pi^G - \pi^{NG}$ is identical in the cases of Cournot and Bertrand competition.[9] This implies that $\widetilde{T}$ is the same in both cases as well. These results imply that product market competition accelerates the time of adoption of green technology when the private benefits are low or when the technological progress is slow.

The intuition for this result is similar to the one of the step-by-step innovation models of Aghion et al. (2001) where firms innovate to escape competition. Differently from their model, our framework highlights how green technologies allow firms to escape competition through "green differentiation". Moreover, our analysis shows that when the private benefits of the green products are high and technological progress is fast adoption time is less sensitive to the degree of product market competition.[10]

4 Firm Asymmetries and Timing of Adoption

In this section, we study the impact of firm asymmetries on green technology adoption. To this end, we reintroduce the parameter $c > 0$ to indicate the marginal cost of production for Firm 2. We start by deriving the profits in the absence of adoption. With Bertrand competition, the two firms will offer an identical product and undercut each others prices. This means that in equilibrium Firm 1 will set a price equal to the marginal cost of Firm 2 and serve a measure of consumers equal to $a - c$. Therefore $\pi_2^0 = 0$ and $\pi_1^0 = (a-c)c$. Notice that for Firm 1, it is optimal to set a price equal to c because we assumed that $a > 2c$.

If Firm 1 adopts the green technology the profit functions are:

$$\begin{aligned} \pi_1^G(p_G, p_{NG}) &= (p_G - \varepsilon)Q_G(p_G, p_{NG}) \\ \pi_2^{NG}(p_G, p_{NG}) &= (p_{NG} - c)Q_{NG}(p_G, p_{NG}). \end{aligned}$$

[9]See Lemma 1 in Milliou and Petrakis (2010). This result also holds for the model of Mussa and Rosen (1978), where consumers enjoy utility $\theta s - p$ when consuming a product of quality s at price p. They describe the population of consumers by the parameter θ which is uniformily distributed between 0 and 1. Firm G produces at cost ε quality $a + \alpha$. Firm NG produces at zero costs quality level a.

[10]Singh and Vives (1984) show that firm profits are larger with Cournot than with Bertrand competition for a large class of demand structures. Their result suggests that the incentive to adopt early and escape the competition through "green differentiation" is likely to extend beyond the specific functional assumptions of our model.

Similarly, if Firm 2 adopts:

$$\begin{aligned} \pi_1^{NG}(p_G, p_{NG}) &= p_{NG} Q_{NG}(p_G, p_{NG}) \\ \pi_2^{G}(p_G, p_{NG}) &= (p_G - \varepsilon) Q_G(p_G, p_{NG}). \end{aligned}$$

With Cournot competition $\pi_2^0 = (a - 2c)^2/9$ and $\pi_1^0 = (a + c)^2/9$ and the corresponding profit functions if Firm 1 adopts are:

$$\begin{aligned} \pi_1^{G}(q_G, q_{NG}) &= (P_G(q_G, q_{NG}) - \varepsilon) q_G \\ \pi_2^{NG}(q_G, q_{NG}) &= (P_{NG}(q_G, q_{NG}) - c) q_{NG}. \end{aligned}$$

If Firm 2 adopts they are

$$\begin{aligned} \pi_1^{NG}(q_G, q_{NG}) &= P_{NG}(q_G, q_{NG}) q_{NG} \\ \pi_2^{G}(q_G, q_{NG}) &= (P_G(q_G, q_{NG}) - \varepsilon) q_G. \end{aligned}$$

Proposition 4 *With Bertrand competition, there exist α^{1B} and α^{2B} with $\alpha^{1B} > \alpha^{2B}$ such that:*

(i) if $\alpha < \alpha^{2B}$, there is a unique equilibrium outcome of the adoption game and Firm 2 adopts the green technology;

(ii) if $\alpha > \alpha^{1B}$, there is a unique equilibrium outcome of the adoption game and Firm 1 adopts the green technology;

(iii) if $\alpha^{2B} \leq \alpha \leq \alpha^{1B}$ the existence of an equilibrium is not guaranteed, if an equilibrium exists either firm may adopt the green technology.

With Cournot competition, there exist α^{1C}, α^{2C} and $\widehat{\alpha}$ with $\alpha^{1C} > \alpha^{2C} > \widehat{\alpha}$ such that:

(i) if $\alpha < \widehat{\alpha}$ there is no adoption of the green technology;

(ii) if $\widehat{\alpha} \leq \alpha < \alpha^{2C}$, there is a unique equilibrium outcome of the adoption game and Firm 2 adopts the green technology;

(iii) if $\alpha > \alpha^{1C}$, there is a unique equilibrium outcome of the adoption game and Firm 1 adopts the green technology;

(iv) if $\alpha^{2C} \leq \alpha \leq \alpha^{1C}$ the existence of an equilibrium is not guaranteed, if an equilibrium exists either firm may adopt the green technology.

The previous proposition shows that we should expect the small firm (the one with larger marginal cost) to adopt the technology when green product private benefits are small and the large firm (with lower marginal cost) to adopt when these benefits are large. Intuitively, when a firm adopts the green technology, it can extract additional surplus from the caring consumers. Because the small firm is making very little profits with the standard product, it is willing to adopt even if the willingness to pay for the green product is small. On the other hand, by adopting, the large firm gives up part of its cost advantage. For this firm adoption is beneficial only if the surplus that can be extracted is large enough, i.e., private benefits are large enough.[11]

The previous proposition also highlights an important difference between our model and the one of Katz and Shapiro (1987). Focusing on a homogeneous Cournot duopoly with linear demand, they show that the larger firm is more likely to be the first to adopt whenever the innovation has the same impact on the cost structure of the two firms. Our model suggests that in the case of green-technology this result may not hold, especially when the private benefits from public good provision are small. Intuitively, in the setting of Katz and Shapiro (1987) technology adoption reduces marginal costs and the incentives to adopt are greater for the larger firm because it can spread the cost reduction over a larger market share. Our model differs from their set-up in two ways. First, firms can switch from homogeneous to differentiated products through "green differentiation". Second, the green technology increases the marginal cost of production. Notice that higher costs tend to reduce the large firm's incentives to adopt whereas differentiation increases consumers' willingness to pay through differentiation. The large firm will therefore be willing to give up its cost advantage only if this second effect is large enough.

As in the previous section, we assume that $K(t) = K_0 e^{-\lambda t}$ with $\lambda > r$. In the parameter

[11] This result is consistent with the empirical findings of Siegel and Vitaliano (2007) that show how in a sample of 696 large North-American firms, the larger firms are not more likely to engage in CSR. Proposition 4 suggests that this may be due to the presence of a small private benefits from contributing in those markets where larger firms are not socially responsible.

range in which firm 2 adopts, adoption time is going to be the minimum between:

$$\widehat{T}_2 = \frac{1}{\lambda - r} \log \frac{\lambda K_0}{\pi_2^G - \pi_2^0}$$

and

$$\widetilde{T}_2 = \frac{1}{\lambda - r} \log \frac{r K_0}{\pi_1^G - \pi_1^{NG}}.$$

This implies that the adoption time will be $\widehat{T}_2$ $(\widetilde{T}_2)$ if:

$$\frac{\lambda}{r} \leq (>) \frac{\pi_2^G - \pi_2^0}{\pi_1^G - \pi_1^{NG}}.$$

Intuitively, when there is little technological progress (λ is low), the incentives to adopt for the large firm are so low that its presence does not affect the adoption decision of Firm 2. In contrast, when λ is large, adoption of the large firm becomes more profitable and its presence affects the timing of Firm 2 adoption. Specifically, Firm 2 will preempt Firm 1 and render it indifferent between adopting and not-adopting the technology.

Proposition 5 *An increase in c accelerates pre-emptive adoptions.*

Proposition 5 shows that firm asymmetries reduce adoption times in the case of pre-emption. Intuitively, when green products private benefits are small (and Firm 2 adopts in equilibrium), an increase in c increases the profits that the large firm can make with the green technology and thus increases the incentives of the small firm to pre-empt the large firm. Similarly, when green products private benefits are large (and Firm 1 adopts in equilibrium), the increase in c increases the incentives of the small firm to adopt the green technology and thus the need for the large firm to pre-empt. In the proof of Proposition 5 we show that the impact of asymmetries on stand-alone adoption times is ambiguous. In this case an increase in c has countervailing effects on the adoption and non-adoption profits and the total effect on timing depends on their relative strengths.

The above analysis has focused on the impact of competition and cost asymmetries on firms' adoption strategies. Because adoption incentives depend only on firm private benefits, the green product public good benefits have played no role in the above analysis. Because the main impact of the green technology has been to generate "green differentiation", the previous results generalize to any technology that enables firms to produce differentiated products at higher marginal production costs. In the next section, we study the impact of government policies on adoption time and social welfare. From a social perspective green products differ from ordinary differentiated goods because they generate public good benefits, therefore the green nature of the technology will play a key role in the following results.

5 Consumer Subsidies and Dynamic Social Welfare

In this section, we discuss the impact of green technology on dynamic social welfare and examine the role of government intervention through subsidies to green product consumers. We first look at the effectiveness of subsidies in accelerating green technology adoption and then assess their impact on social welfare. We also study the impact of competition on dynamic welfare.[12]

With consumer subsidies, the price that a consumer pays for a green product is $p_G - s$. In the presence of this form of government intervention, the demand functions are:

$$Q_G(p_G, p_{NG}) = i_G = \alpha + s - p_G + p_{NG} \tag{6}$$

$$Q_{NG}(p_G, p_{NG}) = i_{NG} - i_G = a - \alpha - s - 2p_{NG} + p_G. \tag{7}$$

Formulas (6) and (7) show that the impact of a subsidy is equivalent to an increase of s in the private benefits of the green product α. In an online appendix available on the authors' websites, we show that a number of additional policies have a similar effect on the demand function and that some of the other government interventions do not have an effect on the demand function.[13]

[12] For an analysis of other types of government intervention, i.e., producers subsidies, consumer education, and lumpsum subsidies, see the online appendix.

[13] In particular a we show that subsidy per product sold (decrease in ε) is equivalent to a consumer subsidy (increase in α). We also we show that the socially preferred policy involves a combination of subsidy types

Following Laffont and Tirole (1993), we assume that the government finances subsidies sQ_G by taxing consumers at a welfare cost $(1+\Lambda)sQ_G$. The parameter $\Lambda \geq 0$ represents the distortion due to the raising of fiscal revenue: when $\Lambda > 0$ the government faces a shadow cost of public funds.

In the next proposition we show that the subsidy accelerates green technology adoption.

Proposition 6 *When firms are symmetric ($c = 0$), a consumer subsidy increases adoption incentives and both $\widehat{T}$ and $\widetilde{T}$ decrease in s.*

We now turn to the case of asymmetric firms. The next result shows that in this setting a large enough subsidy may alter the identity of the adopting firm.[14]

Proposition 7 *If firms are asymmetric ($c > 0$) and α is small, a large subsidy to consumers can change the identity of the adopting firm.*

The intuition for the previous result is the following. In Section 4, we argued that when green product private benefits are small, the large firm has no incentive to adopt and the small firm will sell the green product. The presence of a subsidy may increase the surplus that can be extracted from caring consumers sufficiently so that it may render the green technology appealing to the large firm, inducing it to preempt the small one.

So far we have investigated the impact of consumer subsidies on the time of green technology adoption. Speedy adoption is likely to be the objective of policy makers that face short-term re-election incentives whereas a government with long-term horizon will not only care about how quickly green technologies are adopted but also about their impact on collective welfare.[15]

We start by comparing adoption times privately chosen by firms in the absence of subsidies ($\widehat{T}$ and $\widetilde{T}$) with the socially optimal adoption time, T^*. Specifically, we define T^* as the

[14]Differently from consumers' subsidies, producer subsidies may be targeted to a specific firm. In the online appendix, we show that when firms are asymmetric, a subsidy targeted to the small firm may have the unintended consequence of inducing the large firm to anticipate adoption.

[15]Exploiting two natural experiments in the Argentinean Congress, Dal Bo and Rossi (2008) show how term horizon has a substantial effect on legislation with longer terms leading to better policies.

time that would be chosen by a social planner with the objective to maximize dynamic social welfare. It is important to notice that, T^* is characterized by allowing the social planner to dictate the adoption time and it does not involve the use of other policy instruments as subsidies. Let us indicate with

$$E(i_g) = \int_0^1 b(x, i_g)dx$$

the total level of public good benefits that are experienced with adoption. In the next proposition we show that when these benefits are large enough the socially optimal adoption time, T^*, is always earlier than the private one.

Proposition 8 *There exists a E^* such that if $E(i_g) > E^*$ then $T^* < \min\{\widehat{T}, \widetilde{T}\}$. The threshold E^* is nondecreasing in λ/r.*

Proposition 8 also shows that if $E(i_g)$ is not large enough, private adoption may occur too early. This happens because green technology adoption has multiple opposite effects on social welfare. On one hand, the provision of green product increases social welfare through the public good and the private benefits from contributing to the public good, α. On the other hand, earlier green technology adoption reduces social welfare in three ways. First, the adopting firm sustains a higher adoption cost. Second, the green product is more costly to produce. Third, and more importantly, technology adoption relaxes product market competition by generating "green differentiation". The rent seeking incentives generated by this "green differentiation" induce firms to adopt early in order to escape competition. Therefore, *when the social benefits from the green product are not sufficiently large, the rent seeking effect may lead to an equilibrium adoption time that is sooner than the socially optimal adoption time (even when subsidies are not present).*

To better describe this counterintuitive result, we develop an example in which adoption occurs too early when there is Bertrand competition and public good benefits are low. In this example when the green technology has not been adopted all consumers buy the standard product at zero cost. Green technology adoption generates a dead weight loss in this case because firms are not selling to all consumers whose willingness to pay exceeds the marginal cost of production. Therefore, if public good benefits are low the incentives to adopt for firms are very high but the actual gain of consumer surplus is low.

Example 1 *Consider Bertrand competition between two symmetric firms ($c = 0$) and $\alpha = \varepsilon$. From the proof of Proposition 1 one can see that when $\alpha < \widetilde{\alpha}$ adoption occurs at $\widehat{T} = \log(\lambda K_0/(\pi^G - \pi^0))/(\lambda - r)$. Let us define as W^0 the per-period social welfare in the absence of adoption and as $W^G$the per-period social welfare with green technology adoption. The socially optimal adoption time, T^*, is computed by maximizing with respect to T*

$$\frac{1 - e^{-rT}}{r} W^0 + \frac{e^{-rT}}{r} W^G - K(T)$$

and it is equal to:

$$T^* = \frac{1}{\lambda - r} \log \frac{\lambda K_0}{W^G - W^0}.$$

Notice that $\widehat{T} < T^*$ when $\pi^G - \pi^0 > W^G - W^0$. With symmetric Bertrand competition $\pi^G = (p_G - \varepsilon) i_G$ and $\pi^0 = 0$. Moreover $W^0 = I + a - 1/2$ and $W^G = I + E(i_g) + \alpha i_G + a i_{NG} - i_G^2/2 - {i_{NG}}^2/2 - \varepsilon i_G$. This implies that $\widehat{T} < T^*$ when

$$(p_G - \varepsilon) i_G > E(i_g) + a i_{NG} - \frac{i_G^2}{2} - \frac{i_{NG}^2}{2} - a + \frac{1}{2}.$$

Using the equilibrium values derived in the proof of Proposition 1 it is possible to show that the left hand side of the inequality is positive and that the term $a i_{NG} - i_G^2/2 - i_{NG}^2/2 - a + 1/2$ is negative.[16] *Therefore, if $E(i_g)$ is low enough $\widehat{T} < T^*$.*

When $E(i_g) > E^*$, social welfare is larger if adoption occurs marginally sooner than the privately chosen timing. In such environment a government with long-term horizon may consider using consumer subsidies to accelerate green technology adoption. To study the impact of green consumer subsidies on dynamic social welfare, we focus on the symmetric case ($c = 0$) and following Bagnoli and Watts (2003) we introduce a specific functional form for the public good benefits: $b(i, Y) = bY^2/2$ with $b \leq 1$. Let us indicate with $T(0)$ the

[16] When $\alpha = \varepsilon$ the equilibrium cutoff values are $i_G = a/7$ and $i_{NG} = 5a/7$. The result follows because our model assumes $a > 1$.

private adoption time in the absence of consumer subsidies and with $T(s)$ the adoption time in the presence of consumer subsidy, $s > 0$. As above we indicate with T^* the adoption time that maximizes social welfare in the absence of subsidies. Proposition 9 studies the impact of consumer subsidies on dynamic welfare and it summarizes the main trade-offs associated with the use of such policy.

Proposition 9 *If $b - \Lambda$ is large enough, there exists an $\overline{s} > 0$ such that any subsidy $s \in [0, \overline{s}]$ with $T(0) > T(s) \geq T^*$ increases dynamic welfare. $\overline{s}$ increases in b, a, α and decreases in ε and Λ.*

The main result is that when the public good benefits are sufficiently large with respect to the fiscal revenue distortion, it is possible to characterize an upper bound to consumer subsidies, $\overline{s}$, such that dynamic social welfare increases with a subsidy $s \leq \overline{s}$ and that reduces adoption time from $T(0)$ to $T(s) \geq T^*$. In other words, under some conditions, it is possible to identify a range of subsidies that unambiguously increase dynamic social welfare.

The conditions required to identify this range of welfare enhancing subsidies suggest settings where government intervention may reduce social welfare. First subsidies are not guaranteed to increase welfare when $T^* > T(0)$. As shown in Proposition 8, when $T^* > T(0)$ the government would like to slow down green technology adoption and subsidies by accelerating adoption have a negative effect on welfare. At the same time, subsidies also increase the per-period consumption of public good and therefore have a positive effect on welfare too. So the total effect of a subsidy on dynamic welfare when $T^* > T(0)$ depends on the relative strength of these two countervailing effects.[17]

Second, subsidies may reduce dynamic welfare when the difference $b - \Lambda$ is not large enough. Intuitively, by increasing the consumption of green products, subsidies generate an increase in public good benefits b for each additional unit consumed. At the same time, subsidies are financed with taxes that reduce welfare by reducing the income of the consumers and because of the distortion due to the raising of fiscal revenue, Λ. Therefore, when the

[17] Specifically, T^* is the socially optimal adoption time when the period consumption of public good is not influenced by subsidies. Because subsidies increase the per-period consumption of green product the socially optimal adoption time in the presence of subsidies may well be earlier than T^*.

distortion is large compared to the public good effect, subsidies may have a negative impact on dynamic social welfare.

Finally, the upper bound $\overline{s}$ indicates that subsidies may reduce dynamic welfare if they are too large. This occurs despite our assumption that marginal public good benefits $\partial b(i, Y = Q_G)/\partial Y = bQ_G$ increase proportionally with the consumption of public good. This result arises because the marginal private benefits of the green product relative to the non-green product $\alpha - i_G - \varepsilon$ decrease with Q_G (i.e. i_G) and because the taxes raised to finance the subsidies reduce welfare.

We conclude our analysis of social welfare by examining the impact of competition on dynamic welfare. In the absence of government intervention, when public good benefits are large enough an increase in product market rivalry (i.e. a switch from Cournot to Bertrand competition) leads to an increase in dynamic social welfare. Intuitively, with Bertrand competition not only there is greater provision of public good but also adoption occurs earlier (as shown in Proposition 3).[18] This result is formalized by the following proposition.

Proposition 10 *If b is large enough, dynamic social welfare is higher under Bertrand competition than under Cournot competition.*

Singh and Vives (1984) show that total surplus generated in the product market is higher under Bertrand competition (relative to Cournot competition) with differentiated products. Moreover, in the pre-adoption period, the firms sell homogeneous products and also in this case welfare is higher under Bertrand competition. This implies that with Cournot competition social welfare can be higher only if with Bertrand competition firms adopt "too early" (i.e. at a cost $K(t)$ that is too large). When the public good benefits b are large enough, adoption does not occur too early and welfare is higher with Bertrand competition.

[18] In a static model of adoption of a cost reducing technology Pal (2010) finds conditions under which Cournot competition leads to higher social welfare than Bertrand.

6 Extensions

In what follows, we discuss some natural extensions of our model. We first examine the case where there may be diffused adoption, that is, both firms may adopt but at different times. The second extension is one where there may be asymmetries in green technology production costs. That is, one firm (not necessarily the large firm) may have a technological advantage in the production of the green technology. Finally, we briefly discuss how persistent cost asymmetries may be introduced in our model.

Diffused Adoption

In our baseline model, following Katz and Shapiro (1987), we assume that once a firm offers the green product, the firms have no further opportunities to change their technologies, for example, in the case where the leader has a patent. Focusing on the symmetric case ($c = 0$), we now remove the assumption that only one firm can adopt. A large enough market for the green product (α) and Cournot competition together with the assumption on our form of the cost of adoption $K(t)$ (as discussed by Quirmbach (1986)) could result in both firms adopting but at different times. To this end, we re-write the payoffs of the leader (that adopts at t_1) and the follower that adopts at $t_2 > t_1$ as:

$$
\begin{aligned}
L(t_1, t_2) &= = \frac{1 - e^{-rt_1}}{r}\pi^0 + \frac{e^{-rt_1} - e^{-rt_2}}{r}\pi^G + \frac{e^{-rt_2}}{r}\pi^D - K(t_1) \\
F(t_1, t_2) &= \frac{1 - e^{-rt_1}}{r}\pi^0 + \frac{e^{-rt_1} - e^{-rt_2}}{r}\pi^{NG} + \frac{e^{-rt_2}}{r}\pi^D - K(t_2)
\end{aligned}
$$

where π^D is the payoff when both firms adopt the green technology. In this setting, following Fudenberg and Tirole (1985), we define $\widehat{t}_1$ and $\widehat{t}_2$ as the optimal adoption time for Firm 1 and Firm 2 when firms precommit themselves to introduction times. In addition, we define t^* as the optimal date for simultaneous adoption, i.e., t^* maximizes $L(t, t)$. To simplify the analysis, we assume that $L(\widehat{t}_1, \widehat{t}_2) > L(t^*, t^*)$ so that it is always better to be the leader than to have coordinated joint adoption.[19]

[19] Fudenberg and Tirole (1985) show that if this assumption does not hold, there is a continuum of joint-adoption equilibria.

Notice that a necessary condition to have diffused adoption is $\pi^D > \pi^{NG}$. If this does not happen, the second firm will never find it profitable to adopt the technology. Focusing on the case in which $\pi^D > \pi^{NG}$, the following proposition provides condition for a policy to accelerate adoption.

Proposition 11 *A policy accelerates (slows down) the adoption of green technologies if it increases (decreases) both $\pi^G - \pi^{NG}$ and $\pi^D - \pi^{NG}$.*

We can derive a series of implications from the previous proposition. First, the impact of consumer subsidies on adoption time generalizes to this environment as long as the policies increase the difference between adoption (diffused and unique) and non-adoption profits.[20] Secondly, the proposition suggests that policies that increase π_{NG} unambiguously have a negative effect on adoption time. This implication, not surprising from a theoretical point of view, suggests that bail-out policies that reduce losses for non-adopting firms have a negative impact on the timing of adoption.

Asymmetry in Green Product Production Costs

In the baseline model, we assume that when a firm adopts the green technology its marginal cost becomes $\varepsilon > 0$. In this section, focusing on the case in which the two firms are symmetric before adoption ($c = 0$), we explore the impact of asymmetry in post-adoption production costs. We assume that Firm 1 has an advantage in green technology production, i.e., $\varepsilon_1 < \varepsilon_2$. The next proposition shows that in this case the low cost firm will be the adopter as long as the proportion of caring consumers is not too small.

Proposition 12 *There exists α^ε such that if $\alpha > \alpha^\varepsilon$ there is a unique equilibrium outcome of the adoption game and Firm 1 adopts the green technology.*

The result has an interesting policy implication: a subsidy targeted to the more efficient firm may reduce its incentives to adopt and a subsidy targeted to the less efficient firm may anticipate adoption by the efficient firm.

[20] When firms compete a la Cournot, these differences are $\pi^D - \pi^{NG} = (a + \alpha - \varepsilon)^2/18 - (3a - \alpha + \varepsilon)^2/49$ and $\pi^G - \pi^{NG} = 2(a + 2\alpha - 2\varepsilon)^2/49 - (3a - \alpha + \varepsilon)^2/49$ that are both increasing in α and decreasing in ε.

Corollary 1 *If $\alpha > \alpha^{\varepsilon}$, a reduction in ε_1 may delay adoption by Firm 1 and a reduction in ε_2 may accelerate adoption time by Firm 1.*

Note that in this case, the policy is more likely to backfire when technological progress is fast (λ large).

Persistent Cost Asymmetries

The baseline model assumes that the production cost of the firm adopting the green technology becomes equal to ε independently on the level of pre-adoption cost. This is a natural assumption given that the cost of bringing the green technology online is the same for both firms.

Nevertheless, there are a number of reasons why we may expect cost asymmetries to persist after adoption. For example, Bloom and Van Reenen (2007) document a large variation in managerial practices across firms that are associated with differences in productivity. Persistent cost asymmetries may be introduced in our model by assuming that after adoption the marginal cost of production is equal to ε for firm 1 and equal to $c + \varepsilon$ for firm 2.

We can show that in this extended setting Proposition 4 still holds and we can characterize two cut-offs indicating that the small firm (the one with larger marginal cost) has an incentive to be the one adopting the technology when green product private benefits are small. On the other hand, the impact of an increase in c on adoption time becomes now more complex since c affects the degree of asymmetry both ex-ante and ex-post. In fact, Proposition 5 no longer holds and an increase in c has an ambiguous effect on the speed of adoption.

7 Conclusions

In this study, we build a tractable model of green technology adoption in which two asymmetric firms compete to develop an innovation. The model differs from the previous literature on timing of technology adoption in three main aspects. First, the green technology increases marginal production cost of the adopting firm, whereas in most of the previous literature this cost decreases with adoption of an innovation. Second, the green technology product has a public good component and generates public good benefits to non-consumers. Third, we consider a spectrum of consumers with a differing willingness to pay for the green product.

We have shown that more intense product market competition leads to earlier adoption of green technology. We have then studied the impact of firm asymmetries and find that the identity of the adopting firm depends on the private benefits from contributing to the public good; the small (large) firm adopts when these benefits are small (large). We also show that an increase in firm asymmetry has an ambiguous impact on adoption time.

We then examine the effect of consumer subsidies on adoption time. We provide sufficient conditions for the policy to enhance welfare - if these conditions are not met then welfare may be decreased by subsidies.

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Appendix: Proofs

Proof of Proposition 1

In equilibrium, the profits are:

$$\begin{aligned} \pi^G &= \frac{1}{49}(a+3\alpha-3\varepsilon)^2 \\ \pi^{NG} &= \frac{2}{49}(2a-\alpha+\varepsilon)^2 . \end{aligned}$$

First, notice that $\pi^G > \pi^0 = 0$ so that each firm has an incentive to adopt if the other firm commits not to adopt. Moreover:

$$\pi^G - \pi^{NG} = \frac{1}{49}(a+3\alpha-3\varepsilon)^2 - \frac{2}{49}(2a-\alpha+\varepsilon)^2$$

that is positive as long as:

$$\alpha \geq \widetilde{\alpha} = \left(\sqrt{2}-1\right)a+\varepsilon.$$

This implies that if $\alpha \leq \widetilde{\alpha}$, each firm prefers being the non-adopter to being the adopter. In this case, there is an equilibrium in which one firm adopts and the other does not and adoption occurs at $\widehat{T}$. When $\alpha > \widetilde{\alpha}$, each firm prefers being the one adopting and tries to preempt the other. In this case, adoption time is going to be the minimum between $\widehat{T}$ and $\widetilde{T}$.

Proof of Proposition 2

Equilibrium profits are equal to:

$$\begin{aligned} \pi^G &= \frac{2}{49}(a+2(\alpha-\varepsilon))^2 \\ \pi^{NG} &= \frac{1}{49}(3a-\alpha+\varepsilon)^2 . \end{aligned}$$

Notice that $\pi^G > \pi^0 = a^2/9$ only if:

$$\alpha > \alpha^* \equiv \left(\frac{7}{12}\sqrt{2}-\frac{1}{2}\right)a+\varepsilon$$

and that $\pi^G - \pi^{NG} > 0$ only if:

$$\alpha \geq \widetilde{\alpha} = \left(\sqrt{2}-1\right) a + \varepsilon.$$

Notice that $\widetilde{\alpha} > \alpha^*$. These results imply that for $\alpha < \alpha^*$, there is not adoption of green technology because no firm has an incentive to switch to green. For $\alpha^* \leq \alpha \leq \widetilde{\alpha}$, adoption is at time $\widehat{T}$ and for $\alpha > \widetilde{\alpha}$ adoption time is going to be the minimum between $\widehat{T}$ and $\widetilde{T}$.

Proof of Proposition 3

Let us define as T^B adotion time with Bertrand competition and as T^C adoption time with Cournot competition. When $\alpha \leq \alpha^*$, adoption occurs with Bertrand competition but does not occurs with Cournot competition so $T^B < T^C$ trivially holds in this parameter range. When $\alpha > \alpha^*$ and $\alpha < \widetilde{\alpha}$ adoption time occurs at $\widehat{T}$. Let us indicate with $\widehat{T}^B$ the value of (4) with Bertrand competition, and with $\widehat{T}^C$ its value with Cournot competition. Let us define $\left(\pi^G - \pi^0\right)^{Cournot}$ as the difference between π^G and π^0 with Cournot competition and $\left(\pi^G - \pi^0\right)^{\text{Bertrand}}$ as the difference with Bertrand competition. The definition of $\widehat{T}$ implies that $\widehat{T}^C > \widehat{T}^B$ if $\left(\pi^G - \pi^0\right)^{\text{Cournot}} - \left(\pi^G - \pi^0\right)^{\text{Bertrand}} < 0$. We have:

$$\begin{aligned}
\left(\pi^G - \pi^0\right)^{\text{Cournot}} - \left(\pi^G - \pi^0\right)^{\text{Bertrand}} &= \\
\frac{2}{49}\left(a + 2(\alpha-\varepsilon)\right)^2 - \frac{a^2}{9} - \frac{1}{49}\left(a + 3(\alpha-\varepsilon)\right)^2 &< \\
\frac{2}{49}\left(a+2\right)^2 - \frac{1}{49}\left(a+3\right)^2 &= \\
-\frac{2}{441}a\left(20a-9\right) &< 0
\end{aligned}$$

where the first inequality follows because $2/49\left(a + 2(\alpha-\varepsilon)\right)^2 - 1/49\left(a + 3(\alpha-\varepsilon)\right)^2$ increases in $(\alpha - \varepsilon)$, and the second follows because $a > 1$. When $\alpha > \alpha^*$ and $\alpha \geq \widetilde{\alpha}$ adoption occurs at the minimum between $\widetilde{T}$ and $\widehat{T}$. Millou and Petrakis (2010) show that the difference $\pi^G - \pi^{NG}$ is identical in the cases of Cournot and Bertrand competition. This implies that $\widetilde{T}$ is the same in both cases as well. Because $\widetilde{\alpha} = \left(\sqrt{2}-1\right) a + \varepsilon$ is the same under Betrand

and Cournot competition, the Betrand adoption time cannot exceed the Cournot one also in this parameter range.

Proof of Proposition 4

Katz and Shapiro (1987) building on Fudenberg and Tirole (1985) show that if $\pi_i^G - \pi_i^{NG} > \pi_j^G - \pi_j^{NG}$ and $\pi_i^G - \pi_i^0 > \pi_j^G - \pi_j^0$ then the adoption game has a unique equilibrium in which firm i adopts. The profit functions described above give the following equilibrium payoffs in the Bertrand game:

$$\begin{aligned} \pi_1^G &= \frac{1}{49}\left(a + 2c + 3\alpha - 3\varepsilon\right)^2 \\ \pi_2^{NG} &= \frac{2}{49}\left(2a - 3c - \alpha + \varepsilon\right)^2 \\ \pi_1^{NG} &= \frac{2}{49}\left(2a - \alpha + \varepsilon\right)^2 \\ \pi_2^G &= \frac{1}{49}\left(a + 3\alpha - 3\varepsilon\right)^2. \end{aligned}$$

These payoffs imply that $\pi_2^G - \pi_2^{NG} > \pi_1^G - \pi_1^{NG}$ as long as $\alpha < \alpha^{2B} = 5a/6 - 11c/12 + \varepsilon$. In addition, $\pi_2^G - \pi_2^0 > \pi_1^G - \pi_1^0$ if $\alpha < \alpha^{1B} = 15a/4 - 53c/12 + \varepsilon$. Because $a > 2c$ then $\alpha^{2B} < \alpha^{1B}$ so α^{2B} is the relevant cutoff for Firm 2 adoption and α^{1B} is the relevant cutoff for Firm 1 adoption. In the intermediate region $\alpha^{2B} \leq \alpha \leq \alpha^{1B}$ the preemption incentives are greater for firm 1 ($\pi_1^G - \pi_1^{NG} > \pi_2^G - \pi_2^{NG}$) but firm 2 has greater stand-alone incentives ($\pi_2^G - \pi_2^0 > \pi_1^G - \pi_1^0$). For this "mixed" case Katz and Shapiro (1987) show that any one of the following possibilities may arise: (i) no equilibrium exists; (ii) firm 1 adopts at the earlier of $\widehat{T}_1$ and $\widetilde{T}_2$; (iii) firm 2 adopts at $\widehat{T}_2$. In the Cournot game the equilibrium payoffs are:

$$
\begin{aligned}
\pi_1^G &= \frac{2}{49}\left(a+c+2\alpha-2\varepsilon\right)^2 \\
\pi_2^{NG} &= \frac{1}{49}\left(3a-4c-\alpha+\varepsilon\right)^2 \\
\pi_1^{NG} &= \frac{1}{49}\left(3a-\alpha+\varepsilon\right)^2 \\
\pi_2^G &= \frac{2}{49}\left(a+2\alpha-2\varepsilon\right)^2 .
\end{aligned}
$$

These payoffs imply that $\pi_2^G - \pi_2^{NG} > \pi_1^G - \pi_1^{NG}$ as long as $\alpha < \alpha^{2C} = a/5 - c/10 + \varepsilon$. In addition, $\pi_2^G - \pi_2^0 > \pi_1^G - \pi_1^0$ if $\alpha < \alpha^{1C} = 43a/12 - 55c/12 + \varepsilon$. Because $a > 2c$ then $\alpha^{2C} < \alpha^{1C}$ so α^{2C} is the relevant cutoff for Firm 2 adoption and α^{1C} is the relevant cutoff for Firm 1 adoption. In the intermediate region $\alpha^{2C} \leq \alpha \leq \alpha^{1C}$ the preemption incentives are greater for firm 1 $(\pi_1^G - \pi_1^{NG} > \pi_2^G - \pi_2^{NG})$ but firm 2 has greater stand-alone incentives $(\pi_2^G - \pi_2^0 > \pi_1^G - \pi_1^0)$. For this "mixed" case Katz and Shapiro (1987) show that any one of the following possibilities may arise: (i) no equilibrium exists; (ii) firm 1 adopts at the earlier of $\widehat{T}_1$ and $\widetilde{T}_2$; (iii) firm 2 adopts at $\widehat{T}_2$. Differently from the Bertrand case, the differences $\pi_2^G - \pi_2^0$ and $\pi_1^G - \pi_1^0$ are negative when α is small enough. This implies that there exists an $\widehat{\alpha}$ for which there is not adoption if $\alpha < \widehat{\alpha}$.

Proof of Proposition 5

With Bertrand competition the impact on timing depends on the derivatives

$$
\begin{aligned}
\frac{\partial}{\partial c}\left(\pi_1^G - \pi_1^{NG}\right) &= \frac{\partial}{\partial c}\pi_1^G > 0 \\
\frac{\partial}{\partial c}\left(\pi_2^G - \pi_2^0\right) &= 0 \\
\frac{\partial}{\partial c}\left(\pi_2^G - \pi_2^{NG}\right) &= -\frac{\partial}{\partial c}\pi_2^{NG} > 0 \\
\frac{\partial}{\partial c}\left(\pi_1^G - \pi_1^0\right) &= \frac{106}{49}c - \frac{45}{49}a + \frac{12}{49}\alpha - \frac{12}{49}\varepsilon \gtrless 0.
\end{aligned}
$$

Similarly with Cournot competition the impact on timing depends on the derivatives

$$
\begin{aligned}
\frac{\partial}{\partial c}\left(\pi_1^G - \pi_1^{NG}\right) &= \frac{\partial}{\partial c}\pi_1^G > 0 \\
\frac{\partial}{\partial c}\left(\pi_2^G - \pi_2^0\right) &= -\frac{\partial}{\partial c}\pi_2^0 > 0 \\
\frac{\partial}{\partial c}\left(\pi_2^G - \pi_2^{NG}\right) &= -\frac{\partial}{\partial c}\pi_2^{NG} > 0 \\
\frac{\partial}{\partial c}\left(\pi_1^G - \pi_1^0\right) &= \frac{8}{49}\alpha - \frac{62}{441}c - \frac{62}{441}a - \frac{8}{49}\varepsilon \gtrless 0.
\end{aligned}
$$

Proof of Proposition 6

With Bertrand competition, the equilibrium profits are:

$$
\begin{aligned}
\pi^G &= \frac{1}{49}\left(a + 3(\alpha + s) - 3\varepsilon\right)^2 \\
\pi^{NG} &= \frac{2}{49}\left(2a - \alpha - s + \varepsilon\right)^2.
\end{aligned}
$$

First, notice that $\pi^G > \pi^0 = 0$ so that each firm has an incentive to adopt if the other firm commits not to adopt. Moreover:

$$
\pi^G - \pi^{NG} = \frac{1}{49}\left(a + 3(\alpha + s) - 3\varepsilon\right)^2 - \frac{2}{49}\left(2a - \alpha - s + \varepsilon\right)^2
$$

that is positive as long as:

$$
\alpha \geq \widehat{\alpha} = \left(\sqrt{2} - 1\right)a + \varepsilon - s.
$$

Because $\widehat{\alpha} \leq \widetilde{\alpha}$ each firm prefers being the one adopting and tries to preempt the other for a larger set of parameters. Because

$$
\begin{aligned}
\frac{\partial}{\partial s}\left(\pi^G - \pi^{NG}\right) &= \frac{2}{7}(a + s + \alpha - \varepsilon) > 0 \\
\frac{\partial \pi^G}{\partial s} &= \frac{6}{49}\left(a + 3s + 3\alpha - 3\varepsilon\right) > 0
\end{aligned}
$$

we have that both $\widehat{T}$ and $\widetilde{T}$ decrease in s. With Cournot competition, equilibrium profits are:

$$\pi^G = \frac{2}{49}\left(a + 2\left(\alpha + s - \varepsilon\right)\right)^2$$
$$\pi^{NG} = \frac{1}{49}\left(3a - \alpha - s + \varepsilon\right)^2$$

and

$$\frac{\partial}{\partial s}\left(\pi^G - \pi^{NG}\right) = \frac{2}{7}(a + s + \alpha - \varepsilon) > 0$$
$$\frac{\partial}{\partial s}\left(\pi^G - \pi^0\right) = \frac{8}{49}a + \frac{16}{49}s + \frac{16}{49}\alpha - \frac{16}{49}\varepsilon > 0$$

imply that also in this case both $\widehat{T}$ and $\widetilde{T}$ decrease in s.

Proof of Proposition 7

Consider the case of Bertrand competition. Formulas (6) and (7) imply that a consumer subsidy, s, has the same impact of an increase in the private benefits α. Assume that the initial level of α is lower than α^{2B} so that in equilibrium the small firm is the adopter. If the subsidy is large enough so that $\alpha + s > \alpha^{1B}$ the game will have a unique equilibrium in which Firm 1 will adopt the green technology.

Proof of Proposition 8

Let us define as W^0 the (static) social welfare in the absence of adoption and $W^G = RS + E(i_g)$ the (static) social welfare with green technology adoption where $E(i_g)$ indicates the public good benefits and RS captures the rest of the welfare. The socially optimal adoption time, T^*, is computed by maximizing with respect to T

$$\frac{1 - e^{-rT}}{r}W^0 + \frac{e^{-rT}}{r}W^G - K(T)$$

which yields:

$$T^* = \frac{1}{\lambda - r}\log\frac{\lambda K_0}{W^G - W^0}.$$

Notice that $T^* < \widehat{T}$ if $E(i_g) > \pi^G - \pi^0 - (RS - W^0)$ and that $T^* < \widetilde{T}$ if $E(i_g) > \frac{\lambda}{r}\left(\pi^G - \pi^{NG}\right) - (RS - W^0)$. Therefore $T^* < \min\left\{\widehat{T}, \widetilde{T}\right\}$ if

$$E(i_g) > E^* = \max\left\{\pi^G - \pi^0, \frac{\lambda}{r}\left(\pi^G - \pi^{NG}\right)\right\} - (RS - W^0)$$

that is non-decreasing in λ/r.

Proof of Proposition 9

Consider subsidy s such that $T(0) > T(s) \geq T^*$. Let us indicate with W^G the (static) social welfare with green technology adoption in the absence of subsidies and with $W^G(s)$ the (static) social welfare with green technology adoption in the presence of subsidies $s > 0$. Notice that if $W^G(s) \geq W^G$ we have that:

$$\begin{aligned}
\frac{1 - e^{-rT(s)}}{r}W^0 + \frac{e^{-rT(s)}}{r}W^G(s) - K(T(s)) &\geq \\
\frac{1 - e^{-rT(s)}}{r}W^0 + \frac{e^{-rT(s)}}{r}W^G - K(T(s)) &\geq \\
\frac{1 - e^{-rT(0)}}{r}W^0 + \frac{e^{-rT(0)}}{r}W^G - K(T(0)).
\end{aligned}$$

where the second inequality arises because the function is quasiconcave (Fudenberg Tirole, 1985). This implies that a sufficient condition for the subsidy to increase dynamic welfare is that $W^G(s) \geq W^G$. In our set-up:

$$\begin{aligned}
W^G(s) &= \pi^G + \pi^N + I - (p_G - s)q_G - p_N q_N + b(i_G)^2/2 + \\
&\quad (\alpha + a)i_G + a\left(i_{NG} - i_G\right) - (i_G)^2/2 - (i_{NG})^2/2 - q_G s_G(1 + \Lambda) \\
&= I + b(i_G)^2/2 + (\alpha + a)i_G + \\
&\quad a\left(i_{NG} - i_G\right) - (i_G)^2/2 - (i_{NG})^2/2 - \varepsilon i_G - \Lambda s i_G
\end{aligned}$$

that allows us to characterize the static social welfare for any subsidy s. Exploiting the above formula we have that in the case of Cournot competition $W^G(s) \geq W^G$ if

$$s \leq \overline{s}^C = 2\frac{a(1+2b-7\Lambda)+(9+4b-14\Lambda)(\alpha-\varepsilon)}{5-4b+28\Lambda}$$

whereas with Bertrand competition

$$s \leq \overline{s}^B = 2\frac{(\alpha-\varepsilon)(11+9b-21\Lambda)+(3b-1-7\Lambda)a}{10-9b+42\Lambda}.$$

Notice that cutoffs are negative if $b-\Lambda$ is not large enough (it is negative if $b=\Lambda$ and may be negative even if $b>\Lambda$). For both cut-offs the derivatives respect to b, a, α are positive and those respect to ε and Λ are negative.

Proof of Proposition 10

Proposition 6 implies that adoption occurs too late both under Bertrand and under Cournot when b is large enough. Moreover, let us define W^{0B} the per-period social welfare under Bertrand competition when the green technology has not been adopted and W^{GB} the per-period welfare with adoption. We indicate with W^{0C} and W^{GC} the per period welfare functions with Cournot competition and with T^B and T^C (private) adoption time with Bertrand and Cournot competition. We have that:

$$\begin{aligned}
\frac{1-e^{-rT^B}}{r}W^{0B}+\frac{e^{-rT^B}}{r}W^{GB}-K(T^B) &\geq \\
\frac{1-e^{-rT^C}}{r}W^{0B}+\frac{e^{-rT^C}}{r}W^{GB}-K(T^C) &\geq \\
\frac{1-e^{-rT^C}}{r}W^{0C}+\frac{e^{-rT^C}}{r}W^{GC}-K(T^C).
\end{aligned}$$

where the first inequality arises because the function is quasiconcave (Fudenberg Tirole, 1985). To see why the second inequality holds, first notice that $W^{0B} \geq W^{0C}$. In fact, $W^{0B} = I + a - 1/2$ and

$$W^{0C} = \begin{cases} I + 4/9a^2 \text{ if } \ 1 < a < 1.5 \\ I + a - 1/2 \text{ if } a \geq 1.5 \end{cases}.$$

Second notice that $W^{GB} \geq W^{GC}$. In fact, independently on the competition regime

$$W^G = I + b(i_G)^2/2 + (\alpha + a)i_G + a\,(i_{NG} - i_G) - (i_G)^2/2 - (i_{NG})^2/2 - \varepsilon i_G$$

and $\partial W^G/\partial i_G \geq 0$ if b is large enough and $\partial W^G/\partial i_{NG} \geq 0$. Let us define as $i_G^C = (a + 3(\alpha - \varepsilon))/7$ and $i_{NG}^C = (a + 2(\alpha - \varepsilon))/7$ the demand cutoffs with Cournot competition and $i_G^B = (5a + (\alpha - \varepsilon))/7$ and $i_{NG}^B = (4a + (\alpha - \varepsilon))/7$ the cutoffs with Bertrand competition. It is easy to see that $i_G^C < i_G^B$ and that $i_{NG}^C < i_{NG}^B$. Therefore $W^{GC} = W^G(i_G^C, i_{NG}^C) \leq W^G(i_G^B, i_{NG}^C) \leq W^G(i_G^B, i_{NG}^B) = W^{GB}$.

Proof of Proposition 11

Following Fudenberg and Tirole (1985) we solve this game using backward induction. Once the leader has adopted the green technology the optimal adoption time for the follower is equal to:

$$\pi^D - \pi^{NG} = -e^{r\widehat{t}_2}K'(\widehat{t}_2)$$

The function $-e^{rt}K'(t)$ is decreasing in t because we assumed that $(K(t)e^{rt})'' > 0$. This implies that $\widehat{t}_2$ goes up when $\pi^D - \pi^{NG}$ decreases. Fudenberg and Tirole (1985) show that at leader adoption time there is rent equalization:

$$\begin{aligned} L(t) &= F(t) \\ \frac{\pi^G - \pi^{NG}}{r} &= \frac{K(t) - K(\widehat{t}_2)}{e^{-rt} - e^{-r\widehat{t}_2}}. \end{aligned} \tag{8}$$

Let us indicate as $g(t)$ the right hand side of (8). The sign of $g'(t)$ is equal to the sign of $K'(t) + K'(t)e^{-r(t_2^* - t)} + rK(t) - rK(t_2^*)$ that is negative because $K(t)e^{rt}$ decreases in t. This implies that the right hand side of (8) decreases in t and increases in t_2^*. Therefore, when the policy decreases both $\pi^D - \pi^{NG}$ and $\pi^G - \pi^{NG}$ then $g(t)$ increases and the right hand side of (8) decreases so that adoption will occur at a larger value of t.

Proof of Proposition 12

Katz and Shapiro (1987), show that if $\pi_i^G - \pi_i^{NG} > \pi_j^G - \pi_j^{NG}$ and $\pi_i^G - \pi_i^0 > \pi_j^G - \pi_j^0$ then the adoption game has a unique equilibrium in which firm i adopts. The profit functions described above give the following equilibrium payoffs in the Bertrand game:

$$\begin{aligned}
\pi_1^G &= \frac{1}{49}(a + 3\alpha - 3\varepsilon_1)^2 \\
\pi_2^{NG} &= \frac{2}{49}(2a - \alpha + \varepsilon_1)^2 \\
\pi_1^{NG} &= \frac{2}{49}(2a - \alpha + \varepsilon_2)^2 \\
\pi_2^G &= \frac{1}{49}(a + 3\alpha - 3\varepsilon_2)^2 .
\end{aligned}$$

These payoffs imply that $\pi_2^G - \pi_2^{NG} < \pi_1^G - \pi_1^{NG}$, as long as $\alpha > \alpha^\varepsilon = a/11 + (\varepsilon_1 + \varepsilon_2)/2$. In addition, because $\pi_2^0 = \pi_1^0 = 0$ the condition $\pi_2^G - \pi_2^0 < \pi_1^G - \pi_1^0$ is always satisfied.

Proof of Corollary 1

If $\alpha > \alpha^\varepsilon$, adoption time is the minimum between:

$$\widehat{T}_1 = \frac{1}{\lambda - r} \log \frac{\lambda K_0}{\pi_1^G - \pi_1^0}$$

and:

$$\widetilde{T}_1 = \frac{1}{\lambda - r} \log \frac{r K_0}{\pi_2^G - \pi_2^{NG}}.$$

It is easy to see that a reduction in ε_2 by increasing π_2^G reduces $\widetilde{T}_1$. Moreover a reduction in ε_1 by reducing π_2^G reduces $\widetilde{T}_1$ too.

Appendix for: "Switching to Green: the Timing of Socially Responsible Innovation"

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July 30, 2012

In this Appendix, we present a number of additional results from Galasso and Tombak, 2011 (working paper). Specifically, we study how different policies affect the adoption equilibrium both in terms of which firm adopts and when that firm adopts. We also derive the socially optimal policy and show that it involves a combination of subsidy types.

Additional Policies

Consumer Education

A policy often espoused as a measure to accelerate the adoption of green technologies is a consumer education campaign. Under this policy, the government devotes resources to advertising to make consumers aware of the benefits associated with the use of green technologies. In our model, this has the effect of increasing the value that consumers obtain from participating in the provision of the public good, α, and the value that they obtain from having Y units of the public good available, $b(i, Y)$. The analysis in the paper shows how in our model firms' profits do not depend on $b(i, Y)$. Interestingly this implies that if consumer education has the only impact of altering the perception of the externality, $b(i, Y)$, it has no effect on the timing of adoption. This idea is summarized in the next result.[1]

Observation A1 *Consumer education may have no impact on the timing of green technology adoption.*

If consumer education does increase private benefits from consuming the green product, α, formulas the effect of this policy is identical to the one of a consumer subsidy. Therefore, exploiting the previous finding, we may conclude that the campaign will reduce adoption time by increasing both stand-alone and preemption incentives. In addition, if the policy increases dramatically these private benefits (e.g. from a value below α^{2B} to a value above α^{1B}), the identity of the adopting firm may change from the small one to the big one.[2]

[1] For simplicity, we have assumed that consumer education has the same impact across all consumers. More complex education programs would imply different effects for different type of consumers (e.g. high income vs low income).

[2] The welfare implication of consumer education may be difficult to pin down. This occurs because the policy alters the utility function of the consumers. If the policy affects only the perception of the externalities, $b(i, Y)$, then it has the effect of reducing welfare because firms' adoption decisions do not change whereas consumer preferred adoption time is anticipated. If the policy affects also the value from contributing, α, it has an ambiguous effect on welfare because both the private and the socially optimal adoption times are reduced.

Firm Subsidies

We now study the effect of subsidies to firms. We start by looking at transfers aimed at a reduction in the adoption cost and that are unrelated to the quantity of green product sold. The first transfer that we consider is a lump-sum subsidy to the adopting firm. In our setting, we can model a lump-sum subsidy as a transfer of Fe^{rT} at the time of adoption and it is equivalent to a reduction of F in the present value of the cost function: $K(t) = K_0 e^{-\lambda t} - F$. The next proposition describes the effects of a lump-sum subsidy on adoption time. The proposition also shows that a subsidy that decreases over time (as a reduction in K_0) always reduces the time of adoption.

Proposition A1 *A lump-sum subsidy does not affect the optimal times $\widehat{T}$, but would reduce the preemption times, $\widetilde{T}$ whereas a firm subsidy that decreases over time always reduces the time of adoption.*

The above proposition has an important implication. When the speed of technological progress is low, so that $\widehat{T}$ is lower than $\widetilde{T}$, a lump sum subsidy may be ineffective.

Finally, we turn to the analysis of subsidies per product sold. In the next observation we show how in our framework the functional forms of the utility and cost functions imply that a subsidy per product sold (decrease in ε) is equivalent to a per consumer subsidy (increase in α). Therefore, all the results in the previous section apply. Differently from consumers' subsidies, producer subsidies may be targeted to a specific firm. In the following observation, we also show that when firms are asymmetric, a subsidy targeted to the small firm may have the unintended consequence of inducing the large firm to anticipate adoption.

Observation A2 *A subsidy per product sold (decrease in ε) is equivalent to a consumer subsidy (increase in α). If α is large, a per product subsidy targeted to the small firm may induce the large firm to adopt earlier.*

To see the intuition for the last result consider the case in which α is large and in equilibrium the large firm preempts the small one. A subsidy to the small firm will increase its incentives to adopt, but if α is big enough the large firm will still preempt the small one and the effect of the subsidy will be to anticipate adoption by the large firm. Thus, a policy may seem to be ineffective in that a firm that receives support would not be the adopter but in fact *is effective* in inducing earlier adoption by the nonsubsidized firm.

Government may also intervene by increasing the rate at which the adoption cost of the green product falls, λ. In the next result we show that this policy may have an ambiguous impact on adoption time.

Observation A3 *Policies that increase the rate of technological progress, λ, reduce $\widetilde{T}$ but have ambiguous impact on $\widehat{T}$.*

The impact of an increase in the rate of technological progress on adoption time is ambiguous. The reason is that technological progress reduces the cost of adoption but has an ambiguous impact on the marginal benefit of waiting (the benefits from marginally postponing adoption). While in a preemption equilibrium is the total cost of adoption that matters, in a stand-alone equilibrium is the marginal benefit of waiting that affects adoption incentives. Therefore, in this second case, faster technological progress may increase firm incentives to delay adoption.

Policy Effectiveness in Accelerating Adoption

Focusing on the symmetric case ($c = 0$), we now compare the effect of the different policies on green technology adoption time. First, we classify the various policies described above into two groups: policies increasing the mark-up of the firm selling the green product (these policies are consumer subsidies, consumer education, and per product subsidies) and policies that reduce the cost of developing the green technology (policies affecting $K(t)$).

An example of the first type of policies is the Car Allowance Rebate System (CARS), which subsidizes consumers to purchase fuel-efficient vehicles when trading in less fuel efficient vehicles. We argue above that in our framework these consumer subsidies are equivalent to an increase in α or a reduction in ε. An example of the second type of policies is the Michigan Angel Investment Incentive program, which offers tax reductions to investors financing a qualified green-technology company. This policy reduces the cost of capital for a company and therefore the cost of developing the green technology but most likely does not affect marginal revenues and marginal costs of green products. In our framework, we can model these policies with a reduction in K_0.

Which of the two types of policies is more effective in accelerating adoption time? Our model suggests that a reduction in K_0 is more effective as long as the initial development cost is not too large.

Observation A4 *There exists a* K^* *such that if* $K_0 > K^*$, *a reduction in* K_0 *has a lower impact on adoption time than a reduction in* ε.

More precisely, because of the convexity of the development cost function, our model indicates that a reduction in K_0 has a greater impact than a reduction in marginal cost of production only if the percentage reduction in K_0 is large enough.[3]

Optimal Policy

Because the dynamic social welfare analysis increases the complexity of our model, we focus on the symmetric case ($c = 0$) absence of distortion $\Lambda = 0$ and following Bagnoli and Watts (2003) we introduce a specific functional form for the externalities: $b(i, Y) = bY^2/2$ with $b \leq 1$.

We study the optimal policy that a government can implement to maximize the dynamic social welfare in our model of green technology adoption. We say that a policy is optimal if dynamic social welfare cannot be improved by either altering the level of public good provision or by shifting adoption time. Let us indicate with $p_G(s)$ and $p_{NG}(s)$ the equilibrium prices of the green and standard product in the presence of a consumer subsidy of size s. In addition let us indicate with π^{G*}, π^{NG*} and W^{G*} the per-period profits and welfare flows with green technology adoption in the presence of the optimal consumer subsidy, s^*. Finally, we indicate with W^0 and π_0 per-period profits and welfare flows in the absence of adoption. In the next proposition we show that the planner can maximize dynamic social welfare using a combination of per-product (consumer) subsidies and adoption cost subsidies (reduction in $K(t)$).

[3] Alternatively, the policy may be modeled as a reduction in r. In our setting

$$\partial\widehat{T}/\partial r = \frac{1}{(\lambda - r)^2} \log \frac{\lambda K_0}{\pi^G - \pi^0}$$

and

$$\partial\widetilde{T}/\partial r = \frac{1}{(\lambda - r)^2} \log \frac{r K_0}{\pi^G - \pi^0} + \frac{1}{r(\lambda - r)}$$

that are both positive. Moreover, it is easy to see that if r is large enough both $\left|\partial\widehat{T}/\partial r\right| > \left|\partial\widehat{T}/\partial\varepsilon\right|$ and $\left|\partial\widetilde{T}/\partial r\right| > \left|\partial\widetilde{T}/\partial\varepsilon\right|$ hold.

Proposition A2: *Dynamic social welfare is maximized by a consumer subsidy, s^*, and an adoption cost subsidy, F^*, that satisfy:*

$$s^* = \frac{\alpha - \varepsilon}{1-b} + p_G(s^*) - p_{NG}(s^*) - \alpha \tag{1}$$

and

$$F^* = \begin{cases} K_0\left(1 - \dfrac{\pi^{G*} - \pi_0}{W^{G*} - W^0}\right) & \text{if } \dfrac{\lambda}{r} \leq \dfrac{\pi^{G*} - \pi^0}{\pi^{G*} - \pi^{NG*}} \\ K_0\left(1 - \dfrac{\lambda}{r}\dfrac{\pi^{G*} - \pi^{NG*}}{W^{G*} - W^0}\right) & \text{if } \dfrac{\lambda}{r} > \dfrac{\pi^{G*} - \pi^0}{\pi^{G*} - \pi^{NG*}} \end{cases}. \tag{2}$$

While the specific formulas for s^* and F^* depend heavily on the functional form of the utility and cost functions, the proposition highlights a more general trade-off faced by the social planner. First, the time of adoption that firms choose non-cooperatively may differ from the one maximizing total welfare (in particular, when externalities are large enough, adoption occurs too late). Second, when externalities are large enough, firms under-produce the green product. The two policy instruments act on these two dimensions of the planner's problem. Specifically, the consumer subsidy, s^*, is chosen to equate the marginal social benefits and the marginal social costs of the public good. This subsidy, while solving the under-provision problem does not guarantee that the adoption time is the optimal one. Because adoption cost subsidies affect the time of adoption, but not the production decisions, the planner chooses F^* to implement the optimal adoption time without affecting the level of green product provision.[4]

Because $p_G(s^*)$ and $p_{NG}(s^*)$ are linear in s^*, condition (1) can be inverted to obtain the explicit formula of the consumer subsidy. In the case of Bertrand competition the subsidy equals

$$s^*_B = \frac{1}{3}\left(\frac{7(\alpha - \varepsilon)}{1-b} - (a + 3(\alpha - \varepsilon))\right)$$

[4]When firms are asymmetric it is more difficult to derive the optimal policy because a subsidy may affect not only the quantity of green product produced but also the identity of the adopting firm. In this environment a social planner may find optimal to have the large firm adopting and not the small one. To see this, let us indicate with i_{G1} and i_{NG2} the cutoffs when the large firm adopts and i_{G2} and i_{NG1} the cutoffs when the small firm adopts. Moreover, we define as $D(i_G, i_{NG}) = I + b(i_G)^2/2 + (\alpha + a)i_G + a\,(i_{NG} - i_G) - (i_G)^2/2 - (i_{NG})^2/2$ the consumer gross utility from adoption. Adoption from the large firm is associated with greater per-period welfare flow if $D(i_{G1}, i_{NG2}) - D(i_{G2}, i_{NG1}) > \varepsilon\,(i_{G1} - i_{G2}) + c(i_{NG2} - i_{G2})$. The condition suggests that switching the identity of the adopter from the small to the large firm is welfare improving if the increase in consumer utility exceeds the increase in cost due to larger production of green product and to the increase in cost of production of the standard product.

whereas with Cournot competition the subsidy is equal to

$$s_C^* = \frac{1}{2}\left(\frac{7(\alpha-\varepsilon)}{1-b} - (a + 2(\alpha-\varepsilon))\right).$$

It is easy to see that when the optimal subsidies are positive $s_C^* > s_B^*$ confirming that a less government intervention is required when product market competition is intense.

Overall, our analysis of the optimal policy indicates that while it is possible for a benevolent social planner to guarantee both efficient production of green product and dynamically efficient adoption time, it is difficult to implement this outcome with simple policy tools. Because policies that lead to an efficient level of per-period public good provision do not guarantee optimal adoption time, the use of more than one policy tool is required to reach dynamic efficiency. Moreover, Proposition A2 indicates that policies need to be customized to market conditions (i.e. competitive pressure, externalities and technological progress).

References

[1] Bagnoli M. and S. Watts, 2003, "Selling to Socially Responsible Consumers: Competition and the Private Provision of Public Goods", *Journal of Economics and Management Strategy* **12**, 419-445.

[2] Galasso A. and M. Tombak, 2011, "Switching to Green: Policies to Accellerate Socially Responsible Innovation", Rotman School of Management working paper.

Proofs

Proof of Observation A1

The demand functions $Q_G(p_G, p_{NG}) = \alpha - p_G + p_{NG}$ and $Q_{NG}(p_G, p_{NG}) = a - \alpha - 2p_{NG} + p_G$ do not depend on $b(i, Y)$. This implies that both the profit functions and green technology adoption time do not depend on $b(i, Y)$. Therefore consumer education policies that affect only $b(i, Y)$ have no impact on technology adoption time.

Proof of Proposition A1

First, note that we obtain the formula for $\widehat{T}$ from the maximization of $L(T)$, which is not affected by the lump sum subsidy. Conversely, the formula for $\widetilde{T}$ is affected by F and its new value $\widetilde{T}^{LS}$ will now satisfy:

$$\frac{e^{-r\widetilde{T}^{LS}}}{r}\pi^G - \frac{e^{-r\widetilde{T}^{LS}}}{r}\pi^{NG} - K_0 e^{-\lambda\widetilde{T}^{LS}} = -F. \tag{3}$$

Notice that at $\widetilde{T}$ the left hand side exceeds the right hand side. Because $L(T) < F(T)$ (the right hand side of (3) is negative) when $T < \widetilde{T}$ and $L(T) > F(T)$ (the right hand side of (3) is positive) when $T > \widetilde{T}$, we have that $\widetilde{T}^{LS} < \widetilde{T}$.

Next, let us consider a subsidy that decreases at a rate $\theta : Fe^{-\theta T}$.Consider first the case in which adoption occurs at time $\widehat{T}$. After the introduction of the subsidy, the new value for $\widehat{T}$ will satisfy the following condition:

$$-e^{-rT}(\pi^G - \pi^0) + \lambda K_0 e^{-\lambda T} = \theta F e^{-\theta T}.$$

At the previous level of $\widehat{T}$, the left hand side is zero. Because $\widehat{T}$ was a maximum, the the condition is now satisfied for a level of $T < \widehat{T}$. Consider now the condition for $\widetilde{T}$. The new optimal value now satisfies:

$$\frac{e^{-rT}}{r}\pi^G - K_0 e^{-\lambda T}\frac{e^{-rT}}{r}\pi^{NG} = -Fe^{-\theta T}.$$

Because $L(T) < F(T)$ (the right hand side of the above formula is negative) when $T < \widetilde{T}$, the new optimal value will be lower than $\widetilde{T}$.

Proof of Observation A2

The first result follows from the following derivatives:

$$\begin{aligned}
\frac{\partial}{\partial\varepsilon}\left(\pi_2^G-\pi_2^{NG}\right) &= -\frac{\partial}{\partial\alpha}\left(\pi_2^G-\pi_2^{NG}\right)\\
\frac{\partial}{\partial\varepsilon}\left(\pi_1^G-\pi_1^0\right) &= -\frac{\partial}{\partial\alpha}\left(\pi_1^G-\pi_1^0\right)\\
\frac{\partial}{\partial\varepsilon}\left(\pi_1^G-\pi_1^{NG}\right) &= -\frac{\partial}{\partial\alpha}\left(\pi_1^G-\pi_1^{NG}\right)\\
\frac{\partial}{\partial\varepsilon}\left(\pi_2^G-\pi_2^0\right) &= -\frac{\partial}{\partial\alpha}\left(\pi_2^G-\pi_2^0\right).
\end{aligned}$$

For the second part of the observation consider the case of Bertrand competition. If $\alpha > \alpha^{1B}$ in equilibrium the large firm is the adopter. The result follows immediately from the fact that a subsidy increases the difference $\pi_2^G - \pi_2^{NG}$ and therefore reduces $\widetilde{T}_1$.

Proof of Observation A3

This follows because

$$\begin{aligned}
\frac{\partial\widehat{T}}{\partial\lambda} &= -\frac{1}{(\lambda-r)^2}\log\frac{\lambda K_0}{\pi^G-\pi^0}+\frac{1}{\lambda(\lambda-r)}\lesseqgtr 0 \qquad (4)\\
\frac{\partial\widetilde{T}}{\partial\lambda} &= -\frac{1}{(\lambda-r)^2}\log\frac{rK_0}{\pi^G-\pi^{NG}}<0.
\end{aligned}$$

Proof of Observation A4

Notice that:

$$\begin{aligned}
\frac{\partial\widehat{T}}{\partial K} &= \frac{1}{\lambda-r}\frac{1}{K}\\
\frac{\partial\widehat{T}}{\partial\varepsilon} &= -\frac{1}{\lambda-r}\frac{1}{\pi^G}\frac{\partial\pi^G}{\partial\varepsilon}
\end{aligned}$$

therefore:

$$\left|\frac{\partial\widehat{T}}{\partial K}\right| < \left|\frac{\partial\widehat{T}}{\partial\varepsilon}\right|$$

only if:

$$K_0 > \frac{\pi^G}{\partial\pi^G/\partial\varepsilon} \equiv K_1.$$

Similarly,

$$\left|\frac{\partial\widetilde{T}}{\partial K}\right| < \left|\frac{\partial\widetilde{T}}{\partial\varepsilon}\right|$$

only if:

$$K_0 > \frac{\pi^G - \pi^{NG}}{\partial(\pi^G - \pi^{NG})/\partial\varepsilon} \equiv K_2.$$

Setting $K^* = \max\{K_1, K_2\}$ we obtain the result.

Proof of Proposition A2

The problem of the social planner is to choose the optimal level of public good and the optimal adotion time, i.e.:

$$\max_{i_G, T} \frac{1 - e^{-rT}}{r} W^0 + \frac{e^{-rT}}{r} W^G(i_G) - K(T)$$

solution i_G^*, T^* satisfying:

$$\begin{cases} \dfrac{dW^G(i_G^*)}{di_G} = 0 \\ -\dfrac{dK(T^*)}{dt} = e^{-rT^*}\left(W^G(i_G^*) - W^0\right) \end{cases}.$$

The per-period social surplus with adoption is equal to

$$W^G(i_G) = I + b(i_G)^2/2 + (\alpha + a)i_G + a\left(i_{NG} - i_G\right) - (i_G)^2/2 - (i_{NG})^2/2 - \varepsilon i_G$$

and the marginal social benefits are equal to the marginal social costs of the public good (i.e. $dW^G/di_G = 0$) when:

$$i_G^* = \frac{\alpha - \varepsilon}{1 - b}.$$

In general, $i_G = \alpha + s - p_G + p_{NG}$ this implies that the per period welfare is maximized with a subsidy that satisfies

$$\alpha + s^* - p_G(s^*) + p_{NG}(s^*) = (\alpha - \varepsilon)/(1 - b).$$

The second condition for welfare maximization combined with $K(T) = K_0 e^{-\lambda T}$ implies

$$T^* = \frac{1}{\lambda - r} \log \frac{\lambda K_0}{W^G(i_G^*) - W^0}.$$

The optimal transfer leads to a private chosen adoption time $\min\left\{\widehat{T}, \widetilde{T}\right\}$ equal to the socially optimal time T^*. If $\widehat{T} = \min\left\{\widehat{T}, \widetilde{T}\right\}$ the subsidy satisfies:

$$\frac{\lambda K_0}{W^G(i_G^*) - W^0} = \frac{\lambda(K_0 - F)}{\pi^{G*} - \pi^0}.$$

If $\widetilde{T} = \min\left\{\widehat{T}, \widetilde{T}\right\}$ the subsidy satisfies:

$$\frac{\lambda K_0}{W^G(i_G^*) - W^0} = \frac{r(K_0 - F)}{\pi^{G*} - \pi^{NG*}}.$$