Switching to Green: Policies to Accelerate Provision of Socially Responsible Products

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Abstract

We examine policies which could affect the timing of provision of socially responsible products. A model is developed of a game of timing between asymmetric firms adopting a product technology which features a public good and where there is a proportion of consumers willing to pay for the public good ("caring consumers"). We find the effects of the degree of product market competition, the proportion of caring consumers, and firm asymmetries, on the timing of adoption and the proliferation of the public good. The effects on equilibrium timings are examined of different types of subsidies: for technology development; for consumers to adopt; and for small firms and we find that the socially preferred policy involves a combination of types of subsidies.

1 Introduction

Environmental concerns are among the top priorities for many governments around the world. With the ongoing and widespread alarm over global warming there is substantial and increasing pressure on policy makers to address these concerns as soon as possible. Many government leaders are pinning their hopes on new "green" technologies to allow their societies to enjoy high standards of living with less of the polluting emissions, fuel consumption, and solid waste that present technologies emit. The challenge for governments is to devise policies that would be effective in inducing private industry to accelerate their development, adoption and marketing of such green technologies while minimizing the distortions to the economy that may arise from such policies. Similar challenges are faced for a variety of socially responsible

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products such as fair trade coffee, organic food, and socially responsible investment (SSRI) funds. The effectiveness of such government policies in accelerating the provision of socially responsible products is the subject of this study.

There are a number of possible policies governments can enact. On the supply side, governments can fund or subsidize research and development of selected technologies or of selected firms. On the demand side, consumers can be induced to purchase green technologies through public awareness campaigns, or even through cash subsidies on their purchases. For example, in the automobile industry, the Obama administration has awarded $1.3 bil in battery and electric vehicle grants to Michigan based projects and in the stimulus bill increased funding by 30% to help small and medium sized manufacturers get access to new technologies - this subsidy for smaller firms is set to double in the 2010 budget (Shepardson, 2009). In the U.S. Department of Energy program to help small firms for example, $528 mil was given to Fisker in California to produce electric cars and $118.5 mil was granted to Enerdel in Indiana to produce lithium ion batteries for cars (Proudfoot, 2009). Simultaneously $3 bil was earmarked for U.S. consumers in 2009 in the "Cash for Clunkers" program resulting in an estimated 700,000 transactions replacing old cars for newer vehicles (Szezesny, 2009). The program for smaller firms suggests that firm size plays a significant role in the adoption of new technologies. An alternative approach is that of California which passed a law regulating car companies to sell a certain proportion of low emission cars. A further U.S. federal government regulation calculates the weighted average mileage of the cars sold by a company and assesses a tax if it is under a certain mileage. All of these programs and regulations (and many more) act on this industry to create (or destroy) incentives to adopt new technologies, some may even be counterbalancing. In this study we analyze how effective each policy would be in accelerating the adoption of green product technologies, or under which conditions are each of the policies likely to be effective.

The literature on the timing of adoption of new technologies is extensive.[1] The salient result of these models for the purposes of this study is that strategic interaction can push firms to adopt before their optimal adoption time, i.e., preemptive adoption. Consequently, we develop a model of a game of timing with imperfect competition that extends previous literature by considering the adoption of “green” technologies - by which we mean technologies which in consumption provide a public good. In the environmental case, that public good is an absence of pollution which is of benefit to the consumers of the new green technology as well as to the consumers of the nongreen technology and that benefit grows with the increased consumption of green technology. For this we follow Bagnoli and Watts (2003), Besley and Ghatak (2007) who formulated a static model of private provision of a public good whereby there

[1] See, for example, 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).

is a segment of consumers who obtain private value from consuming the public good ("caring consumers") and are willing to pay more for it.[2] We study how the size of this proportion of caring consumers affects which firm adopts the green technology, the proliferation of the green product, and the timing of such an adoption.[3]

We analyze this model under different degrees of product market competition (Bertrand or Cournot), different levels of firm asymmetry, and under different policy regimes. There are 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 firms are asymmetric, the identity of the innovating firm depends on the proportion of caring consumers. If this fraction is small (large) the small (large) firm will adopt the green technology. Third, we highlight a difference between policies that increase the mark-up of green products (as consumer subsidies, consumer education and per-product firm subsidies) and policies that reduce the cost of adoption (as R&D subsidies). Policies that increase the green product mark-up both anticipate the time of adoption and increase the provision of public good, policies that reduce the cost of the technology anticipate adoption only.

Our study is organized 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 how different policies will affect the adoption equilibrium both in terms of which firms adopts and when that firm adopts. Extensions are examined 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 the timing of adoption to provide a socially responsible product under rivalry between two firms. Our model extends the technology adoption games of timing of Fudenberg and Tirole (1985) and Katz and Shapiro (1987) by introducing private provision of public goods as modeled in Bagnoli and Watts (2003) and Besley and Ghatak (2007).

[2] Another related paper is Kotchen (2006) that studies the choice of consumers between consuming a “green product” and contributing to a pure public good.

[3] A recent TIME poll shows that 40% of consumers purchased a product in 2009 because they liked the social values of the company that produced it (Stengel, 2009).

Firms

There are two firms indexed 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 it involves a socially responsible activity).[4] 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 $\delta \to 0$.[5]

The green product or "*green technology*" is developed and marketed with a cost of $c(t)$, 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 $e^{rt}c(t)$ decreases in t and that $d^2\left(e^{rt}c(t)\right)/dt^2 > 0$.[6] We also assume that as $t \to \infty$ the cost $c(t)$ tends to zero. As in Katz and Shapiro (1987) we $\int$ 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 the non-adopter.

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

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

Firm $j \neq i$ obtains:

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

[4] This public good aspect of the product forms the basis for what could be a market failure and thereby the rationale for a government intervention.

[5] 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.

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

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 $(L_i(T) + F_i(T))/2$.[7] 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.

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 $c \geq 0$. When a firm adopts the the green technology its marginal cost increases by $\varepsilon > 0$. In order to more fully characterize these profit functions we need to specify the demand functions for the two technologies.

Consumers

We follow Bagnoli and Watts (2003) and consider a continuum of consumers indexed by $i \in [0, 1]$ with measure 1. In each period each consumer buys 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 $x = G, NG$ indicate the consumption of green and standard product, respectively. The term $b(i, Y)$ is a measure of the value to consumer i of the having Y units of green product consumed in the economy ($b(i, Y) \geq 0, b_Y > 0$ and $b_{YY} < 0$). 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. The term $\alpha - i$ indicates the extra value that the particular consumer gets from buying the green version of the product. As α increases the fraction of consumers receiving a private benefit from buying the green product increases. As in Besley and Ghatak (2007) we refer to this particular proportion of consumers as "*caring*" consumers.[8]

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, he 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

[7] 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.

[8] 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.

two marginal consumers: i_G who is indifferent between 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.[9]

If the following condition is satisfied

$$\alpha - a - p_G + 2p_{NG} < 0 \qquad (1)$$

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

$$Q_G(p_G, p_{NG}) = i_G = \alpha - p_G + p_{NG} \qquad (2)$$

$$Q_{NG}(p_G, p_{NG}) = i_{NG} - i_G = a - \alpha - 2p_{NG} + p_G. \qquad (3)$$

Finally, we assume that $a + \alpha > c + \varepsilon$ and that $a > 2c$ to ensure that marginal costs are small enough so that some consumers' willingness to pay for either version exceed 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 new technologies are considered 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 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 $c(t) = K_0 e^{-\lambda t}$ 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

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

Fudenberg and Tirole (1985) and Katz and Shapiro (1987) we define

$$\widehat{T} = \frac{1}{\lambda - r}\log\frac{\lambda K_0}{\pi^G - \pi^0} \qquad (4)$$
$$\widetilde{T} = \frac{1}{\lambda - r}\log\frac{rK_0}{\pi^G - \pi^{NG}}.$$

Intuitively, if firm j never develops and firm i chooses to develop at T its payoff is $L(T)$. $\widehat{T}$ is the date that maximizes $L(T)$, we will refer to this date as *stand-alone date* of development. $\widetilde{T}$ is defined by $L(\widetilde{T}) = F(\widetilde{T})$ and we 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 $\widetilde{T}$. The intuition for this result can be obtained from Figure 1.

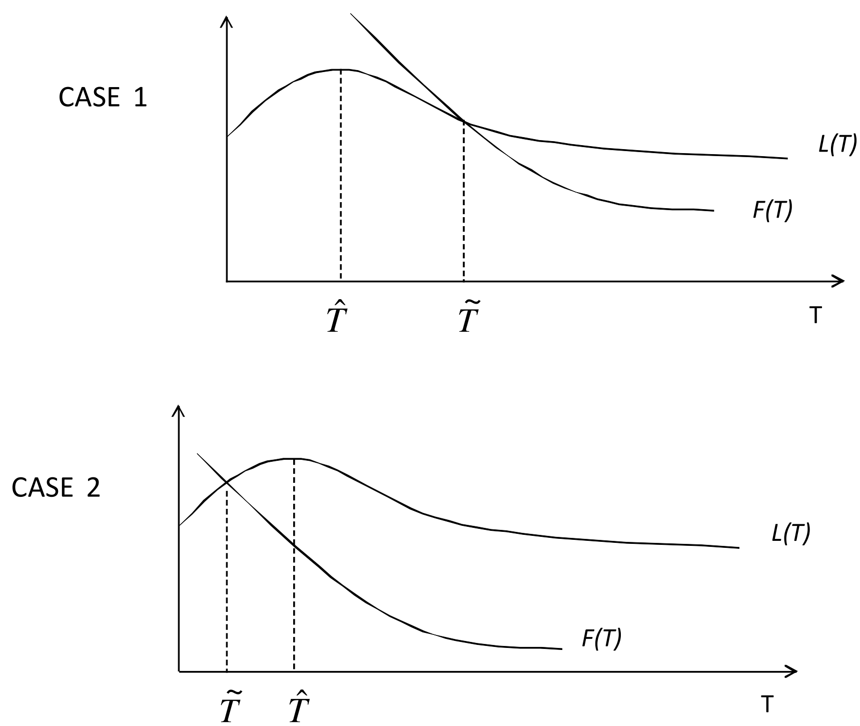

Figure 1: Adoption Time

Let us start by considering Case 1. Adoption cannot occur after $\widehat{T}$ because in this case the adopter has an incentive to anticipate adoption time and obtain a larger payoff. Adoption cannot occur before $\widehat{T}$. To see this suppose the contrary and that firm i adopts at $T^* < \widehat{T}$. In this case firm j should not adopt at that date because $F(T^*) > L(T^*)$. But then firm i could adopt a little later than at T^* and would prefer to do so because $L(T)$ increases for $T < \widehat{T}$. So adoption occurs at $\widehat{T}$ in this case.

Consider now Case 2. Adoption does not occur before $\widetilde{T}$ because if this happens the adopting firm would be better off by waiting or letting the other firm adopt. Adoption cannot occur after $\widetilde{T}$ because in this case the non-adopting firm has an incentive to preempt the adopter and offer the green product at an earlier time. Therefore adoption occurs at $\widetilde{T}$ in case 2.

Bertrand Competition

We analyze now 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 will undercut each other prices. This means that in equilibrium profits are equal to $\pi^0 = 0$.[10] If one firm adopts the green technology the profits for the adopter and non-adopter are respectively:

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

In the next 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 $\widetilde{T}$.*

Three things need to be noted 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 share of caring consumers is 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 $\alpha > \widetilde{\alpha}$ adoption time depends on the rate of technological progress. Specifically, adoption time will be $\widehat{T}$ ($\widetilde{T}$) if

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

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

so that preemption incentives are taken into account only if technological progress is fast enough. When the rate of technological progress is high (large λ) the marginal benefit of waiting is high and therefore the stand-alone time tends to be large. This implies that payoffs are likely to be of the form depicted in Figure 1, Case 2 and preemption leads to adoption before $\widehat{T}$.

Cournot Competition

We analyze now 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 the demand functions that the firms face are obtained by inverting (2) and (3) and 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 the fraction of green consumers is not large enough, firms may find unprofitable to switch to green 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

The first thing to notice is that for $\alpha \leq \alpha^*$ adoption occurs with Bertrand competition but does not occur with Cournot competition. This implies that adoption is not guaranteed when product market competition is relaxed.

We now compare Bertrand and Cournot adoption times in the case in which $\alpha^* \leq \alpha \leq \widetilde{\alpha}$ or $\alpha > \widetilde{\alpha}$ and low technological progress, i.e. (5) holds. In both these cases adoption time occurs at $\widehat{T}$. Let us define as $\widehat{T}^B$ the value of (4) with Bertrand competition and $\widehat{T}^C$ its value with Cournot competition. Next proposition shows that adoption occurs earlier with Bertrand competition.

Proposition 3 *Stand-alone development occurs earlier with Bertrand competition:* $\widehat{T}^{\,B} < \widehat{T}^{\,C}$.

Interestingly, the difference $\pi^G - \pi^{NG}$ is identical in the case of Cournot and Bertrand competition.[11] This implies that $\widetilde{T}$ is the same in both cases.

These results imply that time of adoption of green technology is accelerated with product market competition when the number of caring consumers is 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. (1997, 2001) where firms innovate to escape competition. Differently from these models, our framework highlights how competition interplays with the fraction of "caring consumers": when the number of caring consumers is high and technological progress is fast adoption time is less sensitive to the degree of product market competition.

4 Firm Asymmetries and Timing of Adoption

In this section we focus on the case in which firms compete a la Bertrand and study the impact of firm asymmetries. 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. In this case the two firms will offer an identical product and will undercut each other 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

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

similarly if Firm 2 adopts

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

[11] 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. The population of consumers is described by the paramether 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.

Proposition 4 *If (1) is satisfied there exists* 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.*

The previous proposition shows that we should expect the small firm (the one with larger marginal cost) to adopt the technology when the share for caring consumers is small and the large firm (with lower marginal cost) to adopt when this share is large. Intuitively, when a firm adopts the green technology it can extract additional surplus from the caring consumers. Because the small firm is making no profits with the standard product, it is willing to adopt even if the share of caring consumers is small. On the other hand, by adopting the large firm gives up part of his cost advantage. For this firm therefore adoption is beneficial only if the surplus that can be extracted is large enough, i.e. there are enough caring customers.

The previous proposition also highlights an important difference between our model and the one of Katz and Shapiro (1987). Focusing on a cost-reducing innovation, they show that whenever the innovation has the same impact on the cost structure of the two firms (i.e. ε is the same for the large and the small firm) the large firm tends to be the innovator. Our model suggests that in the case of green-technology this result may not hold and that the presence of a small group of caring consumers encourages development by small firms.

As in the previous section we assume that $C(t) = K_0 e^{-\lambda t}$ with $\lambda > r$. If $\alpha \leq \alpha^{2B}$ 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. In the next proposition we study the impact of an increase in cost asymmetry (parameter c).

Proposition 5 *With Bertrand competition and:*

(i) $\alpha \leq \alpha^{2B}$, $\widehat{T}_2$ *increases in* c *and* $\widetilde{T}_2$ *may increase or decrease in* c. *As* $\alpha \rightarrow \alpha^{2B}$ $\widetilde{T}_2$ *decreases in* c;

(ii) $\alpha > \alpha^{1B}$, $\widetilde{T}_1$ *increases in* c *and* $\widehat{T}_1$ *may increase or decrease in* c. *If* c *and* α *are large* $\widehat{T}_1$ *is more likely to decrease in* c.

Part (i) of the previous proposition shows that when the size of caring customers is small ($\alpha \leq \alpha^{2B}$) the impact of an increase in firm asymmetry on adoption time is ambiguous and depends on the level of technological progress. When technological progress is slow (λ small) Firm 2 is not affected by Firm 1 and an increase in c reduces its incentives to adopt. With fast technological progress (λ high) Firm 1 is willing to adopt and because both its profits as adopter and its profits as non-adopter increase in c, its incentives to adopt may increase or decreases with c. If the share of caring consumers is large enough (α close to α^{2B}) its incentives to adopt increase and adoption time is reduced with an increase in asymmetry.

Part (ii) of the above proposition shows that when the size of caring consumers is large, and technological progress is fast (λ large) an increase in c unambiguously reduces Firm 1's incentives to adopt. With slow technological progress (λ small) the effect is ambiguous. Adoption occurs earlier when the initial level of asymmetry is large enough.

The proposition shows that the impact of firm asymmetry on the time of adoption is generally ambiguous. When the number of caring consumers is small (and Firm 2 adopts in equilibrium) an increase in c has two opposite effects. On one hand it reduces the profits of the small firm; this reduces its incentives to adopt and delays the switch to the green technology. On the other hand, an increase in c increases the profits that the large firm can make with the green technology and raises the incentives to adopt for that firm. If this second effect is strong enough the equilibrium adoption time decreases in c. When the number of caring consumer is large (and Firm 1 adopts in equilibrium) the impact is still ambiguous. The increase in profits for the big firm increases its incentives to adopt, the reduction in profits for the small firm reduces the need for preemption.[12] With fast technological progress (λ large) preemption motives are muted and equilibrium adoption time increases with c.

5 Policy Implications

In this section we introduce various government policies and evaluate their effect on the time of green technology adoption. We start with examining policies which act on consumers and then we examine policies which act directly on firms.

[12] More precisely, an increase in c increases both π_1^G and π_1^0. The effect on π_1^G dominates when the green market is very attractive (α is very large).

Consumer Subsidies

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:

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

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

Formulas (6) and (7) show that the impact of a subsidy is equivalent to an increase of s in the share of caring consumers. The subsidy increases the amount of surplus that the green technology adopter can extract from the consumers and it induces earlier adoption. In addition, the presence of a subsidy increases the range of parameters in which both firms are better off by being the adopter. The next proposition summarizes these findings.

Proposition 6 *When firms are symmetric ($c = 0$) a consumer subsidy increases preemption incentives and both $\widehat{T}$ and $\widetilde{T}$ decrease in s but the impact is greater on the preemption time than on the optimal times, i.e., $\left|\partial\widetilde{T}/\partial s\right| > \left|\partial\widehat{T}/\partial s\right|$.*

In the above proposition we study how the effect of the subsidy varies with the speed of technological progress. Interestingly, the impact is greater when the speed of technological progress is fast. The presence of a subsidy increases the profits of the adopter and reduces those of the non-adopter. This implies that the effects of the subsidy are going to be stronger when there is preemption and the profits of the non-adopter are taken into account in the timing decision. Because preemption is more likely when technological progress is fast, the impact of a subsidy will be stronger in that case.

Finally we 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.

Observation 1 *If firms are asymmetric and α is small, a large subsidy to the consumers can change the identity of the adopting firm.*

The intuition for the previous result is the following. In section 4 we noticed that when the fraction of caring consumers is small the large firm has no incentive to adopt and the small firm will sell the green product. The presence of a subsidy may increaseso much the surplus that can be extracted from the caring consumers that it may render appealing the green technology to the large firm and it may induce it to preempt the small one. This may be a socially desireable outcome as the adopting firm is the more efficient producer.

Observation 2 *When technological progress is slow (fast) a consumer subsidy reduces the time of adoption of the smaller firm by more (less) than the adoption time of a larger firm.*

The above observation is due to the fact that a consumer subsidy has a stronger impact on the profits of the small firm than on those of the big firm. This implies that there will be a greater reduction in adoption time when the small firm adopts without considering the presence of the large one ($\widehat{T}_2$) or when the large firm adopts preempting the small one ($\widetilde{T}_1$).

Finally, we investigate whether an increase in firm asymmetry renders the policy more or less effective. The next result shows that asymmetry has an ambiguous impact on the efficacy of the policy.

Observation 3 *An increase in firms asymmetry may amplify or reduce the impact of a per-unit subsidy.*

There are various effects that determine whether the impact of the subsidy is greater or smaller when we increase firm asymmetry. First, because asymmetry may increase adoption time its impact may go in the opposite direction of the one of the subsidy. Second, the asymmetry may increase or decrease the impact of the subsidy on $\pi_i^G - \pi_i^{NG}$ and $\pi_i^G - \pi_i^0$. In the appendix we show that it is not possible to unambiguously sign the cross-partial derivative of stand-alone or preemption times. Nonetheless, we can obtain an indication of the settings in which the subsidy is less effective. For example, when Firm 1 adopts and its stand alone time increases in c (α is not too large) then the impact of the subsidy is muted by asymmetry. The same happens when Firm 2 adopts and $\widetilde{T}_2$ increases in c.

Consumer Education

Another policy espoused as a measure to accelerate the adoption of green technologies is a consumer education campaign. Under this policy the government would devote resources to advertising to make consumers aware of the benefits associated with the use of green technologies. In our model this would have the effect of increasing the fraction of caring consumers, α. Formulas (6) and (7) show that 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, the impact of this policy will be stronger when technological progress is fast. Moreover, if the policy increases dramatically the fraction of caring consumers (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. We now shift to examining supply side policies.

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 a lump-sum subsidy can be modeled 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: $c(t) = K_0 e^{-\lambda t} - F$. 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 7 *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 much lower than $\widetilde{T}$, a lump sum subsidy may be ineffective.

Finally, we turn to the analysis of subsidies per product sold. These next results show that the effect is identical to the one of a consumer subsidy so the results in the previous section applies.

Observation 4 *A subsidy per product sold (decrease in ε) is equivalent to a per consumer subsidy (increase in α).*

Differently from consumers' subsidies, producer subsidies may be targeted to a specific firm. In the next proposition we show that when firms are asymmetric a subsidy targeted to the small firm may back-fire and induce the large firm to anticipate adoption.

Observation 5 *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 considers 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 large 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, it is effective in inducing earlier adoption by the nonsubsidized firm.

Policy Comparisons and Public Good Provision

Focusing on the symmetric case ($c = 0$) we now compare the effect of the different policies. 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 $c(t)$).

An example of the first type of policies is the Car Allowance Rebate System (CARS) that subsidizes consumers to purchase fuel efficient vehicles when trading in less fuel efficient vehicles. We argued 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 that 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 it does not affect marginal revenues and marginal costs of green-products. In our framework these policies can be modeled 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 6 *There exists a K^* such that if $K_0 > K^*$ a reduction in K_0 has 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.

So far, we only investigated the impact of the different policies on adoption time. Policies affecting α or ε differ from policies affecting $c(t)$ in another aspect. The next proposition shows that when the proportion of caring consumers is large enough, policies that increase α (consumer subsidy and consumer education) or reduce ε (per product sold subsidy) unambiguously lead to more efficient public good provision.[13] The proposition also shows that the result does not depend on the regime of product market competition (i.e. it is valid both with Cournot and Bertrand competition).

Proposition 8 *With Bertrand competition and $c = 0$ if $a/4 + \varepsilon < \alpha$ consumer subsidies, consumer education and per-product sold firm subsidies always lead to a more efficient level of public good provision. If $a/4 + \varepsilon > \alpha$ these policies lead to a more efficient level of public good provision only if externalities are sufficiently large. In addition, whenever there is underprovision of public good with Bertrand competition there is also underprovision under Cournot competition.*

This result has an important implication: policies affecting the profits of the adopting firm allow policy makers to kill two birds with one stone. In fact these policies not only anticipate adoption but also reduce the under-provision of public good. Conversely, policies targeted toward a reduction in the adoption costs, because they do not affect per-period profits do not alter the level of public good provision.

[13] As in Bagnoli and Watts (2003) we define the efficient level of green products as the amount for which the marginal social benefits are equal to the marginal social costs.

Even though a full welfare comparison of the different policies is outside the scope of our paper, Proposition 8 provides useful insights on how a social planner may maximize welfare in our environment. Let us indicate with W^0 the (static) social welfare in the absence of adoption and as $W^G(s)$ the (static) social welfare with green technology adoption where s is a per-product firm subsidy (reduction in ε).[14] If externalities are large enough, there will be underprovision of green products and $dW^G(0)/ds > 0$. Let us denote with s^* the level of subsidy that maximize the static welfare: i.e. $dW^G(s^*)/ds = 0$. It is important to note that per-product subsidies affect not only the quantity of green products produced but also the timing of adoption. Specifically, if the only policy instrument used by the social planner is a per-product subsidy, his objective function is

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

that generates the following first order condition

$$\frac{dT(s)}{ds}\left[e^{-rT(s)}(W^0 - W^G(s)) - \frac{dC(T(s))}{dT}\right] + \frac{e^{-rT(s)}}{r}\frac{dW^G(s)}{ds} = 0. \tag{8}$$

Condition (8) illustrates the two problems faced by the social planner in our environment. The first part of the formula is related to the fact that the time of adoption that firms choose non-cooperatively may differ from the one maximizing total welfare (when externalities are large enough adoption occurs too late). The second part of the formula captures the idea that when externalities are large enough firms under-produce the green product. The expression in (8) also suggests a very simple way in which the planner can maximize social welfare: by using a combination of per-product subsidies and adoption cost subsidies (reduction in K). Specifically the planner can set a subsidy equal to s^* so that the provision of green products is optimal from a static perspective. Then the socially optimal adoption time, T^*, will be determined by:

$$\max_T \frac{1-e^{-rT}}{r} W^0 + \frac{e^{-rT}}{r} W^G(s^*) - C(T) \tag{9}$$

Using adoption cost subsidies, the planner will be able to implement the optimal adoption time, T^*, without affecting the level of green product provision.

[14] In our model the static social welfare is computed by integrating the utility of the consumers and subtracting the cost of production. Specifically if externalities are identical across consumers (i.e. $b(i,Y) = b(Y)$) :

$$W^G(0) = \int_0^{i_G} (I + b(i_G) + \alpha - x + a - x)dx + \int_{i_G}^{i_{NG}} (I + b(i_G) + a - x)dx + \int_{i_{NG}}^{1} (I + b(i_G))dx - \varepsilon i_G.$$

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.

Diffused Adoption

In our baseline model, following Katz and Shapiro (1987) we assumed 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 ($c(t)$,s 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:

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

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 as 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.[15]

Notice that a necessary condition to have diffused adoption is to that $\pi^D > \pi^{NG}$. If this does not happen the second firm will never find 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 9 *A policy accelerates the adoption of green technologies if it increases both $\pi^G - \pi^{NG}$ and $\pi^D - \pi^{NG}$. It slows down adoption if it decreases $\pi^G - \pi^{NG}$ and $\pi^D - \pi^{NG}$.*

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

There are a series of implications that can be derived from the previous proposition. First, the impact of consumer subsidies, consumer education and per-product sold firm subsidy generalize to this environment as long as the policies increases the difference between adoption (diffused and unique) and non-adoption profits.[16] Secondly, the proposition suggests that policies that increase π_{NG} have unambiguously 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. Thirdly, differently from the unique adoption case described in the previous section, a lump sum subsidy conditional on adoption is never effective in this environment. The intuition is that when adoption is unique a preempting firm is indifferent between adoption and non-adoption and therefore compares sustaining the adoption cost with not sustaining the cost. With joint adoption a firm compares sustaining the cost early with sustaining the cost late, and this cancels out the effect of any lump sum subsidy at the time of adoption. [17]

Finally, this extended model suggests a role for antitrust authorities in enforcing green technology adoption. By relaxing their standards after the green technology has been adopted (e.g. increasing π^D) they may accelerate the timing of adoption. On the other hand, results presented in section 3 suggest that greater competition in the non-green technology market may speed up technology adoption. The combination of these two results indicates that a stricter enforcement of competition among non-green companies and a more lenient enforcement among green companies may accelerate the timing of adoption.

Asymmetry in Green Product Production Costs

In the baseline model we assumed that when a firm adopts the green technology its marginal cost increases by $\varepsilon > 0$. 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 the 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 10 *If (1) is satisfied 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.

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[16] 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.

[17] This follows from formula (11) where any costant term in the cost function cancels out in the difference $c(t) - c(\widehat{t_2})$.

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, as in Observation 5, the policy is more likely to backfire when technological progress is fast (λ large).

7 Conclusions and discussion

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. Second, the green technology product has a public good component and generates positive externalities to non-consumers. Third, we consider consumers with differing willingness' to pay for the green product.

We have shown that more intense product market competition leads to earlier adoption of green technology. Then, focusing on Bertrand competition, we have studied the impact of firm asymmetries and find that the identity of the adopting firm depends on the share of "caring consumers" - the small (large) firm adopts when this share is small (large). We also show that an increase in firm asymmetry as an ambiguous impact on adoption time.

We then tested the effect of different public policies on adoption time. Our model illustrates a distinction between policies that increase the mark-up of green products (consumer subsidies, consumer education and per-product firm subsidies) and policies that reduce the cost of adoption (R&D subsidies). The second group of policies only anticipates adoption, whereas policies in the former group have two effects: they anticipate the time of adoption and they increase the provision of public good. We also show that, in the presence of preemption incentives, a subsidy targeted to small firms, while not directed at the adopter, may still induce large firms to adopt earlier. Finally, we discuss how differential anti-trust treatment of green and nongreen producers can accelerate adoption but contribute to the underprovision of green production.

There are a number of other policy measures which we do not examine here but can be accommodated with an extension of the above framework. For example, in the U.S. automakers must meet certain goals for the gas mileage of the fleet sold and if they do not meet these criteria then a tax is levied. This, in essence, is the reverse of a subsidy for producing the green technology and as the policy concerns the entire portfolio of cars sold by a company it can encourage both firms to adopt the green technology and raise the costs of both. While, in the context of our model, this may be inefficient in an allocative sense it does mitigate the underproduction of the public good issue. Another possible policy is regulation as per that proposed in California which requires that automakers reduce their fleetwide CO_2 emissions of cars sold in the state. Again this has the effect of inducing both firms to produce some green product and at least one, and possibly both, firms may produce green products and regard it only as a cost of being able to sell nongreen products. Both of these measures may have the unanticipated consequence of delaying the adoption of a green technology, e.g., until the last moment dictated by the regulation which may be later than the time for one firm to adopt at the equilibrium timing.

This study can be extended in a number of ways. One potentially fruitful line of research is to include the possibility of successive innovation. That is, even better green technologies may appear in the future allowing followers to leapfrog leaders. Clearly, this would reduce the incentive to adopt first as the period over which monopolistic rents can be obtained in the green technology market will be limited and the leader could find itself locked into an inferior technology. This could have the effect of delaying adoption albeit green technologies would ultimately be more diffused. Another possible avenue for research would be the incorporation the negative effects of the subsidy - the distortion effects. Such distortion effects would be larger with the size of the public outlay. Furthermore, some provision should be made for the timing of the outlay subsidies of the costs of firms may be earlier than those which subsidize consumer purchases. Also for a more complete accounting of the welfare effects, however, one should also consider the benefits of adoption of the green technology on the entire population which may be larger than just those consumers in the market portraited.

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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 $\pi^G - \pi^0 > 0$ 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 $\left(\pi^G - \pi^0\right)^{Cournot}$ the difference between π^G and π^0 with Cournot competition and $\left(\pi^G - \pi^0\right)^{\text{Bertrand}}$ the difference with Bertrand competition. We have that

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

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 $a > 1$.

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

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

These payoffs imply that $\pi_2^G - \pi_2^{NG} > \pi_1^G - \pi_1^{NG}$ as long as $\alpha \leq \alpha^{2B} = 11/23\left(a - c/2\right) + \varepsilon$. In addition $\pi_2^G - \pi_2^0 > \pi_1^G - \pi_1^0$ if $\alpha < \alpha^{1B} = 13/10a - 22/15c + \varepsilon$. 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.

Proof of Proposition 5

For the first part of the proposition note that when Firm 2 sells the green product the quantity provided is $Q_G(p_G, p_{NG}) = i_G = (a - 3c + 3\alpha - 3\varepsilon)/7$ that is positive as long as $a > 3c - 3(\alpha - \varepsilon)$. Second notice that the derivative

$$\frac{\partial}{\partial c}\left(\pi_1^G - \pi_1^{NG}\right) = \frac{4}{49}(c - a + 4\alpha - 4\varepsilon)$$

is negative if α is close to zero and positive if $\alpha = \alpha^{2B}$. The derivative

$$\frac{\partial}{\partial c}\left(\pi_2^G - \pi_2^0\right) = \frac{6}{49}(3c - a - 3\alpha + 3\varepsilon)$$

is negative if $\alpha \leq \alpha^{2B}$ and $a > 3c - 3(\alpha - \varepsilon)$.

For the second part of the proposition, note that when Firm 1 provides the green product the quantity of green product provided is $Q_G(p_G, p_{NG}) = i_G = (a + 2c + 3(\alpha - \varepsilon))$ always positive if that is positive. Second notice that the derivative

$$\frac{\partial}{\partial c}\left(\pi_2^G - \pi_2^{NG}\right) = \frac{6}{49}(3a - 3c - 5\alpha + 5\varepsilon)$$

is negative when $\alpha > \alpha^{1B}$. Finally, the derivative

$$\frac{\partial}{\partial c}\left(\pi_1^G - \pi_1^0\right) = \frac{106}{49}c - \frac{45}{49}a + \frac{12}{49}\alpha - \frac{12}{49}\varepsilon$$

has ambiguous sing. The derivative is positive if c and α are large.

Proof of Proposition 6

In equilibrium the 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. Furtheromore,

$$\frac{\partial \widehat{T}}{\partial s} = -\frac{1}{\lambda - r}\frac{1}{\pi^G}\frac{\partial \pi^G}{\partial s}$$

and

$$\frac{\partial \widetilde{T}}{\partial s} = -\frac{1}{\lambda - r}\frac{1}{\pi^G - \pi^{NG}}\frac{\partial (\pi^G - \pi^{NG})}{\partial s}.$$

The result follows because $\left|\partial \pi^G/\partial s\right| < \left|\partial (\pi^G - \pi^{NG})/\partial s\right|$ and because $\pi^G - \pi^{NG} < \pi^G$.

Proof of Observation 1

Formulas (6) and (7) imply that a consumer subsidy has the same impact of an increase of s in the fraction of caring consumers 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 Observation 2

Notice that

$$\begin{aligned}
\frac{\partial}{\partial \alpha}\left(\pi_2^G - \pi_2^{NG}\right) &= \frac{2}{7}(a - \frac{15}{7}c + \alpha - \varepsilon) > 0 \\
\frac{\partial}{\partial \alpha}\left(\pi_1^G - \pi_1^{0}\right) &= -\frac{6}{49}(a + 2c + 3\alpha - 3\varepsilon) > 0 \\
\frac{\partial}{\partial \alpha}\left(\pi_1^G - \pi_1^{NG}\right) &= \frac{2}{7}(a + \frac{8}{7}c + \alpha - \varepsilon) > 0 \\
\frac{\partial}{\partial \alpha}\left(\pi_2^G - \pi_2^{0}\right) &= \frac{6}{49}(a - 3c + 3\alpha - 3\varepsilon) > 0.
\end{aligned}$$

that implies $\frac{\partial}{\partial \alpha}\left(\pi_2^G - \pi_2^{NG}\right) > \frac{\partial}{\partial \alpha}\left(\pi_1^G - \pi_1^{NG}\right)$ and $\frac{\partial}{\partial \alpha}\left(\pi_2^G - \pi_2^{0}\right) > \frac{\partial}{\partial \alpha}\left(\pi_1^G - \pi_1^{0}\right)$,which implies,respectively, $\left|\frac{\partial \widetilde{T_1}}{\partial \alpha}\right| > \left|\frac{\partial \widetilde{T_2}}{\partial \alpha}\right|$ and $\left|\frac{\partial \widehat{T_2}}{\partial \alpha}\right| > \left|\frac{\partial \widehat{T_1}}{\partial \alpha}\right|$.

Proof of Observation 3

Note that

$$\begin{aligned}
\frac{\partial^2 \widehat{T}_i}{\partial s \partial c} &= \frac{1}{\lambda - r}\frac{1}{\pi_i^G - \pi_i^0}\left(\frac{\partial\left(\pi_i^G - \pi_i^0\right)}{\partial s}\frac{\partial\left(\pi_i^G - \pi_i^0\right)}{\partial c} - \frac{1}{\lambda - r}\frac{1}{\pi_i^G - \pi_i^0}\frac{\partial^2\left(\pi_i^G - \pi_i^0\right)}{\partial s \partial c}\right) \\
\frac{\partial^2 \widetilde{T}_i}{\partial s \partial c} &= \frac{1}{\lambda - r}\frac{1}{\pi_j^G - \pi_j^{NG}}\left(\frac{\partial\left(\pi_j^G - \pi_j^{NG}\right)}{\partial s}\frac{\partial\left(\pi_j^G - \pi_j^{NG}\right)}{\partial c} - \frac{1}{\lambda - r}\frac{1}{\pi_j^G - \pi_j^{NG}}\frac{\partial^2\left(\pi_j^G - \pi_j^{NG}\right)}{\partial s \partial c}\right).
\end{aligned}$$

Moreover we have that

$$\begin{aligned}
\frac{\partial^2(\pi_1^G - \pi_1^0)}{\partial s \partial c} &= \frac{12}{49} > 0 \\
\frac{\partial^2(\pi_2^G - \pi_2^{NG})}{\partial s \partial c} &= -\frac{30}{49} < 0 \\
\frac{\partial^2(\pi_2^G - \pi_2^0)}{\partial s \partial c} &= -\frac{18}{49} > 0 \\
\frac{\partial^2(\pi_1^G - \pi_1^{NG})}{\partial s \partial c} &= \frac{16}{49} > 0.
\end{aligned}$$

Using the results developed in the previous section on the derivatives of profits respect to c and s it is easy to see that it is not possible to sign unambigously any of the cross-partial derivatives.

Proof of Proposition 7

First, note that the formula for $\widehat{T}$ is obtained from the maximization of $L(T)$ and it 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

$$\frac{e^{-r\widetilde{T}^{LS}}}{r}\pi^G - \frac{e^{-r\widetilde{T}^{LS}}}{r}\pi^{NG} - K_0 e^{-\lambda \widetilde{T}^{LS}} = -F. \tag{10}$$

Notice that at $\widetilde{T}$ the left hand side exceeds the right hand side. Because $L(T) < F(T)$ (the right hand side of (10) is negative) when $T < \widetilde{T}$ and $L(T) > F(T)$ (the right hand side of (10) 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 4

The result follows from the following derivatives:

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

Proof of Observation 5

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 6

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 8

First, following Bagnoli and Watt (2003) it is easy to show that because the cost of providing an additional unit of green product is ε the socially efficient level of provision equal to consumer i^* that satisfies $\varepsilon = \alpha - i^* + \int b_Y(i, i^*)di$. In our model $i_G = (a + 3(\alpha - \varepsilon))/7$. It is easy to see that if $a/4 + \varepsilon < \alpha$ it is always the case that $i^* > i_G$. If the condition is not satisfied there is underprovision as long as externalities are large enough. Because policies that increase α and decrease ε push i_G toward i^* there is more efficient provision of public good. In a Cournot duopoly the quantity of green product provided is $q_G = (a + 2(\alpha - \varepsilon))/7$ that is lower than i_G. Therefore whenever there is undeprovision with Betrand competition there is also underporvision with Cournot competition. In the Cournot case it is also necessary that $\alpha > \alpha^* \equiv \left(\frac{7}{12}\sqrt{2} - \frac{1}{2}\right) a + \varepsilon$ that is the minimum level of caring consumers required to have provision of green products.

Proof of Proposition 9

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:

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

The function $-e^{rt}c'(t)$ is decreasing in t because we assumed that $(c(t)e^{rt})'' > 0$. 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:

$$\begin{aligned} L(t) &= F(t) \\ \frac{\pi^G - \pi^{NG}}{r} &= \frac{c(t) - c(\widehat{t}_2)}{e^{-rt} - e^{-r\widehat{t}_2}}. \end{aligned} \tag{11}$$

Let us indicate as $g(t)$ the right hand side of (11). The sign of $g'(t)$ is equal to the sign of $c'(t) + c'(t)e^{-r(t_2^* - t)} + rc(t) - rc(t_2^*)$ that is negative because $c(t)e^{rt}$ decreases in t. This implies that the right hand side of (11) 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 (11) decreases so that adoption will occur at a larger value of t.

Proof of Proposition 10

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_1 increases $\widetilde{T}_1$ and a reduction in ε_2 reduces $\widetilde{T}_1$.