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Direct and indirect subsidies in markets with system goods in the presence of externalities
Preliminary Version

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Abstract

This paper derives a model of markets with system goods and two technological standards. An established standard incurs lower unit production costs but causes a negative externality. The paper derives the conditions for policy intervention and compares the effect of direct and indirect cost-reducing subsidies in two markets with system goods in the presence of externalities. If consumers are committed to the technology by purchasing one of the components, direct subsidies are preferable. For a medium-low cost difference between technological standards and a low externality cost it is optimal to provide a direct subsidy only to the first technology adopter. As the higher the externality cost raises, the more technology adopters should be provided with direct subsidies. This effect is robust in all extensions.

In the absence of consumers' commitment to a technological standard indirect and direct subsidies' are both desirable. In this case, the subsidy to the first adopter is lower then the subsidy to the second adopter. Moreover, for the low cost difference between technological standards and low externality cost the first firm chooses a superior standard without policy intervention. Finally, a perfect compatibility between components based on different technological standards enhances an advantage of indirect subsidies for medium-high externality cost and cost difference between technological standards.

Journal of Economic Literature Classification Numbers: C72, D21, D40, H23, L13, L22, L51, O25, O33, O38.

Keywords: Technological standards; complementary products; externalities; cost-reducing subsidies; compatibility.

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1 Introduction

The adoption of disruptive technologies[1] has recently gained much attention among policy makers. Large funds are destined in order to enhance firms' incentives for adoption of costly emerging technologies. The principal concern of policy makers are markets with externalities, such as environmental impact or national security. In many cases, products in such markets are system goods. This means that consumers derive value from the entire system of components (as for example, mutually compatible charging systems and vehicles, or hardware and software). The set of components that are compatible with one another is determined by firms' choices of technological standards. However, once there is an established technological standard, the transition to superior technologies is often impeded for several reasons. First, there might be a production cost difference between an established and a superior technological standard. For instance, firms can have previous commitments that raise production cost in case of switching to a different standard, which makes the adoption of a superior technological standard unprofitable. Second, once there is an established technological standard, firms might insufficiently engage into the development of other potentially superior technologies. Therefore, the adoption and development of new technologies and products in markets for system goods often depends on public intervention.

The US, the EU, Japan and BRIC countries are especially active in setting policies towards faster technology adoption. For instance, regarding environmental performance, the US provide subsidies to clean technology adopters, car manufacturers and consumers. EU countries introduce high fuel taxes, emission standards for different types of vehicles and the cap-and-trade system, which sets a pollution limit (or cap) allocated to firms in the form of emission permits. Brazil's policy is focused on providing tax reductions and subsidies to the producers of alternative fuels. Similarly to Europe, China applies emission standards and incentive programs, based on funding to support R&D and public procurement of vehicles with low fuel consumption. Japan provides subsidies to consumers of eco-friendly vehicles. Because public funds are scarce, most governments destinate subsidies to particular groups of market players in order to induce the adoption of superior technologies.

As an example for existing policy interventions in these countries consider the market for motor vehicles. The transition to a superior technology (biofuel and electric vehicles) in this market eliminates a negative environmental externality related to the use of an established technology (internal combustion engine vehicles). However, the superior technology implies higher unit production costs. For instance, due to the cost of an electric battery the total cost of an electric vehicle is raised by \$12,000 compared to internal combustion engine vehicles.[2] Therefore, once there is an established combustion technology, car manufacturers have few incentives to switch to a superior technology. In addition, because of complementarity between vehicles and charging systems, consumers value a vehicle that is compatible with a larger charging infrastructure. Accordingly, a larger charging infrastructure is deployed for a specific technology if demand for this technology is expected to be higher. As a result, the producers of complementary components have few incentives to adapt their components to the superior technology. Finally, the level of private R&D associated to a superior technology is considered to be suboptimal as car motor producers find it more profitable to improve the performance of an already established technology. Together, all these factors impede the diffusion of electric or biofuel vehicles in the absence of public intervention.

In order to address this problem, high subsidies are provided directly to vehicle manufacturers or indirectly to providers of complementary components (such as energy and fuels) and charging infrastructure deployment. For instance, in 2009 the US-based car manufacturers, namely, Ford Motor, Nissan Motor and Tesla Motors, were awarded \$8.5bln. (2.2% of the total US R&D budget) in direct loans as assistance in transition from internal

[1] A disruptive technology is an innovation that disrupts an existing market and replaces an earlier technology creating a new market.

[2] Federation of American Scientists, Cannis B. (March 2011): "Battery Manufacturing for Hybrid and Electric Vehicles: Policy Issues".

combustion engines to electrified vehicles under the Advanced Technology Vehicles Manufacturing (ATVM) Loan Program. In Brazil, since 1975 the use and production of biofuels (especially, ethanol) were subsidized. Lately, European countries (Germany, France, Denmark, etc.) announced plans of investments into the deployment of charging infrastructure and R&D activities aimed at cost-reduction of electric vehicles. However, in the context of the stimulation of disruptive technology adoption it is still an open issue whether indirect or direct subsidies perform better. For example, Brazil indirectly stimulates the transition to biofuel vehicles. Historically, Brazil depended exclusively on imported fuel, therefore the promotion of in-house ethanol production was launched as a security policy, which later was transformed into an environmental policy. On the contrary, direct subsidies to car manufacturers were chosen in the US. Although, the project of the American Clean Energy and Security Act (ACES 2009) proposed indirect subsidies ($90bln. by 2025) to producers of clean energy technologies (biofuels, electricity generation). This project has not been approved by now, although in 2011 the vast majority of energy subsidies ($24 billion) was spent on renewable energy ($16 billion) according to a government report.[3]

This paper considers the case when both technological standards, the established and the superior, are potentially available and explores firms' incentives for transition from an established technological standard to a superior technological standard. The product is a system good. The components of this good are produced in two markets. The market, in which technological standards are chosen, is imperfectly competitive. Firms act strategically choosing the technological standard for production of their component and the price. The superior technological standard involves a higher unit production cost though a lower negative externality (or a higher positive externality). The market, in which the complementary component is produced, is perfectly competitive. Firms produce their product using an established or a superior technological standard at the same unit production cost. Consumers' purchasing decisions depend on both components' prices and firms' choices of technological standards. It is shown that without policy intervention firms have no incentives to adopt the superior standard. Consequently, we address the design of optimal policies for transition to a superior standard. In particular, we focus on cost-reducing subsidies that can be given to the components' producers that choose a standard or to the producers of a complementary component. The first subsidy directly affects the production cost of firms that adopt a superior technological standard (*direct subsidy*). The second subsidy indirectly affects the firms' incentives for adoption of a superior technological standard by reducing the production cost of an associated component (*indirect subsidy*). The model analyzes welfare implications of direct and indirect cost-reducing subsidies in markets for system goods in the presence of externalities associated to technological standards.[4]

The results in this paper provide a rationale for the implementation of direct or indirect subsidies that enhance firms' incentives for transition to a superior technology. The conditions for optimal subsidies are indicated depending on the cost difference between standards, the externality cost and the presence of consumers' "commitment" to a determined technology. If consumers' purchasing decision is made before the prices of one of the components of the system good are known, policy intervention is desirable only when the externality cost is not lower than the cost difference between standards. Then, if the externality cost is relatively similar to the cost difference between standards, it is optimal to give a direct subsidy to provide incentives for the transition to the superior standard only to the first technology adopter. As the externality cost raises, more technology adopters must be provided with subsidies. This means that in case of direct subsidies, both technology adopters should be given a direct cost-reducing subsidy per unit of production if using the superior standard. In case of indirect subsidies, the necessary amount of cost-reducing subsidies should be given to the producers of the complementary component per volume of production using the superior standard. The comparison between direct and indirect subsidies suggests that if the cost difference between technological standards is high and the

[3] CNN Money, the Congressional Budget Office USA.

[4] See also Green and Sheshinki (1976), who point out that the presence of substitutes and complements for an externality-causing commodity allows to treat the externality indirectly through the market for related goods.

externality is low or intermediate, direct subsidies are socially preferable. If the externality cost is high and the technology cost difference is low, direct and indirect subsidies perform equally. However, because the optimal indirect subsidy is higher than the direct subsidy, the direct subsidy leads to higher social welfare. If consumers' purchasing decision is made after the prices of all components of the system good are known, the effects of indirect and direct subsidies' are equal. In this case, if the production cost difference is low, the first adopter might have natural incentives to adopt the superior technology. This means that the adoption of the superior technology implies a lower cost for society. If the production cost difference is high, the adoption requires direct or indirect subsidies. Moreover, the subsidy to the second adopter is higher than the subsidy to the first adopter. Finally, compatibility between components based on different technological standards enhances an advantage of indirect subsidies when both the externality cost and the cost difference between an established and a superior technological standard are high.

These results add to the discussion on the choice between direct and indirect subsidies in the markets for system goods. To illustrate this, recall the cases of Brazil and of the US described above. In Brazil, the in-house ethanol production was launched in 1975 due to the highly important environmental and national security concerns. As a result of this policy, by the year 1990, 90% of vehicle manufactures in Brazil used technology allowing to power vehicles by alcohol. According to the results in the present paper, this technology adoption policy is more costly for society in the presence of consumers' "stickiness" to technology, i.e. if consumers are a priori restricted to using the superior or the established technology. In this case indirect subsidies are efficient because at the beginning of new automobile technology adoption consumers by choosing a car are conditioned by the availability of all related infrastructure in their urban area (charging and service stations, parking area). On the contrary, when the infrastructure for both technologies is installed and consumers can make their purchasing decision after the prices for all components are known, both subsidies perform equally. In the US, direct subsidies to car manufacturers were chosen. According to our results, this is the optimal solution at the beginning of superior technology adoption. However, once the infrastructure for both technologies is installed (in other words, in the absence of consumers' "stickiness" to technology), indirect subsidies to producers of clean energy technologies (biofuels, electricity generation) should also be implemented. Similarly, the importance of indirect subsidies is expected to grow in the EU. For example, recently, the deployment of a charging infrastructure all over Europe has been debated. The results of the paper are discussed in the context of optimal subsidy choice to enhance environmental performance in the markets for system goods. However, the results also provide a rationale for optimal subsidy choice in other markets with technology-related externalities, such as national security, for example.

This paper is tightly related to two strands in the literature analyzing technology adoption under different market structures and externalities. The first strand analyzes technology adoption in markets when different technological standards are available. Standards arise in two ways. First, different technologies can be incompatible with each other. Second, producers of the standards can intentionally design technologies to be incompatible. Therefore, the main driving force of technology adoption in such models is compatibility between products chosen by firms. Katz and Shapiro (1992), Regibeau and Rocket (1996), Kristiansen (1998) analyze the timing of product introduction and compatibility between products. Higher compatibility strengthens firms' R&D incentives, which leads to a welfare improving timing of new product introduction. Matutes and Regibeau (1988) show that in a duopoly firms choose full compatibility as an optimal strategy. Moreover, although full compatibility leads to higher prices than incompatibility, it also increases the variety of systems available so that some consumers are better off with compatibility, while others are hurt. The occurrence of standards is tightly related to the presence of network effects, direct or indirect.[5] When a direct network effect is present

[5] The direct network effect means that an increase in the number of consumers directly increases the value for all consumers of the good. The indirect network effect means that an increase in the number of consumers leads to an increase in the value

the size of the installed base positively affects the new standard adoption (Farrel and Saloner, 1986). When an indirect network effect is present, an increase in variety of used technological standards is socially desirable (Church et al, 2008). However, this literature does not provide an insight to the problem of superior technology adoption that arises when the network effect is absent or weak, and the technology adoption is impeded due to the complementarity between components of the system.

The second strand of the literature concerns the choice of optimal policy instruments to address negative externalities, especially, an environmental externality. That regulation affects firms' R&D activities aimed at pollution abatement and development of superior technologies is supported by numerous empirical studies.[6] The theoretical literature discusses the advantages and failures of common policies (subsidies and taxes) and environmental policies (emission and performance standards, tradeable and auctioned permits). The effect of these policies depends on market structure and consumers' preferences for goods. Sartzetakis and Tsigaris (2005) find that in the presence of a direct network effect the tax necessary to induce adoption of a cleaner technology is very high. If tax revenues are earmarked towards subsidizing a cleaner technology, the tax is lower than in the previous case and can be set equal to the marginal external damage. Bansal and Gangopadhyay (2003) compare uniform policies (applied similarly to all firms) and policies that discriminate between firms based on their environmental quality. According to their findings, in the presence of consumers awareness of the externality, uniform as well as discriminatory subsidies reduce total pollution and enhance social welfare. Petrakis and Poyago-Theotoky (1997) argue that technological policies such as R&D subsidies and R&D cooperation would generally lead to increased pollution and thus have a negative environmental impact. However, most of the papers mentioned above analyze firms' abatement costs rather than a technological standard choice. An exception is Conrad (2006) who focuses on the problem of the adoption of a cleaner technology in the car market when a direct network effect impedes the technology adoption. He suggests a cost subsidy for the cleaner technology adopters, or, alternatively, the promotion of clean technologies among consumers through advertisement campaigns.

Despite the extensive literature on technology adoption the present paper offers new insights. It differs from the existing literature in two respects. First, it explores the firms' technological standard choice when the network effect is weak or absent. Instead, technology adoption is prevented by the high cost of the superior technology. This provides a benchmark for the firms' strategic choices in markets for system goods when the direct and indirect network effects do not play a crucial role, as for instance, in the vehicle market. Second, it introduces an externality associated to one of the standards. This allows to derive some relevant policy implications.

The reminder of the paper is organized as follows. Section 2 presents the basic framework. Section 3 derives equilibrium outcomes. Section 4 analyzes the effect of direct and indirect subsidies on the firms' technological standard choice. Section 5 presents the results of the model with an alternative timing of consumer choice. Section 6 introduces compatibility between technological standards. Finally, Section 6 discusses policy implications and concludes. Proofs are in the Appendix.

2 The model

Consider a product that consists of two complementary components, namely, A and B. Both components are produced in different markets, also denoted as A and B, respectively. Consumer preferences for the composite good are uniformly distributed on the lateral surface of a cylinder. Consumer preferences for component A are

of a complementary good that in turn can increase the value of the original good. For details see Economides and Salop (1992), Economides (1996) and Clements (2004).

[6] See Rennings and Rammer (2009), and Rennings and Rexhauser (2010) for details.

given by their location a on the height of the cylinder, while their preferences for component B are given by their location b on the cylinder circle. The height and the circle of the cylinder and the mass of consumers are normalized to 1.

Firms in market A produce component A using one of two technological standards, S ("superior") and E ("established"). The firms that produce components A using technological standard S (the *S-based firms*) are located on the circle at height 0, while firms that produce components A using technological standard E (the *E-based firms*) are located on the circle at height 1. Accordingly, we can interpret consumer location with respect to cylinder height as their preference for change. More "conservative" consumers are located in the upper part of the cylinder in the neighbourhood of 1, while consumers that are eager to change are located in the neighbourhood of 0. Both, S-based and E-based firms produce component A with constant marginal cost c^A. There are no barriers to entry in market A such that perfectly competitive prices equal marginal cost.[7]

Market B is assumed to be imperfectly competitive. Concretely, we assume a duopoly structure. As in Salop (1979), the two firms are located equidistantly on the cylinder unit circle. If a firm in market B uses technological standard S it locates on the bottom circle of the cylinder while if it uses technological standard E it locates on the top circle of the cylinder. Thus, we can have three different scenarios of firm locations, which are represented in Figure 1. Both firms can either produce with the same standard S or E, or use different standards. The unit production cost of firms in market B is c^{BS} if they use technological standard S and c^{BE} if they use technological standard E. The cost difference of using a superior technological standard is given by $\delta = c^{BS} - c^{BE} > 0$. Furthermore, firms in market B incur a fixed cost F.

The consumers' choice of a specific composite good depends on its distance to their preferred option, its price and the distance and price of alternative composite goods. Denote the unit travel cost associated to the components A and B as t^A and t^B. t^A reflects the disutility of using a non-ideal component A with respect to the taste for change, while t^B is the disutility of being located at a distance from the nearest variety of component B. For simplicity, we assume that $t^A = t^B = t > 0$. Prices of components A and B based on standard $k = S, E$ are denoted p^{Ak} and p^{Bk}, respectively. Firm i's demand on component B based on standard k is D_i^k. The total value a consumer derives from using a composite good is U_0. Consumers' reservation utility is 0. This Section assumes that components A and B based on different technological standards are incompatible.[8] Consequently, a consumer located at (a, b) that buys S-based components A and B has utility $U^{SS} = U_0 - p^{AS} - a^2 t^A - p^{BS} - b^2 t^B$. Analogically, the expression for U^{EE} is derived. The transportation costs are quadratic. This implies that the demand and profit functions are continuous and concave and firms in market B have incentives to locate equidistantly in equilibrium.[9] We assume that $U_0 > p^{Ak} + t^A + p^{Bk} + t^B$, which guarantees that consumers always buy a composite good.

The established standard has a negative externality. The cost of the externality is quadratic in total quantity of E-based system goods. The damage function is $\varepsilon \left(\sum_{i=1,2} D_i^E \right)^2 /2$, where $\varepsilon > 0$ indicates the severity of damage. Define social welfare W as the sum of consumers' surplus, firms' profits and externality costs. For the

[7] The structure of the market for the complementary component reflects the absence of strategical interactions between firms. Examples of complementary component producers for the car market can be petrol stations and electricity producers. The market for petrol is close to perfectly competitive, and the electricity market is regulated. Therefore, the producers do not directly compete with each other. The assumption of perfectly competitive pricing simplifies calculations. However, if there were one provider of each technology, the qualitative results would be the same, but with higher prices for component A.

[8] Perfect compatibility between technological standards is introduced in Section 6.

[9] For further details see Economides (1989).

different scenarios we obtain:

$$W(S,S) = 4\int_0^{\frac{1}{4}}\int_0^1 \left(U_0 - p^{AS} - p^{BS} - x^2 t^A - y^2 t^B\right) dxdy + 2\Pi_i^B(S;S), \tag{1}$$

$$W(E,E) = 4\int_0^{\frac{1}{4}}\int_0^1 \left(U_0 - p^{AE} - p^{BE} - (1-x)^2 t^A - y^2 t^B\right) dxdy + 2\Pi_i^B(E;E) - \frac{\varepsilon}{2}, \tag{2}$$

$$\begin{aligned} W(S,E) = {} & 2\int_0^{\frac{1}{2}}\int_0^{a(b)} \left(U_0 - p^{AS} - p^{BS} - x^2 t^A - y^2 t^B\right) dxdy \\ & +2\int_0^{\frac{1}{2}}\int_{a(b)}^1 \left(U_0 - p^{AE} - p^{BE} - (1-x)^2 t^A - \left(\frac{1}{2} - y\right)^2 t^B\right) dxdy \\ & +\Pi_1^B(S;E) + \Pi_2^B(E;S) - \frac{\varepsilon}{2}\left(D_2^E\right)^2, \end{aligned} \tag{3}$$

where $\Pi_i^B(k;l) = \left(p_i^{Bk} - c_i^{Bk}\right) D_i^k$, $k,l = S,E$, is firm i's profit in market B when it uses standard k and its rival uses standard l.

The timing of the interaction between the policy maker and firms in markets A and B is the following. In stage 0, policy makers choose between no intervention or a cost-reducing subsidy s^A or s^B to be given to firms in markets A or B, respectively. In stage 1, the price of component A is determined. In stage 2, the two firms in market B choose a technological standard, S or E, for production. In stage 3, consumers decide on the system good they buy. In stage 4, the prices of components B are determined and consumers buy the system good. The solution concept is Subgame Perfect Nash Equilibrium (SPNE) and the game is solved by backward induction.

This model describes a market structure that can be relevant for the analysis of a number of markets for system goods. Market A is represented by a unit line. Consumers location on this line reflects their preferences with respect to the two opposed standards. Such preferences can be caused by environmental awareness or the taste for change. If a consumer is located in the neighbourhood of S-based producers, she would choose the S-based component unless its price is very high relative to transportation cost or the market for S-based component A disappears because both firms in market B chose standard E. At the same time, in market B consumers are distributed along the unit circle. Such preferences mean that consumers consider both existing products, and their product choices are more sensitive to changes in product prices.

An example for markets of a system good with such a structure are markets for vehicles and energy sources. When a vehicle is purchased, consumers might have preferences regarding the fuel and charging system, while vehicles are considered as similar products. The value derived from a specific vehicle increases when its fuel becomes more available and at a cheaper price. Therefore, due to complementarity between markets, vehicle producers are "locked-in" with an established technology, even if it causes a negative environmental externality. As another example, consider the market for global navigation systems (GNS) and services for civilian use (in all modes of transport, precision agriculture and personal mobility) or signal adopters. The GNS hardware is usually elaborated by the public sector, while services are provided by private firms. In Europe, private firms design their services choosing the signal source between an established foreign technology (for instance, GPS, which belongs to the US) and a national technology (Galileo). The use of the latter generates a positive externality for national security reasons because with Galileo the ESA (European Space Agency) has control over the signal availability. Therefore, national governments aiming to promote national GNS must provide incentives to producers of services to switch to national technological standards.

An important assumption of the model in this paper is that consumers decide on the system good they prefer to buy before the prices for the component in market B are derived. An example, for such a decision structure is the choice between a car with an electric or an internal combustion engine. Once consumers committed to the technology by their choice of component A (i.e. a parking place and all related infrastructure for an electric or a gasoline car in their living area) they are conditioned in their choice of component B (i.e. cars) even when cars based on both technologies are available. In the case of GNS signal receivers that are built into cell phones or vehicles, consumers, firstly, buy a signal receiver (i.e. hardware) disposing information about the availability of services based on the established (for instance, GPS) and the new technology (Galileo). Once the hardware is bought, consumers are conditioned to use the services based on the same standard as their receivers and are less sensible to the price of the service. Alternatively, in the case of public procurement, once the municipal authority has information regarding the availability of vehicles based on a foreign and national technology, the decision of public procurement is made taking into consideration political issues. This assumption is reasonable in the context of the problem of technology adoption since the components B (cars, GNS services) are introduced more frequently than the components A (energy sources, GNS hardware). Nevertheless, components A determine the technological standard and involve permanent future cost for consumers. Therefore, their price plays a more important role in the decision to buy an S- or E-based system good. Section 5 analyzes optimal policy design under the alternative assumption that consumers make the choice of the system good before the prices on component B are derived and compares the results to the basic framework.

3 Equilibrium 'laissez faire' outcomes

In stage 4, firms in market B compete as in the Salop model. In equilibrium, firms locate at maximum distance on the circle.[10] For convenience, denote the location of firm 1 by $b = 0$ and that of firm 2 by $b = 1/2$. If both firms commit to the same technological standard k, the consumer indifferent between the components produced by the two firms are situated at $b^k = \left(p_2^{Bk} - p_1^{Bk}\right)/t + 1/4$. So, the equilibrium demand of firm 1 is $D_1^k = 2b^k$ and that of firm 2 is $D_2^k = 1 - 2b^k$. Prices are determined by profit maximization as $p^{Bk} = c^{Bk} + t/4$. Thus, stage 3 equilibrium profits are:

$$\Pi_i^B(S;S) = \Pi_i^B(E;E) = \frac{t}{8} - F,\ i = 1,2. \tag{4}$$

If the two firms in market B commit to different technologies the consumer indifferent between the S-based and E-based component is located at $b = \left(p_2^{BE} - p_1^{BS}\right)/t + 1/4$.[11] Consequently, equilibrium prices are:

$$p^{BS} = \frac{8c^{BS} + 4c^{BE} + 3t}{12} \quad \text{and} \quad p^{BE} = \frac{8c^{BE} + 4c^{BS} + 3t}{12}. \tag{5}$$

Consumer product choice in stage 3 depends on the technological standards chosen by the firms in market B. Three scenarios can be distinguished. If both firms in market B choose standard S, i.e. locate at $a = 0$, the market share of the S-based standard is 1. If both firms in market B choose standard E, i.e. locate at $a = 1$, the market share of the E-based standard is 1. Finally, if one firm in market B chooses an S-based technological standard and the other firm chooses an E-based technological standard, the demand of each firm is determined

[10] See Salop (1979) and Economides (1989) for details.

[11] Without loss of generality assume that a firm 1 chooses a technological standard S and a firm 2 chooses a technological standard E.

by the location of the consumer indifferent between the S- and E-based system good. From $U^{SS} = U^{EE}$ we obtain her location:

$$a \equiv a(b) = \frac{1}{2t}\left(p^{AE} - p^{AS} + p^{BE} - p^{BS} + \frac{5}{4}t - bt\right). \tag{6}$$

Regarding the location of indifferent consumers we make the following assumption:

Assumption 1. Let $0 < a(b) < 1$, $\forall b \in (0, 1/2)$.

This assumption guarantees that both firms in market B always have positive demand independently of the standard they adopt. This allows to eliminate trivial cases.

The market share in market B for an S-based and an E-based technology can be calculated as the area of a trapezoid with an upper bound determined by (6) which indicates the location of indifferent consumers between the S- and the E-based system. As market A is perfectly competitive, all players anticipate that stage 1 equilibrium prices are $p^{Ak} = c^A$. Thus, after substituting (5) into (6) we obtain

$$a \equiv \frac{5}{8} - \frac{b}{2} - \frac{\delta}{6t}. \tag{7}$$

Consequently, equilibrium demand is given by

$$D_1^S = \frac{a(0) + a(1/2)}{2} = \frac{1}{2} - \frac{\delta}{6t} \tag{8}$$

and stage 4 equilibrium profits are:

$$\Pi_1^B(S; E) = \frac{(3t - 4\delta)(3t - \delta)}{72t} - F \quad \text{and} \tag{9}$$

$$\Pi_2^B(E; S) = \frac{(3t + 4\delta)(3t + \delta)}{72t} - F. \tag{10}$$

In stage 2, firms in market B choose technological standards. By definition, E is the established standard in the market. This standard has lower unit production costs but generates a negative externality. Comparing the payoffs in equation (4) with those in equations (9) and (10) we obtain the following result.

Lemma 1 *Neither the first firm, nor the second firm have incentives to switch to a superior standard in the absence of policy interventions.*

Proof:
Firm 1 will switch to a superior standard iff $\Pi_1^B(S; E) > \Pi_1^B(E; E)$. From equations (4) and (9) we find that this is equivalent to $15t - 4\delta < 0$. Substituting into (7), this yields $a < -b/2$ which contradicts assumption 1. On the other hand, if one firm has adopted standard S, say firm 1, the second firm changes from E to S iff $\Pi_2^B(S; S) > \Pi_2^B(E; S)$. This is equivalent to $9t + 2\delta < 0$, which contradicts $t > 0$ and $\delta > 0$. Therefore, for any rival's strategy neither firm has incentives to switch to the superior technological standard S. **q.e.d.**

Finally, in perfectly competitive market A the prices for an S- and an E-based component A are determined in stage 1. In order to choose the optimal policy intervention, in the following section the equilibrium outcomes are derived for different types of technological policies, concretely, indirect and direct subsidies.

4 Subsidies

4.1 The indirect subsidy

As a policy intervention consider a subsidy to S-based firms in market A. The objective of this subsidy is to reduce production costs (and prices) of the S-based component A and thereby of the S-based composite good. This increases demand and profits of firms in market B that adopt standard S. So, the subsidy indirectly increases firms' incentives in market B to adopt the superior standard. We call this kind of subsidy an *indirect subsidy* and denote it by s^A.

Because market A is perfectly competitive, the indirect subsidy decreases equilibrium prices $p^{AS} = c^A - s^A$ while the price of E-based producers remains $p^{AE} = c^A$. Equilibrium prices in market B are not affected by this subsidy and are given by (5). Substituting these prices into equation (6) we obtain for the location of indifferent consumers between S- and E-based composite goods:

$$a^A \equiv a^A(b) = \frac{5}{8} - \frac{b}{2} - \frac{\delta}{6t} + \frac{s^A}{2t}. \tag{11}$$

This expression corresponds to (7) with a subsidy in market A. Notice, that Assumption 1 requires that $0 < s^A < \frac{9t+4\delta}{12}$.

Stage 3 equilibrium demand is:

$$D_1^S = \frac{3t - \delta + 3s^A}{6t} \quad \text{and} \quad D_2^E = \frac{3t + \delta - 3s^A}{6t} \tag{12}$$

If firms in market B choose the same standard their profits are the same as in the basic framework without subsidies and given by (4). If firms choose different standards, their profits are:

$$\Pi_1^B(S;E) = \frac{(3t-4\delta)\left(3t-\delta+3s^A\right)}{72t} - F \tag{13}$$

$$\Pi_2^B(E;S) = \frac{(3t+4\delta)\left(3t+\delta-3s^A\right)}{72t} - F. \tag{14}$$

The cost of the subsidy is $s^A \sum_{i=1,2} D_i^S$, where $\sum_i D_i^S$ is the total quantity of the S-based systems sold.

With the indirect subsidy, social welfare is given by:

$$W^A(S,S) = 4\int_0^{\frac{1}{4}}\int_0^1 \left(U_0 - p^{AS} - p^{BS} - x^2t - y^2t\right)dxdy + 2\Pi_i^B(S;S) - s^A, \tag{15}$$

$$W^A(E,E) = 4\int_0^{\frac{1}{4}}\int_0^1 \left(U_0 - p^{AE} - p^{BE} - (1-x)^2t - y^2t\right)dxdy + 2\Pi_i^B(E;E) - \frac{\varepsilon}{2}, \tag{16}$$

$$\begin{aligned} W^A(S,E) = {} & 2\int_0^{\frac{1}{2}}\int_0^{a^A(b)} \left(U_0 - p^{AS} - p^{BS} - x^2t - y^2t\right)dxdy \\ & +2\int_0^{\frac{1}{2}}\int_{a^A(b)}^1 \left(U_0 - p^{AE} - p^{BE} - (1-x)^2t - \left(\frac{1}{2} - y\right)^2 t\right)dxdy \\ & +\Pi_1^B(S;E) + \Pi_2^B(E;S) - \frac{\varepsilon}{2}\left(D_2^E\right)^2 - s^A D_1^S. \end{aligned} \tag{17}$$

From Lemma 1 we know that policy makers must pay a positive subsidy to incite firms in market B to switch from standard E to standard S. Consider the minimum subsidy to firms in market A necessary to incite the first and the second firm in market B to adopt standard S. Comparing the payoffs in equation (4) with those in equations (13) and (14) we obtain the following result.

Lemma 2. *Given an E-based or an S-based firm in market B, its rival adopts a superior standard S, if S-based firms in market A get a subsidy* $s \geq \underline{s}_1^A \equiv \delta\frac{15t-4\delta}{9t-12\delta}$. *Given an S-based firm in market B, its rival adopts a superior standard S if it gets a subsidy* $s \geq \underline{s}_2^A = \delta\frac{15t+4\delta}{9t+12\delta}$. *The subsidy* $\underline{s}_1^A$ *is sufficient to make both firms in market B to adopt a superior standard S, i.e.* $\underline{s}_1^A > \underline{s}_2^A$.

Proof:
Firm 1 will change to a superior standard iff $\Pi_1^B(S;E) > \Pi_1^B(E;E)$. From equations (13) and (4) we find that this is true for $s \geq \underline{s}_1^A \equiv \delta\frac{15t-4\delta}{9t-12\delta}$. On the other hand, if one firm has adopted standard S, say firm 1, the second firm changes from E to S iff $\Pi_2^B(S;S) > \Pi_2^B(E;S)$. From equations (14) and (4) we find that this is true if $s \geq \underline{s}_2^A \equiv \delta\frac{15t+4\delta}{9t+12\delta}$. Because $\underline{s}_1^A > \underline{s}_2^A$, $\underline{s}_1^A$ is a sufficient subsidy for S-based producers in market A to induce both firms in market B to adopt standard S [12]. **q.e.d.**

To find the welfare maximizing indirect subsidies to a first and a second adopter of standard S, the policy maker must solve the following problem:

$$s^A = \arg\max\left\{W^A(E,E), \max_{s^A \geq \underline{s}_1^A} W^A(S,S)\right\} \tag{18}$$

We get the following result:

[12] The existence of a sufficient minimum subsidy that affects firms' technology choice is supported by empirical evidence. For instance, the analysis of Aschhoff (2009) for Germany suggests that public R&D grants should have a minimum size to cause an impact on a firm's privately financed R&D.

Proposition 1. The welfare maximizing indirect subsidies to firms in market A are:

$$s^A = \begin{cases} 0 & \text{for} \quad 0 \leq \varepsilon/t \leq \epsilon_1 \quad \text{(Region I)} \\ \underline{s}_1^A & \text{for} \quad \epsilon_1 < \varepsilon/t \quad \text{(Region III)} \end{cases}$$

where $\epsilon_1 = 2\,(\delta/t)$ and $\delta/t < \frac{9}{28}$.

Proof. In the Appendix.

The two regions are displayed in Figure 2. Intuitively, policy intervention is desirable only when the impact of the externality is high in comparison to the cost difference between the two standards. However, the more important the externality becomes, the more technology adopters must be targeted with subsidies. Therefore, if δ/t is low and the negative externality is high, the optimal subsidy to the firms in market A is $\underline{s}_1^A$. With this subsidy, both firms in market B adopt standard S.

4.2 The direct subsidy

The second policy intervention considered in this paper is a subsidy to S-based firms in market B. This subsidy reduces the production cost and the price of the S-based component B. This increases the demand on the S-based system good and, consequently, the profits of superior technology adopters in market B. Therefore, this subsidy directly increases firms' incentives in market B to adopt the superior standard. We call this kind of subsidy a *direct subsidy* and denote it by s^B.

The direct subsidy doesn't affect equilibrium prices in market A, so they remain $p^{AS} = p^{AE} = c^A$. However, it affects equilibrium prices of S-based firms in market B. If both firms adopt S, the prices are $p_i^{BS} = c_1^{BS} - s^B + t/4$. If both firms choose the same technological standard, the resulting profits of firms in market B are equal to (4). If firms B choose different standards, the equilibrium prices are:

$$p_1^{BS} = \frac{2\left(c^{BS} - s^B\right)}{3} + \frac{c^{BE}}{3} + \frac{t}{4} \text{ and } p_2^{BE} = \frac{2c^{BE}}{3} + \frac{\left(c^{BS} - s^B\right)}{3} + \frac{t}{4} \tag{19}$$

Plugging (19) into (6) we obtain for the location of indifferent consumers between S- and E-based composite goods:

$$a^B \equiv a^B(b) = \frac{5}{8} - \frac{b}{2} - \frac{\delta}{6t} + \frac{s^B}{6t}. \tag{20}$$

This is the corresponding expression to (7) with a subsidy in market B. Stage 3 equilibrium demand is:

$$D_1^S = \frac{3t - \delta + s^B}{6t} \quad \text{and} \quad D_2^E = \frac{3t + \delta - s^B}{6t} \tag{21}$$

If firms in market B choose the same standard their profits are the same as in the case without subsidies and given by (4). If firms choose different standards, their profits are:

$$\Pi_1^B\,(S;E) = \frac{\left(3t - \delta + s^B\right)\left(3t - 4\delta + 4s^B\right)}{72t} - F, \tag{22}$$

$$\Pi_2^B\,(E;S) = \frac{\left(3t + \delta - s^B\right)\left(3t + 4\delta - 4s^B\right)}{72t} - F. \tag{23}$$

Again, the cost of the subsidy is $s^B \sum_{i=1,2} D_i^S$, where $\sum_i D_i^S$ is the total quantity of the S-based systems sold. Thus, with the direct subsidy, social welfare is given by:

$$W^B(S;S) = 4\int_0^{\frac{1}{4}}\int_0^{1}\left(U_0 - p^{AS} - p^{BS} - x^2t - y^2t\right)dxdy + 2\Pi_i^B(S;S) - s^B, \tag{24}$$

$$W^B(E;E) = 4\int_0^{\frac{1}{4}}\int_0^{1}\left(U_0 - p^{AE} - p^{BE} - (1-x)^2t - y^2t\right)dxdy + 2\Pi_i^B(E;E) - \frac{\varepsilon}{2}, \tag{25}$$

$$\begin{aligned} W^B(S;E) = {} & 2\int_0^{\frac{1}{2}}\int_0^{a^B(b)}\left(U_0 - p^{AS} - p^{BS} - x^2t - y^2t\right)dxdy \\ & +2\int_0^{\frac{1}{2}}\int_{a^B(b)}^{1}\left(U_0 - p^{AE} - p^{BE} - (1-x)^2t - \left(\frac{1}{2} - y\right)^2 t\right)dxdy \\ & +\Pi_1^B(S;E) + \Pi_2^B(E;S) - \frac{\varepsilon}{2}\left(D_2^E\right)^2 - s^B D_1^S. \end{aligned} \tag{26}$$

First, consider the minimum subsidy necessary to incite the first firm to adopt standard S. Second, consider the minimum subsidy necessary to incite the second firm to adopt standard S. Comparing the payoffs in equation (4) with those in equations (22) and (23) we obtain the following result.

Lemma 3. *Given an E-based firm in market B, its rival adopts a superior standard S, if it gets a subsidy $s \geq \underline{s}_1^B \equiv \delta$. Similarly, given an S-based firm in market B, its rival adopts a superior standard S if it gets a subsidy $s \geq \underline{s}_2^B \equiv \delta$.*

Proof:
Firm 1 will change to a superior standard iff $\Pi_1^B(S;E) > \Pi_1^B(E;E)$. From equations (22) and (4) we find that this is true for $s \geq \underline{s}_1^B \equiv \delta$. On the other hand, if one firm has adopted standard S, say firm 1, the second firm changes from E to S iff $\Pi_2^B(S;S) > \Pi_2^B(E;S)$. From equations (23) and (4) we find that this is true if $s \geq \underline{s}_2^B = \delta$. **q.e.d.**

The results in Lemmas 2 and 3 suggests that the incentives provided by the direct and indirect subsidies to the firms in the market B are distinct. The minimum subsidy to the S-based firms A affects firms B' standard choice depending on the relation between the unit cost difference and the transportation cost, i.e. the disutility of being far from the most preferred variety. The subsidy to the S-based producers in market B provides sufficient incentives only if it is higher than the unit production cost difference between the two technological standards.

To find the welfare maximizing direct subsidies to the first and the second adopter of standard S, the policy maker must solve the problem:

$$\left(s_1^B, s_2^B\right) = \arg\max\left\{W^B(E,E), \max_{s_1^B \geq \underline{s}_1^B} W^B(S,E), \max_{s_1^B \geq \underline{s}_1^B, s_2^B \geq \underline{s}_2^B} W^B(S,S)\right\}.$$

The following result is obtained:

Proposition 2. For all δ the welfare maximizing direct subsidies to firms in market A are:

$$\left(s_1^B, s_2^B\right) = \begin{cases} (0,0) & \text{for} \quad 0 < \varepsilon/t \leq \epsilon_2 & \text{(Region I)} \\ (\underline{s}_1^B, 0) & \text{for} \quad \epsilon_2 < \varepsilon/t \leq \epsilon_3 & \text{(Region II')} \\ (s_{\max}^B, 0) & \text{for} \quad \epsilon_3 < \varepsilon/t \leq \epsilon_4 \text{ and } \varepsilon/t \leq \epsilon_5 & \text{(Region II")} \\ (\underline{s}_1^B, \underline{s}_2^B) & \text{for} \quad \epsilon_4 < \varepsilon/t & \text{(Region III)} \end{cases}$$

where $s_{\max}^B = \frac{(3t+\delta)\varepsilon - 4t\delta - t^2}{2t+\varepsilon}$, $\epsilon_2 = \frac{4}{3}(\delta/t) - \frac{49}{72}$, $\epsilon_3 = 2(\delta/t) + \frac{1}{3}$, $\epsilon_4 = \frac{32}{5}(\delta/t)^2 + \frac{224}{15}(\delta/t) + \frac{302}{45}$, $\epsilon_5 = 8(\delta/t) + \frac{22}{3}$, with $\epsilon_2 < \epsilon_3 < \epsilon_4$ and $\delta/t < \frac{9}{4}$.

Proof. In the Appendix.

The four regions are displayed in Figure 3. When the unit production cost with the superior standard is very high and the negative externality is low, no subsidy is the best policy. Then, for lower delta, $\underline{s}_1^B$ must be given to the first adopter of the superior standard S in market B. When both δ/t and the negative externality are relatively high, $s_{\max}^B$ yields higher social welfare. Similarly, it induces firm 1 in market B to adopt standard S. Finally, when δ/t is very low provided the high level of a negative externality, the optimal policy is to provide $\underline{s}_1^B$ and $\underline{s}_2^B$ to induce both firms in market B to adopt S.

4.3 The choice of optimal policy

Comparing social welfare under optimal indirect and direct subsidies, i.e. the results in Propositions 1 and 2, we obtain the following proposition.

Proposition 3. The optimal policy intervention is determined by the following optimal subsidies:

$$(s_1, s_2) = \begin{cases} (\underline{s}_1^B, 0) & \text{for} \quad 0 < \varepsilon/t \leq \epsilon_3 & \text{(Region 2'B)} \\ (s_{\max}^B, 0) & \text{for} \quad \epsilon_3 < \varepsilon/t \leq \epsilon_4 \text{ and } \varepsilon/t \leq \epsilon_5 & \text{(Region 2"B)} \\ \left\{\underline{s}_1^A, (\underline{s}_1^B, \underline{s}_2^B)\right\} & \text{for} \quad \epsilon_4 < \varepsilon/t & \text{(Region 3AB)} \end{cases}$$

where $0 \leq \delta/t \leq 9/28$, $\underline{s}_1^A > \underline{s}_1^B$. Social welfare is higher with a direct subsidy in Regions 2 and 3 and is equal with indirect and direct subsidies in Region 4.

Proof. In the Appendix.

The different regions are displayed in Figure 4. Given the range of values for the production cost difference between the standards, providing a direct or an indirect subsidy such that at least to one firm adopts a superior technology is socially preferable to no intervention. Though social welfare is equal with direct and indirect subsidies in Region 3AB, notice that a welfare maximizing direct subsidy in this region is lower than an indirect subsidy. Therefore, a direct subsidy provided to S-based firms in market B is socially preferable in the presence of costly public fund raising (due to administrative costs or corruption). Then, a lower subsidy leads to a lower efficiency loss. Remarkably, this result suggests the implementation of direct subsidies despite the fact that the positive effect of an indirect subsidy on the adoption of a superior technology by consumers is higher than the effect of a direct subsidy in the model[13].

[13] $\frac{\partial a^A}{\partial s^A} > \frac{\partial a^B}{\partial s^B}$

5 An alternative timing of consumer choice

This section reexamines the basic model introducing a modification in the timing of the game. Consider that, now, consumers choose the system good when the prices of components A and B are determined. As in Section 2, in stage 0, policy makers choose between a cost-reducing subsidy s^A or s^B to be given to firms in markets A or B, respectively. In stage 1, the price of component A is determined. In stage 2, the two firms in market B choose a technological standard, S or E, for production. In stage 3, the prices of components B are determined and consumers buy the composite good.

In stage 3, consumers choose the system good. If both firms in market B choose the same technological standard, S or E, the resulting outcomes are the same as in Section 2. Similarly, if firms in market B choose different technological standards, S and E, the indifferent consumer is determined by (6). However, the demand functions of firms B are now affected by their own prices and the prices of the complementary good. Calculating demand as in (8) we obtain:

$$D_1^S = \frac{t + p^{AE} - p^{AS} - p^{BS} + p^{BE}}{2t} \quad \text{and} \quad D_2^E = \frac{t + p^{AS} + p^{BS} - p^{AE} - p^{BE}}{2t}.$$

Consequently, stage 3 equilibrium prices are:

$$p_1^{BS} = \frac{3t + 2c_1^{BS} + c_2^{BE} - p^{AS} + p^{AE}}{3} \quad \text{and} \quad p_2^{BE} = \frac{3t + c_1^{BS} + 2c_2^{BE} + p^{AS} - p^{AE}}{3}.$$

Again, in stage 1, $p^{Ak} = c^A$. The resulting payoffs of firms in market B are

$$\Pi_1^S(S,E) = \frac{(3t-\delta)^2}{18t} - F \quad \text{and} \quad \Pi_2^E(S,E) = \frac{(3t+\delta)^2}{18t} - F. \tag{27}$$

Lemma 4 *Neither the first firm, nor the second firm have incentives to switch to a superior standard in the absence of policy interventions for $\frac{3}{2}t < \delta < \frac{9}{4}t$. The first firm chooses a superior standard and the second firm chooses an established standard in the absence of policy interventions for $0 < \delta < \frac{3}{2}t$.*

Proof:

Firm 1 will change to a superior standard iff $\Pi_1^B(S;E) > \Pi_1^B(E;E)$. From equations (27) and (4) we find that this is true for $0 < \delta < \frac{3}{2}t$. On the other hand, for $\frac{3}{2}t < \delta < \frac{9}{4}t$ neither the first nor the second firm will change to a superior standard as $\Pi_1^B(E;E) > \Pi_1^B(S;E)$ and $\Pi_2^B(E;S) > \Pi_2^B(S;S)$. **q.e.d.**

If an indirect subsidy is given to S-based firms in market A, this increases the prices of the S-based firm in market B and decreases the prices of the E-based firm in market B. This is because consumers' choice will be shifted towards an S-based system good and firms in market B can anticipate that adjusting their prices:

$$p_1^{BS} = \frac{3t + 2c^{BS} + c^{BE} + s^A}{3} \quad \text{and} \quad p_2^{BE} = \frac{3t + c^{BS} + 2c^{BE} - s^A}{3}. \tag{28}$$

The demands are also affected by change in prices in market A:

$$D_1^S = \frac{3t - \delta + s^A}{6t} \quad \text{and} \quad D_2^E = \frac{3t + \delta - s^A}{6t}. \tag{29}$$

The resulting payoffs are:

$$\Pi_1^S(S,E) = \frac{\left(3t - \delta + s^A\right)^2}{18t} - F \quad \text{and} \quad \Pi_2^E(S,E) = \frac{\left(3t + \delta - s^A\right)^2}{18t} - F. \tag{30}$$

If a direct subsidy is given to firms in market B, this decreases the prices of both firms in market B, although it affects p_1^{BS} more than p_2^{BE}:

$$p_1^{BS} = \frac{3t + 2c^{BS} + c^{BE} - 2s^B}{3} \text{ and } p_2^{BE} = \frac{3t + c^{BS} + 2c^{BE} - s^B}{3}.$$

The resulting demands are equal to 29. Because an S-based firm in market B is given direct subsidies, the resulting payoffs are the same as 30.

Lemma 5. *Given an E-based firm in market B, its rival adopts a superior standard S, if it gets a subsidy* $s \geq \underline{s}_1^A \equiv \underline{s}_1^B \equiv \delta - \frac{3}{2}t$. *Similarly, given an S-based firm in market B, its rival adopts a superior standard S if it gets a subsidy* $s \geq \underline{s}_1^A \equiv \underline{s}_1^B \equiv \delta + \frac{3}{2}t$. *Furthermore, the subsidy to the first adopter is lower than the subsidy to the second adopter, i.e.* $\underline{s}_1^A \equiv \underline{s}_1^B < \underline{s}_2^A \equiv \underline{s}_2^B$.

Proof:
Firm 1 will change to a superior standard iff $\Pi_1^B(S;E) > \Pi_1^B(E;E)$. From equations (30) and (4) we find that this is true for $s \geq \underline{s} \equiv \delta - \frac{3}{2}t$. Similarly, if one firm has adopted standard S, say firm 1, the second firm changes from E to S iff $\Pi_2^B(S;S) > \Pi_2^B(E;S)$. From equations (30) and (4) we find that this is true if $s \geq \underline{s}_2 \equiv \delta + \frac{3}{2}t$.

Comparing the minimum subsidies obtained in Section 4 and Section 5 we obtain the following proposition.

Proposition 4. In the absence of consumers' commitment to the technology the optimal policy intervention is determined by the following optimal subsidies:

$$(s_1, s_2) = \begin{cases} (0,0) & \text{for } 0 < \varepsilon/t \leq \epsilon_7 \text{ and } 0 < \delta/t \leq 3/2 & \text{(Region 1)} \\ \left\{(\underline{s}_1^A, 0), (\underline{s}_1^B, 0)\right\} & \text{for } 0 < \varepsilon/t \leq \epsilon_8 \text{ and } 3/2 < \delta/t \leq 9/4 & \text{(Region 2'AB)} \\ \left\{(s_{\max}^A, 0), (s_{\max}^B, 0)\right\} & \text{for } \epsilon_8 < \varepsilon/t \leq \epsilon_9 \text{ and } 3/2 < \delta/t \leq 9/4 & \text{(Region 2''AB)} \\ \left\{\left(\underline{s}_1^A, \underline{s}_2^A\right), \left(\underline{s}_1^B, \underline{s}_2^B\right)\right\} & \text{for } \epsilon_7 < \varepsilon/t \text{ and } 0 < \delta/t \leq 3/2 & \text{(Region 3AB)} \\ \left\{\left(\underline{s}_1^A, \underline{s}_2^A\right), \left(\underline{s}_1^B, \underline{s}_2^B\right)\right\} & \text{for } \epsilon_9 < \varepsilon/t \text{ and } 3/2 < \delta/t \leq 9/4 & \text{(Region 3AB)} \end{cases}$$

where $\epsilon_7 = \frac{304(\delta/t)+80(\delta/t)^2+147}{48(\delta/t)+8(\delta/t)^2+72}$, $\epsilon_8 =, \frac{4}{3}(\delta/t) - \frac{4}{9}$, $\epsilon_9 = \frac{32}{5}(\delta/t)^2 + \frac{224}{15}(\delta/t) + \frac{302}{45}$.
Proof. In the Appendix.

The five regions are displayed in Figure 5. Interestingly, given a relatively low cost difference between two standards and a low externality cost, the first firm in market B adopts a superior technological standard even in the absence of policy intervention. The fact that consumers choose the system good after all prices are known, decreases the indirect and direct subsidies that are needed to provide sufficient incentives to the first adopter of technological standard S, but raises the subsidies to the second adopter. This result suggests that consumers' ex ante decision regarding the system good to be purchased (or a "commitment" to a certain technology caused, for instance,by the availability of infrastructure for using a system good based on a determined technology) creates inefficiencies increasing the optimal size of the subsidies in the beginning of adoption. The higher is the degree of consumers' "commitment" the more we move from the situation, in which indirect and direct subsidies perform equally, towards the situation, in which the direct subsidy is preferable.

The comparison of two scenarios, the basic framework and the alternative timing, provides intuition on the choice of the optimal subsidy in a dynamic context of new technology adoption. In an early stage of technology adoption, when the initial cost difference between the established and superior technology is crucial and consumers are "locked-in" with a certain technology, it is better to provide direct subsidies to firms that potentially adopt superior technologies. Further, when the consumers' restriction does not dominate, and their purchasing decisions are made once the prices of all components are known, both direct and indirect subsidies perform equally and can be applied. In this case, given the low cost difference between the two technologies, one of the firms will adopt the superior technology without policy intervention. In addition, when the impact of the externality becomes relatively more important than the production cost difference, all firms in the market should be given subsidies.

6 Extension: compatibility between S- and E-based components

This section introduces compatibility between system good components based on different technological standards. The parameter of compatibility is introduced as a discrete value $\beta \in \{0, 1\}$ in the denominator of the transportation cost related to the distance of consumers to the available variety of component B. If $\beta = 0$ we obtain the model presented in Section 2, where only U^{SS} and U^{EE} are relevant for consumers' choices. With compatibility between different standards ($\beta = 1$), the consumers' utility from using the system composed of an S-based component A and an E-based component B is given by $U^{SE} = U_0 - p^{AS} - a^2 t - p^{BE} - \left(\frac{1}{2} - b\right)^2 t$. Analogically, consumers' utility from the system composed of an E-based component A and an S-based component B is given by $U^{ES} = U_0 - p^{AE} - (1-a)^2 t - p^{BS} - b^2 t$.

The timing of the game is similar to that in Sections 3 and 5 independently of whether consumers commit or not to the technological standard in stage 3. Firms compete between them in markets A and B independently of the market for the complementary component.

As in Section 2, the established standard has a negative externality. If a system good consists of two E-based components, the cost of the externality is quadratic in the total quantity of E-based system goods with damage function is $\varepsilon \left(\sum_{i=1,2} D_i^E\right)^2 /2$, $\varepsilon > 0$. If the system good consists of an S- and an E-based component, it is assumed that only half of the system good generates a negative externality, such that the damage function is $\varepsilon \left(\sum_{i=1,2} D_i^{SE}/2\right)^2 /2$. For instance, a hybrid car generates fewer emissions than an internal combustion car. Social welfare W is defined as the sum of consumers' surplus in the two markets, firms' profits and externality costs.

In stage 4, the prices of firms in market B are derived similarly as in the basic model. If both firms in market B choose the same technological standard the prices are determined by profit maximization as $p^{Bk} = c^{Bk} + t/4$. If firms in market B choose different standards, the prices are the same as in 5.

Due to perfect compatibility between all components, the consumer choice of component A in stage 3 does not depend on the technological standards chosen by the firms in market B. The demand of S- and E-based components in market A is determined by the location of the consumer indifferent between the S- and E-based component A. From $U^{SS} = U^{ES}$ and $U^{SE} = U^{EE}$ we obtain her location as:

$$a = \frac{1}{2t}\left(p^{AE} - p^{AS} + t\right) \tag{31}$$

Provided that the choice of component A does not determine the market share of S- and E-based systems, the demand of firms in market B is only affected by their strategic interaction. The consumer indifferent between S- and E-based components B is situated at $b = -\delta/3t + 1/4$, therefore, the equilibrium demand of firm 1 is $D_1^S = 2b$ and that of firm 2 is $D_2^E = 1 - 2b$. In stage 2, firms in market B choose technological standards. Three possible scenarios are represented in 6. If both firms in market B choose standard S, i.e. locate at $a = 0$, the system goods available are S,S and E,S. The market shares of an S-based system good and an ES-based system good are 1/2. If both firms in market B choose standard E, i.e. locate at $a = 1$, the market shares of an E-based and an SE-based system goods are 1/2, too. Then, stage 3 equilibrium profits are the same as in (4). Finally, if one firm in market B chooses an S-based technological standard and the other firm chooses an E-based technological standard, stage 3 equilibrium profits are given by

$$\begin{aligned} \Pi_1^S(S,E) &= \frac{(3t-4\delta)^2}{72t} - F \\ \Pi_2^E(S,E) &= \frac{(3t+4\delta)^2}{72t} - F \end{aligned} \tag{32}$$

Because $\Pi_1^S(S,E) < \Pi_1^E(E,E)$ and $\Pi_2^S(S,S) < \Pi_2^E(E,S)$ the firms in market B have no incentive to adopt a superior technology without policy intervention. However, consumers that are located in the neighbourhood of S in market A will now choose the S-based component A for any location with respect to component B. Therefore, with compatibility between the components, the negative externality imposed on society will be lower.

The implementation of indirect and direct subsidies affects consumers choices differently. Regarding the indirect subsidy, it affects adoption behaviour only in market A. With the indirect subsidy, as in the basic framework, the price for S-based component A is given by $p^{AS} = c^A - s^A$. This increases the share of consumers of S-based component A to

$$a = \frac{1}{2} + \frac{s^A}{2t}. \tag{33}$$

Although, in the case of perfect compatibility the indirect subsidies have no effect on demand and, consequently, profits and technological standard choices of firms in market B, they affect the consumers' choice regarding the component A increasing the market share of an S-based component A. Thus, a negative externality is diminished. Because firms B' strategies are not affected by indirect subsidies, the only possible equilibrium will be the one in which both firms in market B choose technological standard E. Then, the social welfare is given by:

$$\begin{aligned} W^A(E,E) &= 2A\int_0^{\frac{1}{4}}\int_0^{a^A}\left(U_0 - p^{AS} - p^{BE} - x^2t - y^2t\right)dxdy \\ &+2A\int_0^{\frac{1}{4}}\int_{a^A}^{1}\left(U_0 - p^{AE} - p^{BE} - (1-x)^2t - y^2t\right)dxdy \\ &+2\Pi_i^{BE}(E,E) - \frac{\varepsilon}{2}\left(D^{EE}\right)^2 - \frac{\varepsilon}{2}\left(\frac{D^{SE}}{2}\right)^2 - s^A D^{SE} \end{aligned}$$

Deriving the welfare maximizing indirect subsidy we obtain the following result:

Lemma 6. *The optimal indirect subsidy to firms in market A is* $s^A = \frac{3t\varepsilon}{8t+5\varepsilon}$.

In the case of direct subsidies, if both firms in market B choose standard S, their prices are $p_i^{BS} = c_1^{BS} - s^B + t/4$ and profits are equal to (4). If one firm choose standard S and another firm chooses standard E, the prices in market B are the same as in (19). Now direct subsidies affect also the demands of firms in market B. The market share of an S-based component B is given by $b = \frac{s^B}{3t} - \frac{\delta}{3t} + \frac{1}{4}$ and the market share of an E-based component B is $\frac{1}{2} - b = \frac{\delta - s^B}{3t} + \frac{1}{4}$. Then, firms' profits are

$$\begin{aligned} \Pi_1^S(S,E) &= \frac{\left(3t - 4\delta + 4s^B\right)^2}{72t} - F \\ \Pi_2^E(S,E) &= \frac{\left(3t + 4\delta - 4s^B\right)^2}{72t} - F \end{aligned} \tag{34}$$

Comparing the payoffs of firms in market B with direct subsidies we obtain the following result.

Lemma 7. *Given an E-based firm in market B, its rival adopts a superior standard S, if it gets a subsidy $s \geq \underline{s}_1^B \equiv \delta$. Similarly, given an S-based firm in market B, its rival adopts a superior standard S if it gets a subsidy $s \geq \underline{s}_2^B \equiv \delta$.*

Proof. Analogically to Proof of Lemma 5.

Given equilibria of the model the analysis of social welfare with compatibility yields the following result.

Proposition 5. In the presence of perfect compatibility between technologies the optimal policy intervention is determined by the following optimal subsidies:

$$(s_1, s_2) = \begin{cases} (0,0) & \text{for} \quad 0 < \varepsilon/t \leq \epsilon_{10} \text{ and } 0 < \varepsilon/t \leq \epsilon_{11} & \text{(Region 1)} \\ \left\{s_{\max}^A\right\} & \text{for} \quad \epsilon_{11} < \varepsilon/t \leq \epsilon_{12} & \text{(Region 2A)} \\ \left(\underline{s}_1^B, \underline{s}_2^B\right) & \text{for} \quad \epsilon_{10} < \varepsilon/t \text{ and } \epsilon_{12} < \varepsilon/t & \text{(Region 3B)} \end{cases}$$

where $\epsilon_{10} = 8(\delta/t)$, $\epsilon_{11} = \frac{5+\sqrt{889}}{54}$ and $\epsilon_{12} = \frac{80}{11}(\delta/t) + \frac{1}{66}\sqrt{230\,400(\delta/t)^2 + 4416(\delta/t) + 9145} - \frac{101}{66}$.

Proof. In the Appendix.

The regions different regions are displayed in Figure 7. With perfect compatibility between components based on different technological standards the indirect subsidies gain advantage in comparison to direct subsidies if both the externality cost and the production cost difference between the two standards are high (Region 2A). Direct subsidies are optimal if the externality cost is high but the cost difference between the established and the superior technology is low (in Region 3B). Even in the presence of perfect compatibility the result that all technology adopters should be given direct subsidies provided a high externality cost is confirmed.

7 Concluding remarks

This paper addresses optimal subsidy choice in the context of markets with complementary goods in the presence of externalities. Subsidies are aimed at enhancing firms' incentives for transition from an established technological standard, which is cheaper but causes a negative externality, to a superior standard. We show that once there is an established technological standard, without policy intervention, firms have no incentives to adopt a superior standard. The policy instruments analyzed are indirect and direct subsidies. The conditions for optimal subsidies are indicated depending on the cost difference between standards, the impact of the externality and the presence of consumers' "commitment" to a determined technology. If consumers' purchasing decision is made before the prices of one of the components of the system good are known, policy intervention is desirable only when the impact of the externality is not lower than the cost difference between standards. Then, if the impact of the externality is relatively similar to the cost difference between standards, it is optimal to give a direct subsidy to provide incentives for the transition to the superior standard only to the first technology adopter. Furthermore, the higher the externality becomes, the more technology adopters must be targeted with subsidies. This means that in case of direct subsidies, both technology adopters should be given a direct cost-reducing subsidy per unit of production using the superior standard. In case of indirect subsidies, the necessary amount of cost-reducing subsidies should be given to the producers of the complementary component per volume of production using the superior standard. The comparison between direct and indirect subsidies suggests that when the cost difference between technological standards is high and the externality is low or intermediate, direct subsidies are socially preferable. When the externality cost is high and the cost difference is low, direct and indirect subsidies perform equally. However, because the optimal indirect subsidy is higher than the direct subsidy, the direct subsidy leads to higher social welfare. If consumers' purchasing decision is made after the prices of all components of the system good are known (i.e. in the absence of "commitment"), the effects of indirect and direct subsidies' are equal. In this case, if the production cost difference is low the first adopter might have natural incentives to adopt the superior technology. This means that the adoption of the superior technology implies a lower cost for society. If the production cost difference is high, the adoption requires direct or indirect subsidies. Moreover, the subsidy to the second adopter is higher than the subsidy to the first adopter. Finally, compatibility between components based on different technological standards enhances an advantage of indirect subsidies for the case of a high externality cost and a high cost difference between the established and the superior technological standard.

Regarding the before mentioned policy examples of Brazil and of the US the results have some interesting implications. In Brazil, as a result of indirect subsidies implementation, by the year 1990, 90% of vehicle manufactures in Brazil used technology allowing to power vehicles by alcohol. According to our results, this technology adoption policy is more costly for society in the presence of consumers' "stickiness" to technology, i.e., if consumers are a priori restricted to use the superior or the established technology. In this case indirect subsidies are less efficient because at the beginning of new car technology adoption, consumers by choosing a car are conditioned by the availability of all related infrastructure in their urban area (charging and service stations, parking area). On the contrary, when the infrastructure for both technologies is installed and consumers can make their purchasing decision after the prices for all components are known, both subsidies perform equally. In the US, direct subsidies to car manufacturers were chosen. According to our results, this is the optimal solution at the beginning of superior technology adoption. However, once the infrastructure for both technologies is installed (in other words, in the absence of consumers' "stickiness" to technology), indirect subsidies to producers of clean energy technologies (biofuels, electricity generation) should also be implemented.

The results have been discussed in the context of optimal subsidy choice to enhance environmental performance in the markets for system goods. However, these results provide a rationale for a wide range of policies. A similar problem of technology adoption arises in industries related to national defense. The systems' components are produced by a number of public and private firms. Usually, public companies elaborate the basic architecture of the system (hardware), while some of the components are provided by external private firms. In this interaction private firms need incentives for transition to a new technology. For instance, satellite navigation services are enabled by equipment of GPS. Many private firms provide a number of applications using the GPS signal. Therefore, nowadays, the world market for satellite navigation is dominated by GPS, which is under military control of the US. For the European economy this sector has become very important (about 7% of the EU GDP in 2009) and is expected to grow. Therefore, in order to provide Europe independence in satellite navigation, the Galileo project was launched. The use of Galileo generates a number of positive externalities for security and economic reasons. Therefore, the national government aiming to promote a national GNS must provide incentives to the producers of services to switch to the national technological standard, for instance, to substitute GPS chipsets by Galileo ones in cell phones. This might raise costs as further development of devices and applications is needed to explore higher precision possibilities of Galileo. Two approaches to provide firms with incentives for R&D collaboration can be applied. First, the contract between public entity and private firms can be improved to make more favorable conditions than with GPS. Second, direct subsidies can be given to private firms to adopt Galileo. In order to choose between the two policies, the positive externalities, the cost difference between the two technologies and the effect of consumers "commitment" should be considered. The "less optimistic" estimates taking account of the possible impacts of the economic crisis suggest that the total accumulated benefits coming from Galileo over the period 2008-2030 would be between €55 and €62b. The consumers of GNS-based applications can be committed to the use of national system by political means. In this case, because the positive externality is estimated as very high, and the cost difference is relatively small, our results suggest that it would be socially optimal to subsidize firms that produce Galileo-based instead of GPS-based applications, i.e. to use a direct subsidy.

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8 Appendix

8.1 Proof of Proposition 1

First, consider the situation that both firms adopt standard E. Then, $s^A = 0$ and welfare is:

$$W^A(E,E) = U_0 - c^A - c^{BE} - 2F - \frac{17}{48}t - \frac{\varepsilon}{2}. \tag{35}$$

Second, if firms in market A receive subsidies $s^A = s_1^A$, both firms in market B adopt standard S, and welfare is:

$$W^A(S,S) = U_0 - c^A - c^{BE} - 2F - \frac{17}{48}t - \delta. \tag{36}$$

These subsidies are sufficient to make both firms adopt standard S.

Finally, to determine the optimal policy, we must compare social welfare in expressions (35) and (36). We get:

$$W^A(S,S) - W^A(E,E) > 0 \quad \text{for} \quad \epsilon_1 < \varepsilon/t, \tag{37}$$

where $\epsilon_1 = 2(\delta/t)$ and $\delta/t < 9/28$. This expression determines the intervals for subsidies in market A, which are given in Proposition 1 and displayed in Figure 2.

8.2 Proof of Proposition 2

First, consider the optimal subsidy to firm 1 that maximizes $W^B(S,E)$. Substituting $p^{AS} = p^{AE} = c^A$, the prices in (19), equation (20), profits from (22) and (23) and demands from (**??**) into (26), after some calculations we get:

$$\max_{s^B > \underline{s}^B} W^B(S;E) = U_0 - c^A - c^{BE} - 2F - \frac{16s(s+t+4\delta) + 272t\delta - 80\delta^2 + 57t^2}{576t} - \frac{\varepsilon}{72}\left(\frac{3t+\delta-s}{t}\right)^2. \tag{38}$$

The welfare maximizing subsidy is $s^B_{\max} = \frac{(3t+\delta)\varepsilon - 4t\delta - t^2}{2t+\varepsilon}$. This subsidy must fulfill the restriction $s^B_{\max} \geq \underline{s}_1^B$ to provide sufficient incentives to firm 1 to adopt the standard S. This is:

$$\left(s_1^B, s_2^B\right) = \begin{cases} (\underline{s}_1^B, 0) & \text{for} \quad (\varepsilon/t) \leq \epsilon_3 \\ (s^B_{\max}, 0) & \text{for} \quad (\varepsilon/t) > \epsilon_3 \end{cases}, \tag{39}$$

where $\epsilon_3 = 2(\delta/t) + 1/3$. Consequently, we have:

$$W^B(S;E) = \begin{cases} U_0 - c^A - c^{BE} - 2F - \frac{19t+96\delta+24\varepsilon}{192} & \text{for} \quad (\varepsilon/t) \leq \epsilon_3 \\ U_0 - c^A - c^{BE} - 2F - \frac{2\left(240t\delta - 144\delta^2 + 53t^2\right) + 3\varepsilon(83t + 192\delta)}{576(2t+\varepsilon)} & \text{for} \quad (\varepsilon/t) > \epsilon_3 \end{cases}. \tag{40}$$

Second, consider the situation that both firms adopt standard E. Then, $\left(s_1^B, s_2^B\right) = (0,0)$ and welfare is:

$$W^B(E;E) = U_0 - c^A - c^{BE} - 2F - \frac{17}{48}t - \frac{\varepsilon}{2}. \tag{41}$$

Third, if firms in market B receive subsidies $\left(s_1^B, s_2^B\right) = (\underline{s}_1^B, \underline{s}_2^B)$, both firms adopt standard S, and welfare is:

$$W^B(S;S) = U_0 - c^A - c^{BE} - 2F - \frac{17}{48}t - \delta. \tag{42}$$

Therefore, these subsidies are sufficient to make both firms adopt standard S.

Finally, to determine the optimal policy, we must compare social welfare in expressions (40)-(42). From (40) and (41) we get:

$$W^B(S;E) - W^B(E;E) > 0 \quad \text{for} \quad \epsilon_2 < \varepsilon/t \leq \epsilon_3, \tag{43}$$

where $\epsilon_2 = \frac{4}{3}(\delta/t) - \frac{49}{72}$ and $\epsilon_3 = 2(\delta/t) + \frac{1}{3}$. From (40) and (42) we get:

$$W^B(S;E) - W^B(S;S) > 0 \quad \text{for} \quad \epsilon_3 < \varepsilon/t \leq \epsilon_4 \text{ and } \varepsilon/t \leq \epsilon_5, \tag{44}$$

where $\epsilon_4 = \frac{32}{5}(\delta/t)^2 + \frac{224}{15}(\delta/t) + \frac{302}{45}$ and $\epsilon_5 = 8(\delta/t) + \frac{22}{3}$. Together, these expressions determine the intervals for subsidies in market B that are given in Proposition 2 and displayed in Figure 3.

$$\left(s_1^B, s_2^B\right) = \begin{cases} (0,0) & \text{for} \quad 0 < \varepsilon/t \leq \epsilon_2 & \text{(Region I)} \\ (\underline{s}_1^B, 0) & \text{for} \quad \epsilon_2 < \varepsilon/t \leq \epsilon_3 & \text{(Region II')} \\ (s_{\max}^B, 0) & \text{for} \quad \epsilon_3 < \varepsilon/t \leq \epsilon_4 \text{ and } \varepsilon/t \leq \epsilon_5 & \text{(Region II")} \\ (\underline{s}_1^B, \underline{s}_2^B) & \text{for} \quad \epsilon_4 < \varepsilon/t & \text{(Region III)} \end{cases}$$

where $s_{\max}^B = \frac{(3t+\delta)\varepsilon - 4t\delta - t^2}{2t+\varepsilon}$.

8.3 Proof of Proposition 3

If indirect subsidies are given to firms in market A this yields social welfare:

$$W^A = \begin{cases} U_0 - c^A - c^{BE} - 2F - \frac{17}{48}t - \frac{\varepsilon}{2} & 0 \leq \varepsilon/t \leq \epsilon_1 & \text{(Region I)} \\ U_0 - c^A - c^{BE} - 2F - \frac{17}{48}t - \delta & \epsilon_1 < \varepsilon/t & \text{(Region III)} \end{cases}.$$

If direct subsidies are given to firms in market A this yields social welfare:

$$W^B = \begin{cases} U_0 - c^A - c^{BE} - 2F - \frac{17}{48}t - \frac{\varepsilon}{2} & \text{for} \quad 0 < \varepsilon/t \leq \epsilon_2 & \text{(Region I)} \\ U_0 - c^A - c^{BE} - 2F - \frac{19t+96\delta+24\varepsilon}{192} & \text{for} \quad \epsilon_2 < \varepsilon/t \leq \epsilon_3 & \text{(Region II')} \\ U_0 - c^A - c^{BE} - 2F - \frac{2\left(240t\delta - 144\delta^2 + 53t^2\right) + 3\varepsilon(83t + 192\delta)}{576(2t+\varepsilon)} & \text{for} \quad \epsilon_3 < \varepsilon/t \leq \epsilon_4 \text{ and } \varepsilon/t \leq \epsilon_5 & \text{(Region II")} \\ U_0 - c^A - c^{BE} - 2F - \frac{17}{48}t - \delta & \text{for} \quad \epsilon_4 < \varepsilon/t & \text{(Region III)} \end{cases}.$$

Comparing social welfare in each region, we choose between subsidies to S-based firms in markets A and B that lead to higher social welfare:

$$W^{A,B} = \begin{cases} W^B > W^A & \text{for} \quad \epsilon_2 < \varepsilon/t \leq \epsilon_3 & \text{(Region 2)} \\ W^B > W^A & \text{for} \quad \epsilon_3 < \varepsilon/t \leq \epsilon_4 \text{ and } \varepsilon/t \leq \epsilon_5 & \text{(Region 3)} \\ W^A = W^B & \text{for} \quad \epsilon_4 < \varepsilon/t & \text{(Region 4)} \end{cases},$$

where $\delta/t < 9/28$.

8.4 Proof of Proposition 4

If indirect or direct subsidies are given to firms in market A or B this yields social welfare:

$$W^{A,B} = \begin{cases} U_0 - c^A - c^{BE} - 2F - \delta - \frac{17}{48}t & \text{for} \quad 0 < \varepsilon/t \leq \epsilon_7 \text{ and } 0 < \delta/t \leq 3/2 & \text{(Region 1)} \\ U_0 - c^A - c^{BE} - 2F - \frac{23t+48\delta+54\varepsilon}{192} & \text{for} \quad 0 < \varepsilon/t \leq \epsilon_8 \text{ and } 3/2 < \delta/t \leq 9/4 & \text{(Region 2'AB)} \\ \begin{array}{l} U_0 - c^A - c^{BE} - 2F \\ -\frac{1}{576}\frac{480t\delta+249t\varepsilon-288\delta^2+576\delta\varepsilon+106t^2}{2t+\varepsilon} \end{array} & \text{for} \quad \begin{array}{l} \epsilon_8 < \varepsilon/t \leq \epsilon_9 \\ \text{and } 3/2 < \delta/t \leq 9/4 \end{array} & \text{(Region 2"AB)} \\ U_0 - c^A - c^{BE} - 2F - \delta - \frac{17}{48}t & \text{for} \quad \epsilon_7 < \varepsilon/t \text{ and } 0 < \delta/t \leq 3/2 & \text{(Region 3AB)} \\ U_0 - c^A - c^{BE} - 2F - \delta - \frac{17}{48}t & \text{for} \quad \epsilon_9 < \varepsilon/t \text{ and } 3/2 < \delta/t \leq 9/4 & \text{(Region 3AB)} \end{cases}.$$

Comparing social welfare we find the frontiers between Regions.

8.5 Proof of Proposition 5

If indirect or direct subsidies are given to firms in market A or B this yields social welfare:

$$W^{A,B} = \begin{cases} U_0 - c^A - c^{BE} - 2F - \frac{3}{32}t - \frac{5}{32}\varepsilon & \text{for} \quad 0 < \varepsilon/t \leq \epsilon_{10} \text{ and } 0 < \varepsilon/t \leq \epsilon_{11} & \text{(Region 1)} \\ U_0 - c^{BE} - c^A - 2F - \frac{1}{48}\frac{85t\varepsilon+24\varepsilon^2+40t^2}{8t+5\varepsilon} & \text{for} \quad \epsilon_{11} < \varepsilon/t \leq \epsilon_{12} & \text{(Region 2A)} \\ U_0 - c^A - c^{BE} - 2F - \delta - \frac{3}{32}t - \frac{1}{32}\varepsilon & \text{for} \quad \epsilon_{10} < \varepsilon/t \text{ and } \epsilon_{12} < \varepsilon/t & \text{(Region 3B)} \end{cases}.$$

Comparing social welfare we find the frontiers between Regions.

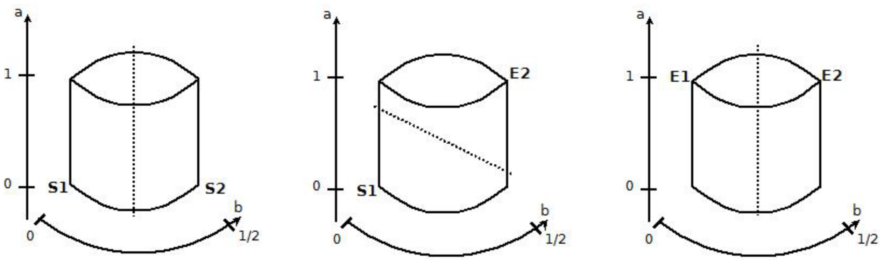

Figure 1: The structure of a market for system goods. The dashed line shows how the market is divided between producers of S- and E-based system goods.

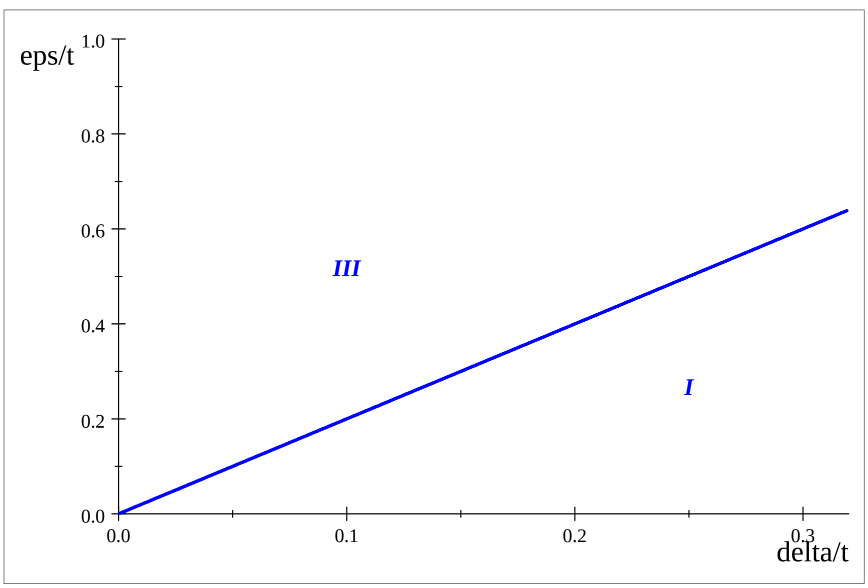

Figure 2: The four regions for optimal subsidies in market A for the superior technology adoption.

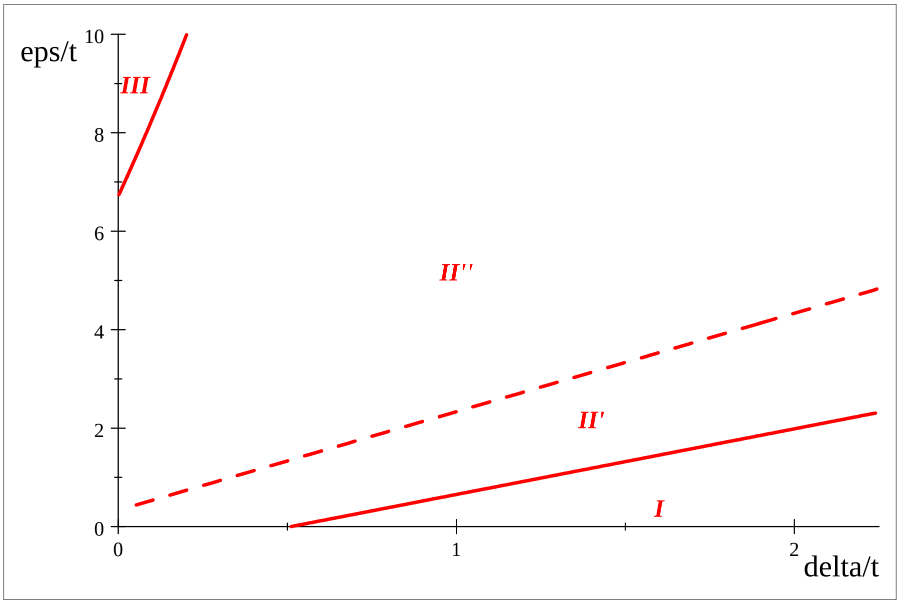

Figure 3: The four regions for optimal subsidies in market A for the superior technology adoption.

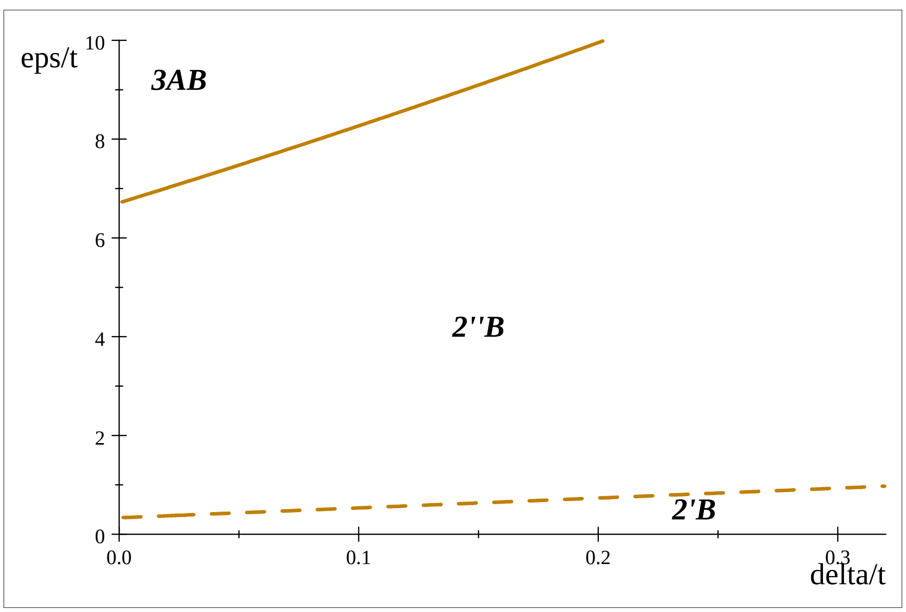

Figure 4: The three regions for optimal policy interventions in markets A and B.

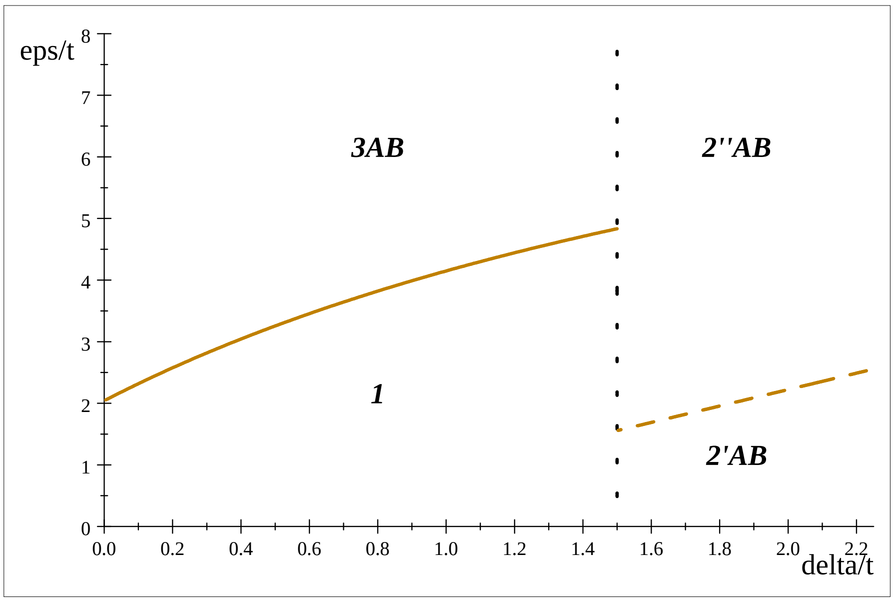

Figure 5: The five regions for optimal policy interventions in markets A and B.

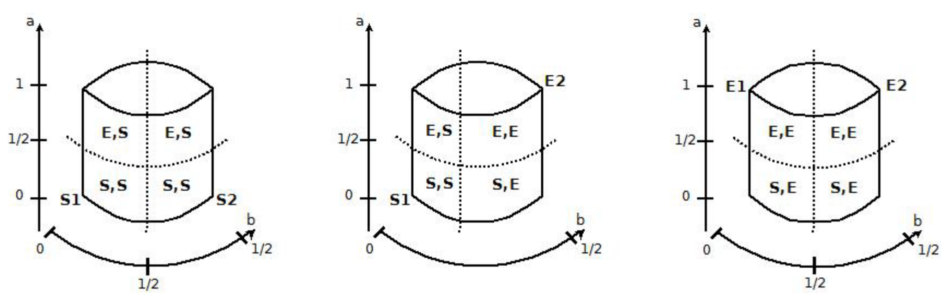

Figure 6: The structure of a market for system goods in the case of perfect compatibility between S- and E-based components. The dashed line shows how the market is divided between different system goods.

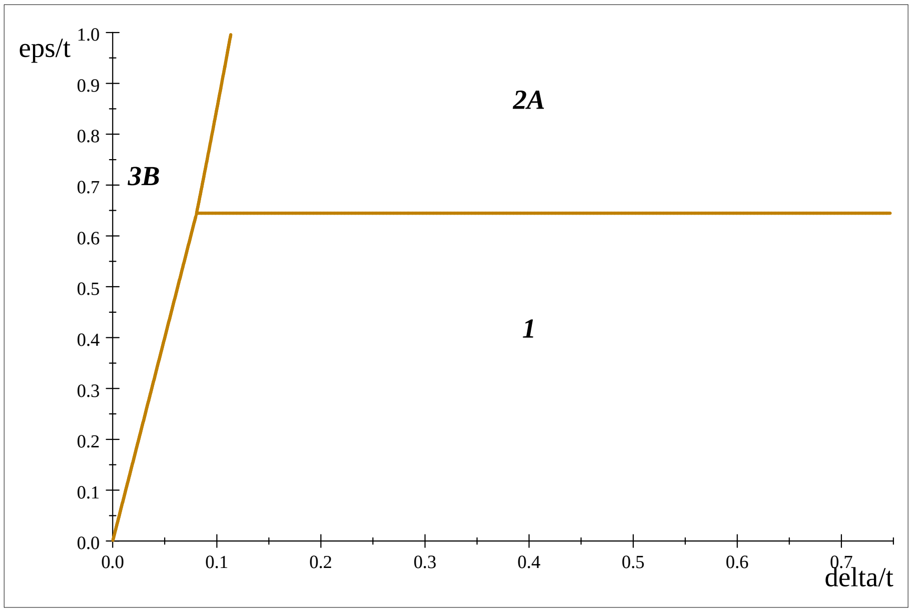

Figure 7: The four regions for optimal policy interventions in markets A and B with perfect compatibility.