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 the markets with system goods and two technological standards. An established standard incurs lower unit production costs but causes a negative externality. In the absence of policy intervention, with an established technological standard, firms have no incentives to adopt a superior standard. Therefore, the present paper compares the effect of direct and indirect cost-reducing subsidies in markets with system goods in the presence of externalities. The results suggest that when the cost difference between technological standards is high and the externality cost is low or intermediate, direct subsidies are socially preferable. However, when the externality cost is high and the cost difference is low, indirect subsidies lead to higher social welfare. In this case, the optimal indirect subsidy is lower than the direct subsidy. Moreover, it decreases with the number of adopters of the superior technological standard.

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1 Introduction

A disruptive innovation is a new technology that creates a new value and a new market, and disrupts an existing market, replacing an earlier technology. The adoption of disruptive technologies 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 policymakers 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, adoption and development of new technologies and products in markets for system goods often depends on public intervention.

The US, 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 and alternative fuel producers. 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 and tax incentives 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.[1] 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 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

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

internal 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 choosen 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). However, this project has not been approved by now.

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 in the former market 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 a 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.

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 technological standard. The conditions for optimal subsidies are indicated depending on the cost difference between standards and the impact of the externality. Intuitively, 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 the production using the superior standard. In case of indirect subsidies, the necessary amount of cost-reducing subsidies should be given to the producers of complementary component per volume of production using the superior standard. Finally, 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. Nevertheless, when the externality impact is high in comparison to the cost difference, indirect subsidies lead to higher social welfare. Furthermore, in this case, the indirect subsidy is lower than the direct subsidy and decreases with the number of adopters of the superior technological standard.

These results add to the discussion on the choice between direct and indirect subsidies. 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 high importance of environmental and national security concern. As a result of this policy, by the year 1990 90% of vehicle manufactures in Brazil used technology allowing to power vehicles by alcohol. This is in accordance to the results in the present paper, which argue in favour of indirect subsidies when the impact of externality is high. On the contrary, in the US the impact of environmental externality was not widely recognized until last decades. Thus, direct subsidies to car manufacturers were chosen. However, recently the importance of externalities, such as oil scarcity and global warming concern, rises. Following the results of the paper, indirect subsidies to producers of clean energy technologies (biofuels, electricity generation) should be implemented. Similarly, the importance of indirect subsidies is expected to grow in the EU. Recently, the discussion was initiated regarding the deployment of charging infrastructure all over Europe. The model results are presented in the context of optimal subsidy choice to enhance environmental performance in the markets for system goods. Nevertheless, these results provide a rationale for the optimal subsidy choice in a number of markets that share similar market structure in the presence of technology-related externalities.

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. The higher compatibility leads to socially more optimal timing of new product introduction and strengthens firms' R&D incentives, which turns to be welfare improving. 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.[2] When a direct network effect is present the installed base size 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 doesn't provide an insight to the problem of superior technology adoption that arises in the absence of network effects due to complementarity between goods.

The second strand of 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.[3] 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). It shows how the effect of these policies depends on market structure and consumers' preferences for goods. Sartzetakis and Tsigaris (2005) find that in the presence of 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 compare uniform policies (applied similarly to all firms) and policies that discriminate between firms based on

[2] The direct network effect means that increase in the number of consumers directly increases the value for all consumers of the good. The indirect network effect means that increase in the number of consumers lead to an increase in the value of a complementary goods that in turn can increase the value of the original good. For details see Economides and Salop (1992), Economides (1996) and Clements (2004).

[3] For example, see Rennings and Rammer (2009), Rennings and Rexhauser (2010) for details.

their environmental quality. According to their finding, in the presence of consumers awareness of the externality uniform as well as discriminatory subsidies reduce total pollution enhancing 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. 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 adoption of a cleaner technology in the car market when the main problem of technology adoption is a direct network effect is present. He suggests a cost subsidy for the cleaner technology adopters, or, alternatively, promotion of clean technology among consumers through advertisement campaign.

Despite the extensive literature on technology adoption the present model 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 network effect does not play a crucial role, for instance, the vehicle market. Second, it introduces an externality associated to one of the standards. This allows to derive important policy implications and makes the results of the paper coherent to the problem of transition to a new technology observed in practice.

The reminder of the paper is organized as follows. Section 2 presents a basic framework for our analysis. 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 if an alternative timing is applied. 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 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.[4]

Market B is assumed to be imperfectly competitive. Concretely, we assume a duopoly structure. As in Salop (1979) model, the two firms are symmetrically distributed 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

[4] This structure of the market for the complementary component reflects the absence of strategical interactions between firms. The examples of the complementary component producers for the car market can be petrol stations and electricity producers. There are many petrol stations and regulated electricity market, and the producers do not directly compete with each other. If there were one provider of each technology, the qualitative results would be the same, but with higher prices for the component A.

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 $t^A = t^B = t > 0$, where $t > 2\delta$.[5] 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. Components A and B based on different technological standards are incompatible. Consequently, a consumer located at (a, b) that buys S-based components A and B has utility $U^{SS} = U_0 - p^{AS} - at^A - p^{BS} - bt^B$. Analogically, the expression for U^{EE} is derived. 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 composite 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 different scenarios we obtain:

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

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

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

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

[5] This model is derived with linear transportation costs, although it can be shown that for quadratic transportation costs our results remain the same. Details are available upon request.

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 situated 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 choosed 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 of complementary markets 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, but the vehicles are considered as similar products. However, if the fuel for a specific type of vehicle is widely available and at a cheaper price then more value is derived of this vehicle. Therefore, due to complementarity between markets vehicle producers are "locked-in" with an established technology, though it causes a negative environmental externality. As another example, consider a 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 due to national security reasons, because in this case ESA (European Space Agency) has control over the signal avalibality. Therefore, national governments aiming to promote national GNS must provide incentives to the producers of services to switch to the national technological standards.

An important characteristic of the model is that it assumes 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 internal combustion engine. Before the car is bought consumers usually consider the availability of the parking place and all related infrastructure for the electric car in their living place. Once they know that the cars based on both technologies are available, they decide among which type of the car will they choose. Another example is the passenger vehicles that use GNS services. Once the municipality has information about availability of vehicles based on a foreign and national technology, the decision of public procurement is made taking into consideration political reasons. 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, the components A determine technological standards and involve permanent future cost for consumers. Therefore, their price is more impornant in the decision to buy an S- or E-based system good. In Section 5 of the paper the assumption that consumers make the choice of the system good before the prices on component B are derived is relaxed and the results are compared to the basic framework.

3 Equilibrium outcomes laissez faire

In stage 4, firms in market B compete as in the Salop model. In equilibrium, firms locate at maximum distance on the circle.[6] 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 $b^k = \left(p_2^{Bk} - p_1^{Bk}\right) / (2t) + 1/4$. So, the equilibrium demand of firm 1 is $D_1^k = 2b^k$

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

and that of firm 2 is $D_1^k = 1 - 2b^k$. Prices are determined by profit maximization as $p^{Bk} = c^{Bk} + t/2$. Thus, stage 3 equilibrium profits are:

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

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 $b = \left(2p_2^{BE} - 2p_1^{BS} + t\right)/(4t)$.[7] Consequently, equilibrium prices are:

$$p^{BS} = \frac{4c^{BS} + 2c^{BE} + 3t}{6} \quad \text{and} \quad p^{BE} = \frac{4c^{BE} + 2c^{BS} + 3t}{6}. \tag{5}$$

Consumer product choice in stage 3 depends on the technological standards chosen by the firms in market B. Three situations 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, too. 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 by the location of the consumer indifferent between the S- and E-based composite good. From $U^{SS} = U^{EE}$ we get that her location is:

$$a \equiv a(b) = \frac{1}{2t}\left(p^{AE} - p^{AS} + p^{BE} - p^{BS} + \frac{3}{2}t - 2bt\right). \tag{6}$$

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

$$a \equiv \frac{3}{4} - b - \frac{\delta}{6t}. \tag{7}$$

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:

$$\Pi_1^B(S;E) = \frac{(3t - 2\delta)(3t - \delta)}{36t} - F \quad \text{and} \tag{9}$$

$$\Pi_2^B(E;S) = \frac{(3t + 2\delta)(3t + \delta)}{36t} - F. \tag{10}$$

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

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 $9t - 2\delta < 0$. Substituting into (7), this yields $a < -b$ 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 subsections we derive equilibrium outcomes with 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:

$$a^A \equiv a^A(b) = \frac{3}{4} - b - \frac{\delta}{6t} + \frac{s^A}{2t}. \tag{11}$$

This is the corresponding expression to (7) with a subsidy in market A. Notice, that assumption 1 requires that $0 < s^A < \frac{3t+2\delta}{6}$.

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:

$$\Pi_1^B(S;E) = \frac{(3t - 2\delta)\left(3t - \delta + 3s^A\right)}{36t} - F \tag{13}$$

$$\Pi_2^B(E;S) = \frac{(3t + 2\delta)\left(3t + \delta - 3s^A\right)}{36t} - F. \tag{14}$$

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:

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

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

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

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* $s \geq \underline{s}_1^A \equiv \delta\frac{9t-2\delta}{9t-6\delta}$*. Given an S-based firm in market B, its rival adopts a superior standard S if it gets a subsidy* $s \geq \underline{s}_2^A = \delta\frac{9t+2\delta}{9t+6\delta}$*. 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 $s \geq \underline{s}_1^A \equiv \delta\frac{9t-2\delta}{9t-6\delta}$. 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 $s \geq \underline{s}_2^A \equiv \delta\frac{9t+2\delta}{9t+6\delta}$.[8] 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. **q.e.d.**

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

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

[8] 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.

We get the following result:

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

$$s^A = \begin{cases} 0 & \text{for} \quad 0 \le \varepsilon/t \le \epsilon_1 \quad \text{(Region I)} \\ \underline{s}_1^A & \text{for} \quad \epsilon_1 < \varepsilon/t \le \epsilon_2 \quad \text{(Region III)} \end{cases}$$

where $\epsilon_1 = 2(\delta/t)$ and $\epsilon_2 = 2 + 4(\delta/t)$, with $\epsilon_1 < \epsilon_2$.

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 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 $p_i^{BS} = c_1^{BS} - s^B + t/2$. 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:

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

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

$$a^B \equiv a^B(b) = \frac{3}{4} - b - \frac{\delta}{6t} + \frac{s^B}{6t}. \tag{20}$$

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:

$$\Pi_1^B(S;E) = \frac{\left(3t - \delta + s^B\right)\left(3t - 2\delta + 2s^B\right)}{36t} - F, \tag{22}$$

$$\Pi_2^B(E;S) = \frac{\left(3t + \delta - s^B\right)\left(3t + 2\delta - 2s^B\right)}{36t} - F. \tag{23}$$

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:

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

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

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

First, consider the minimum subsidy necessary to incite a first firm to adopt standard S. Second, consider the minimum subsidy necessary to incite a 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* $s \geq \underline{s}_2^B = \delta$.

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 result in Lemma 3 suggests that the incentives provided to the firms in the market B by the direct and indirect subsidies 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. The subsidy to the S-based producers in the 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 subsidies to a first and a second adopter of standard S, the policy maker must solve the problem:

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

We get the following result:

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

$$\left(s_1^B, s_2^B\right) = \begin{cases} (0,0) & \text{for} \quad 0 < \varepsilon/t \leq \epsilon_3 \quad \text{(Region I)} \\ (\underline{s}_1^B, 0) & \text{for} \quad \epsilon_3 < \varepsilon/t \leq \epsilon_1 \quad \text{(Region II')} \\ (s_{\max}^B, 0) & \text{for} \quad \epsilon_1 < \varepsilon/t \leq \epsilon_4 \quad \text{(Region II'')} \\ (\underline{s}_1^B, \underline{s}_2^B) & \text{for} \quad \epsilon_4 < \varepsilon/t \leq \epsilon_2 \quad \text{(Region III)} \end{cases}$$

where $s_{\max}^B = \frac{(3t+\delta)\varepsilon - 4t\delta}{2t+\varepsilon}$, $\epsilon_3 = \frac{4}{3}(\delta/t) - \frac{5}{18}$ and $\epsilon_4 = \frac{24}{7}(\delta/t)^2 + \frac{48}{7}(\delta/t) + \frac{10}{7}$, with $\epsilon_3 < \epsilon_1 < \epsilon_4 < \epsilon_2$.

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 delta is lower and negative externality is higher $s_{\max}^B$ 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:

$$(s_1, s_2) = \begin{cases} (0,0) & \text{for} \quad 0 < \varepsilon/t \leq \epsilon_3 \quad \text{(Region 1)} \\ (\underline{s}_1^B, 0) & \text{for} \quad \epsilon_3 < \varepsilon/t \leq \epsilon_1 \quad \text{(Region 2)} \\ (s_{\max}^B, 0) & \text{for} \quad \epsilon_1 < \varepsilon/t \leq \epsilon_4 \quad \text{(Region 3)} \\ \left\{\underline{s}_1^A, (\underline{s}_1^B, \underline{s}_2^B)\right\} & \text{for} \quad \epsilon_4 < \varepsilon/t \leq \epsilon_2 \quad \text{(Region 4)} \end{cases}$$

where $s_{\max}^A < s_{\max}^B$ and $\underline{s}_1^A > \underline{s}_1^B$, $\underline{s}_1^A < \underline{s}_1^B + \underline{s}_2^B$, and $\epsilon_3 < \epsilon_1 < \epsilon_4 < \epsilon_2$. 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.

Notice that a welfare maximizing direct subsidy in Region 4 is higher than an indirect subsidy. Therefore, an indirect subsidy provided to S-based firms in market A must be prefered. This is because the lower subsidy is more efficient in the presence of public cost of policy implementation. For instance, when the shadow costs of raising public funds are present (due to high administrative cost or corruption), lower subsidy leads to lower efficiency loss.

This result in a repeated context of this game can be interpreted as follows. Policies aimed at superior technology adoption should target firms in the principal market as well as firms in the markets with complementary goods. In the earlier stage of technology adoption, when the initial cost difference between the established and superior technology is crucial, it is better to provide direct subsidies to firms that potentially adopt superior technologies. However, when the cost barier is overcome, the impact of externality becomes relatively more important. Then indirect subsidies are necessary to stimulate the new technology adoption in the complementary markets. Furthermore, as the number of technology adopters in the principal market increases the optimal indirect subsidies decrease.

Until now, the policy makers in different countries choose one of the complementary markets for subsidizing. However, our results suggest that the efficiency of subsidies could be higher if both markets were taken in consideration. As the impact of externality (measured in terms of economic losses) can change in time, targeting one or the other complementary market might be more efficient. For instance, the policy recommendation to USA would be to pay more indirect subsidies to producers of clean energy technologies (biofuels, electricity generation) suggested by American Clean Energy and Security Act (ACES).

5 The timing of consumer choice

This Section examines the basic model introducing the modification in the timing of the game. 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 composite goods.

Now, 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 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 equlibrium 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

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

If the 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:

$$p_1^{BS} = \frac{3t + 2c_1^{BS} + c_2^{BE} + s^A}{3} \quad \text{and} \quad p_2^{BE} = \frac{3t + c_1^{BS} + 2c_2^{BE} - s^A}{3}. \tag{27}$$

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

$$D_1^S = \frac{3t - \delta + s^A}{6t} \quad \text{and} \quad D_2^E = \frac{3t + \delta - s^A}{6t}. \tag{28}$$

The resulting payoffs are:

$$\Pi_1^S(S,E) = \frac{\left(3t - \delta + s^A\right)^2}{18t} - F \quad \text{and} \quad \Pi_2^E(S,E) = \frac{\left(3t + \delta - s^A\right)^2}{18t} - F. \tag{29}$$

If the 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}:

$$p_1^{BS} = \frac{3t + 2c^{BS} + c_2^{BE} - 2s^B}{3} \text{ and } p_2^{BE} = \frac{3t + c^{BS} + 2c_2^{BE} - s^B}{3}.$$

The resulting demands are equal to 28. Because an S-based firm in market B is given direct subsidies, the resulting payoffs are the same as 29.

Lemma 4. *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 or S-based firms in market B get a subsidy* $s \geq \underline{s} \equiv \delta - \left(3 - \frac{3\sqrt{2}}{2}\right)t$.

Proof:
Firm 1 will change to a superior standard iff $\Pi_1^B(S;E) > \Pi_1^B(E;E)$. From equations (29) and (4) we find that this is true for $s \geq \underline{s} \equiv \delta - \left(3 - \frac{3\sqrt{2}}{2}\right)t$. 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 (29) and (4) we find that this is true if $s \geq \underline{s} \equiv \delta - \left(3 - \frac{3\sqrt{2}}{2}\right)t$.

Comparing the minimum subsidy obtained in Section 5 with the minimum subsidies obtained in Sections 3-4 we obtain the following proposition.

Proposition 4. For all δ the minimum subsidy $\underline{s}$ satisfies:

(i) $\underline{s} < \underline{s}_1^A$,

(ii) $\underline{s} < \underline{s}_1^B \equiv \underline{s}_2^B$.

Proof:

A straightforward comparison of subsidies eads to the result in Proposition 4.

The fact that consumers choose the system good after all prices are known, lowers the indirect and direct subsidies that are needed to provide sufficient incentives to adopters of technological standard S in market B. This result suggests that consumers' ex ante decision about which system good will be purchased creates inefficiencies increasing the optimal size of the subsidies. The higher is the degree of consumers decision "predetermination", the more we move from the situation, in which indirect and direct subsidies perform equally, to the situation, in which the one or another type of subsidy is prefereable depending on the externality and cost difference between the standards.

6 Concluding remarks

The present paper addresses optimal subsidy choice in the context of markets with complementary goods in the presence of externalities. Subsidies are aimed to enhance 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. We find that if the cost difference between technological standards is high and the externality cost is low or intermediate, direct subsidies are socially preferable. However, when the externality cost is high and the cost difference is low, indirect subsidies lead to higher social welfare. This is because in this case, the size of the subsidy decreases with the number of adopters of the superior technological standard and becomes lower than in the case of direct subsidies.

This result adds to the discussion on the choice between direct and indirect subsidies. For instance, in Brazil, where climate change threats to the economy and the country historically depended exclusively on imported fuel, the policy towards promotion of in-house ethanol production launched in 1975 has achieved its objective. By 1990, 90% of vehicles manufactures in Brazil used technology allowing to power vehicles by alcohol. On the contrary, in the US an impact of environmental externality hasn't been widely recognized until last decade. Thus, direct subsidies to car manufacturers were chosen, which is optimal according to our results. However, recently the importance of externalities (in terms of economy losses), such as oil scarcity and global warming concern rises. According to our result, this fact suggests in favour of large indirect subsidies to producers of clean energy technologies (biofuels, electricity generation) by 2025, which are under discussion lately in the framework of American Clean Energy and Security Act (ACES). Similarly, the importance of indirect subsidies is expected to grow in the EU. Large public investments into the deployment of charging infrastructure all over Europe are being discussed by politicians.

The model 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 GPS signal. Therefore, nowadays, the world market for satellite navigation is dominated by GPS, which is under military control of the US. For European economy this sector that 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, Galileo project was launched. The use of Galileo generates a number of positive externalities due to security and economic reasons. Therefore, the national government aiming at promotion of 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. The 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 in order to make conditions better than with GPS. Second, the direct subsidies can be given to private firms to adopt Galileo. In order to choose between the two policies, one should consider the impact of positive externality together with cost difference with two technologies used. 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. Because the positive externality is estimated as very high, and the cost difference is relatively small, our results suggest providing more beneficial contracts to firms for working with Galileo than with GPS.

Finally, apart from adoption of disruptive technologies, this model can also be applied in other contexts that arise in markets for system goods. An example is housing construction. The construction firms choose to build new housing in the densely populated city, where the infrastructure (kindergardens, schools, shops) is present or in the suburban district, where the infrastructure is absent or not developed enough. The houses are constructed in the city centre, the population density increases, which leads to a negative externality for all city population. Suppose that in order to improve urban design the municipality government aims at decrease of city center population by suburbs exploitation. Note, that some city habitants have stable preferences for the city center or for suburbs, independently of price of the housing. This is an example why the model assumption regarding timing is valid to some extent. Therefore, results of this paper can be applied by policy makers to choose whether the direct subsidies should be given to the construction firms in order to reduce their costs or the indirect subsidies should be given to the entreprises that create infrastructure.

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7 Appendix

7.1 Proof of Proposition 1

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

$$W^A(E,E) = U_0 - c^A - c^{BE} - 2F - \frac{5}{8}t - \frac{\varepsilon}{2}. \tag{30}$$

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

$$W^A(S,S) = U_0 - c^A - c^{BE} - 2F - \frac{5}{8}t - \delta. \tag{31}$$

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

Finally, to determine the optimal policy, we must compare social welfare in expressions (30) and (31). We get:

$$W^A(S,S) - W^A(E,E) > 0 \quad \text{for} \quad \epsilon_1 < \varepsilon/t \le \epsilon_2, \tag{32}$$

where $\epsilon_1 = 2(\delta/t)$ and $\epsilon_2 = 2 + 4(\delta/t)$. This expression determines the intervals for subsidies in market A, which are given in Proposition 1 and displayed in Figure 2.

7.2 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:

$$\max_{s^B > \underline{s}^B} W^B(S;E) = U_0 - c^A - c^{BE} - 2F - \frac{4s(s+4\delta) + 72t\delta - 20\delta^2 + 75t^2}{144t} - \frac{\varepsilon}{72}\frac{(3t+\delta-s)^2}{t^2}. \tag{33}$$

The welfare maximizing subsidy is $s^B_{\max} = \frac{(3t+\delta)\varepsilon - 4t\delta}{2t+\varepsilon}$. This subsidy must fulfill the restriction $s^B_{\max} \ge \underline{s}^B_1$ to provide sufficient incentives to firm 1 to adopt the standard S. This is:

$$\left(s_1^B, s_2^B\right) = \begin{cases} (\underline{s}_1^B, 0) & \text{for} \quad (\varepsilon/t) \le \epsilon_1 \\ (s^B_{\max}, 0) & \text{for} \quad (\varepsilon/t) > \epsilon_1 \end{cases}, \tag{34}$$

where $\epsilon_1 = 2(\delta/t)$. Consequently, we have:

$$W^B(S;E) = \begin{cases} U_0 - c^A - c^{BE} - 2F - \frac{25t+24\delta+6\varepsilon}{48} & \text{for} \quad (\varepsilon/t) \le \epsilon_1 \\ U_0 - c^A - c^{BE} - 2F - \frac{48t\delta+37t\varepsilon-24\delta^2+48\delta\varepsilon+50t^2}{48(2t+\varepsilon)} & \text{for} \quad (\varepsilon/t) > \epsilon_1 \end{cases}. \tag{35}$$

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

$$W^B(E;E) = U_0 - c^A - c^{BE} - 2F - \frac{5}{8}t - \frac{\varepsilon}{2}. \tag{36}$$

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:

$$W^B(S;S) = U_0 - c^A - c^{BE} - 2F - \frac{5}{8}t - \delta. \tag{37}$$

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 (35)-(37). From (35) and (36) we get:

$$W^B(S;E) - W^B(E;E) > 0 \quad \text{for} \quad \epsilon_3 < \varepsilon/t \leq \epsilon_1, \tag{38}$$

where $\epsilon_3 = \frac{4}{3}(\delta/t) - \frac{5}{18}$. From (35) and (37) we get:

$$W^B(S;E) - W^B(S;S) > 0 \quad \text{for} \quad \epsilon_1 < \varepsilon/t \leq \epsilon_4, \tag{39}$$

where $\epsilon_4 = \frac{24}{7}(\delta/t)^2 + \frac{48}{7}(\delta/t) + \frac{10}{7}$. Together, these expressions determine the intervals for subsidies in market A that are given in Proposition 1 and displayed in Figure 3.

7.3 Proof of Proposition 3

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

$$W^A = \begin{cases} U_0 - c^A - c^{BE} - 2F - \frac{5}{8}t - \frac{\varepsilon}{2} & 0 \leq \varepsilon/t \leq \epsilon_1 \quad \text{(Region I)} \\ U_0 - c^A - c^{BE} - 2F - \frac{5}{8}t - \delta & \epsilon_1 < \varepsilon/t \leq \epsilon_2 \quad \text{(Region III)} \end{cases}.$$

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

$$W^B = \begin{cases} U_0 - c^A - c^{BE} - 2F - \frac{5}{8}t - \frac{\varepsilon}{2} & \text{for} \quad 0 < \varepsilon/t \leq \epsilon_3 \quad \text{(Region I)} \\ U_0 - c^A - c^{BE} - 2F - \frac{25t+24\delta+6\varepsilon}{48} & \text{for} \quad \epsilon_3 < \varepsilon/t \leq \epsilon_1 \quad \text{(Region II')} \\ U_0 - c^A - c^{BE} - 2F - \frac{48t\delta+37t\varepsilon-24\delta^2+48\delta\varepsilon+50t^2}{48(2t+\varepsilon)} & \text{for} \quad \epsilon_1 < \varepsilon/t \leq \epsilon_4 \quad \text{(Region II")} \\ U_0 - c^A - c^{BE} - 2F - \frac{5}{8}t - \delta & \text{for} \quad \epsilon_4 < \varepsilon/t \leq \epsilon_2 \quad \text{(Region III)} \end{cases}.$$

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:

$$W^{A,B} = \begin{cases} W^A = W^B & \text{for} \quad 0 < \varepsilon/t \leq \epsilon_3 \quad \text{(Region 1)} \\ W^B > W^A & \text{for} \quad \epsilon_3 < \varepsilon/t \leq \epsilon_1 \quad \text{(Region 2)} \\ W^B > W^A & \text{for} \quad \epsilon_1 < \varepsilon/t \leq \epsilon_4 \quad \text{(Region 3)} \\ W^A = W^B & \text{for} \quad \epsilon_4 < \varepsilon/t \leq \epsilon_2 \quad \text{(Region 4)} \end{cases}.$$

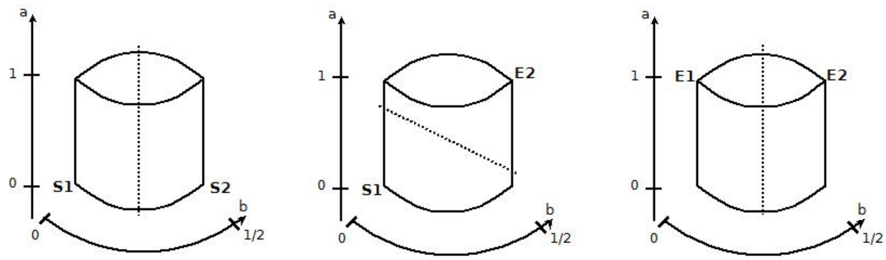

Figure 1: The structure of a market for system goods. The dashed line shows how the market is divided between producers of S- and E-based system goods.

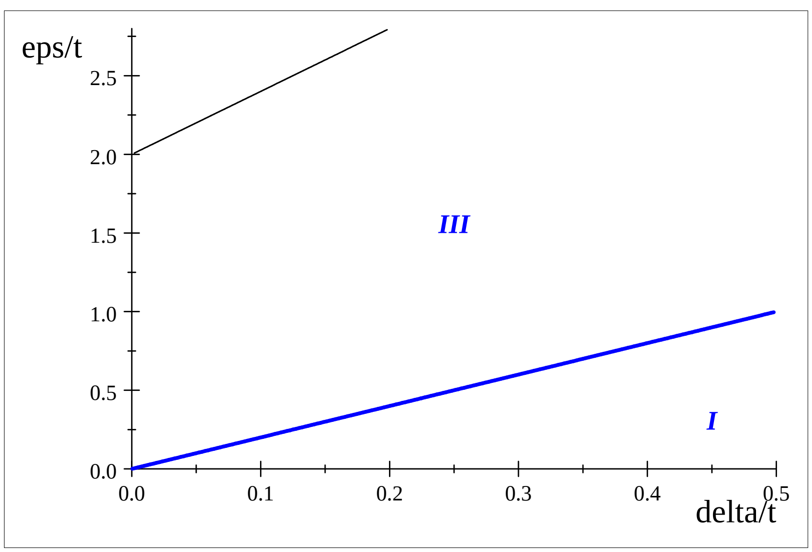

Figure 2: The four regions for optimal subsidies in market A for the superior technology adoption.

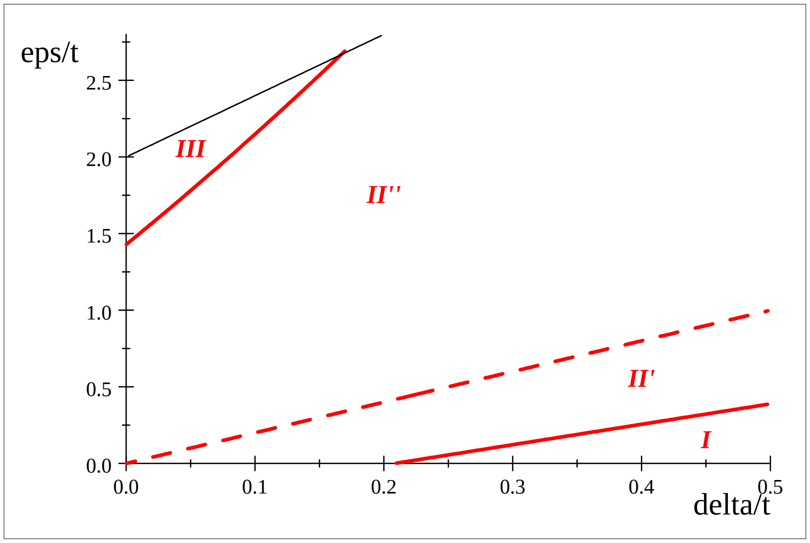

Figure 3: The four regions for optimal subsidies in market B for the superior technology adoption.

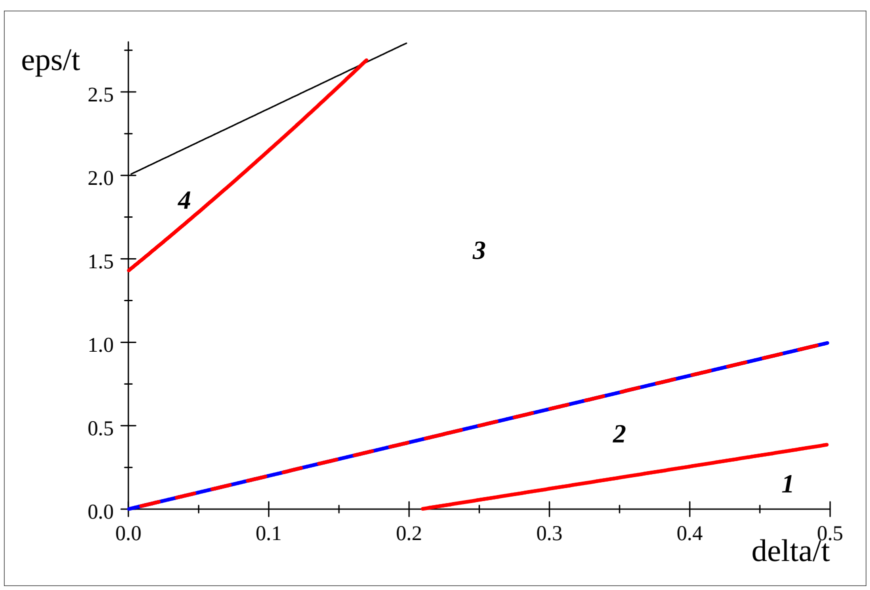

Figure 4: The six regions for optimal policy interventions in markets A and B.