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Environmental Quality Competition and Taxation in the Presence of Green Network Effect Among Consumers

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Abstract We examine the impact of a "green network effect" in a market characterized by consumers' environmental awareness and competition between firms in terms of both environmental quality and product prices. The unique aspect of this model comes from the assumption that an increase in the number of consumers of green (brown) product increases the satisfaction of each green (brown) consumer. We show that, paradoxically, when the network effect of a green product is higher than that of a brown product, this externality reduces product environmental quality and raises consumption of the green product. Conversely, when the network effect of the brown product is higher, the externality improves product environmental quality and raises consumption of the brown product. In both cases, the network effect does not affect the overall pollution level. The externality correction requires the use of three optimal fiscal policies: an *ad valorem* tax on products, an emission tax, and a subsidy or a tax on the green purchase. A second-best optimum can also be reached through the green taxation.

Keywords Consumer behavior · Environmental quality · Network effect · Vertical differentiation · Taxation

1 Introduction

Green products make up an increasingly greater proportion of household expenditure. According to the most recent European Commission surveys (2008, 2009), 83 % of Europeans pay great attention to product environmental impact when making a purchase. 75 % are "ready to buy environmentally friendly products even if they cost a little bit more", compared to 31 % in 2005. However, in 2008, only 17 % had recently bought "products marked with

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an environmental label". In the United States, a recent survey shows that 82 % of consumers continue to buy green, despite the battered economy, even if it costs more.[1]

Green purchasing is primarily motivated by a certain degree of consumer ecological consciousness and by social norms. This consciousness stems from concern about environmental problems and a desire to improve the environment. Frey and Stutzer (2006) have identified a number of reasons behind "environmental motivation": intrinsic motivations, altruism, internalized norms and social norms. Intrinsic motivations are based on individual tastes and ethical values. Altruism, the opposite of egotism, implies that the green product consumers take into account the benefit that their consumption brings to other present and future members of society, through the preservation or improvement of environmental quality. Internalized norms refers to individual morals: the guilt felt when polluting the planet by consuming polluting products and the warm glow resulting from green purchases. Social norms lead individuals to take the opinions of the other members of society into consideration when choosing a green product over another: if they think that their acquaintances approve of green product purchases and disapprove of standard product purchases, there are encouraged to buy green products. For instance, one American consumer out of five claims that word of mouth is a key factor in green purchase decisions.

There is a link to the idea developed by Veblen (1899) and Leibenstein (1950), who emphasized that consumers are aware of the consumption choices of others. This awareness may be explained, for certain products, by consumer vanity or the *snob effect,* which is mainly characterized by the purchase of luxury goods and stems from the satisfaction arising from having a rare product, owned by few consumers. In the case of green products, consumers seem more characterized by a certain conformity or *bandwagon effect*, defined by Leibenstein (1950) as "the extent to which the demand for a commodity is increased due to the fact that others are also consuming the same commodity". Accordingly, several empirical papers highlight the positive influence of social norms in green consumption. Pieters et al. (1998) show that Dutch pro-environmental behavior is positively influenced by both the behavior and ability attributed to other households. Wiser (2007) stresses that, in the United States, people who are willing to pay for renewable energy are more likely to believe that many other Americans would reciprocate and also pay a premium for renewable energy. Welsch and Kûhling (2009) outline that, in Germany, the use of solar thermal systems, the subscription to green electricity and the purchase of organic food are all three conditioned by the consumption patterns of reference persons. The experiment of Carlsson et al. (2010) highlights that the proportion of consumers choosing environmentally-friendly coffee over standard coffee plays a significant and positive role in women's willingness-to-pay for environmenatally-friendly coffee. On the other hand, few papers emphasize an eco-snob effect in green consumption. Maynard (2007) and Barringer (2008) emphasize a "kind of a green pride", like driving a Prius or buying a passive house, especially among celebrities. This conspicuous consumption seems more likely to encourage consumers to be among the first ones to buy green, without turning away from green cars, houses and other visible environmentally friendly products when they become more popular. Furthermore, celebrities' behavior may incite other people to adopt the same eco-friendly products. Therefore, in this paper, we adopt the assumption of a positive spillover effect, or bandwagon effect, of the consumption of green products: the pleasure of consuming a green or a brown product increases with the number of consumers doing the same thing.

[1] Survey conducted in January 2009 by Green Seal and Enviro Media and carried out on 1,000 consumers (www.greenseal.org/resources/green_buying_research.cfm (accessed 21/10/2009)).

The spillover effect in brown consumption can be explained by the feeling that individual action can only play a minor role in the improvement of the environment, leading some consumers to turn away from green products. Indeed, among the 85 % of Europeans who claim to make an effort to protect the environment, more than half do not believe that their efforts have an impact as long as others and the major polluters (corporations and industry) do not do the same (European Commission 2005). These two reasons go a long way to explaining why 15 % of Europeans rarely or never make environmentally motivated choices. Once again, we encounter the idea that the lower the number of green consumers and the higher the number of brown consumers, the lower the individual motivation for green consumption. Some constraints can also limit the purchase of green products, including economic reasons (high prices, budget constraints) and cognitive reasons (lack of information about environmental problems, product features).

A number of consumer surveys show a further feature of green products: most consumers perceive them as having a higher (environmental) quality than their competitors. Indeed, European Commission (2008, 2005) and OCDE (2002) studies emphasize that if they were sold at the same price as their more polluting counterparts, a large majority of consumers would turn towards green products. This assumption has been commonly assumed in the literature since Cremer and Thisse (1999) article, in particular by Lombardini-Riipinen (2005).In this paper, we also adopt this assumption of a market that is vertically differentiated for environmental reasons.[2]

The uniqueness of our model principally stems from the assumption of a network effect in a green market. This assumption is related to that adopted by Grilo et al. (2001). They formalize the effects of both consumer vanity and consumer conformity on product differentiation and competition between firms. Their analysis differs from that in this paper in that it draws upon a model encompassing both cases of horizontal and vertical differentiation[3] and does not deal with product environmental quality. They show two interesting results in the case of conformity: "when bandwagon effects are present but not too strong, both firms remain in business but price competition is fiercer and results in lower equilibrium price" and "when bandwagon effects are strong enough, different price equilibria may coexist in which either firm captures the whole market." The originality of our analysis lies in that it focuses on a green market and aims to provide insight for environmental policies. To our knowledge no previous analysis has been carried out on the network effect in green markets.

In this paper, we study the impact of the network effect not only on company price and quality strategies, but also on the social optimum. We emphasize that, when the green product network effect is higher than that of the brown product, the externality tends paradoxically to lower the environmental quality of both products. Conversely, when the brown product network effect is the highest, the externality improves the environmental quality of products. In both cases, the network effect has no effect on product differentiation. With regard to the first-best optimum, a green market equilibrium leads to an excess of differentiation, an excessively low standard quality, an excessively low (high) green quality when the marginal environmental damage is high (low) and insufficient consumption of the green product when the green network effect dominates. Nevertheless, using taxation, the regulator is able to

2 See also Amacher et al. (2004), Eriksson (2004), Conrad (2005), Motta and Thisse (1999), Brecard (2008), Arora and Gangopadhyay (1995), Moraga-González and Padrón-Fumero (2002), Poyago-Theotoky and Teerasuwannajac (2002), Bansal and Gangopadhyay (2003).

3 Lambertini and Orsini (2005) transcribe the vanity assumption into a market where products are vertically differentiated. They focus on a positional effect such that the utility consumers derive from the high-quality product decreases with the number of consumers of the same product. Their model differs from ours since we assume the high and the low quality products benefit from positive consumption externality.

move the market equilibrium towards the optimum. We show that the association of an *ad valorem* tax, a pollution tax and a subsidy or a tax for the green purchase can reconcile equilibrium and optimum. Our analysis of the second-best optimum shows that green taxation alone achieves an improvement in social welfare.

The remainder of the paper is organized as follows. In Sect. 2, we introduce the model. In Sect. 3, we study the unregulated equilibrium and the impact of the network effect on equilibrium qualities and prices. In Sect. 4, we examine the first-best optimum. In Sect. 5, we introduce taxation, investigate the regulated equilibrium and deal with optimal taxation. Section 6 is a conclusion.

2 The model

We assume that the environmental characteristics of a product do not affect the other characteristics of the product. A green product is thus viewed as being of better quality than the standard product and is therefore more expensive. As in the models of vertical product differentiation developed by Mussa and Rosen (1978) and Cremer and Thisse (1999), each firm produces one variant of a product and decides on its price. Each consumer only gains satisfaction from the consumption of the first unit of the product and buys one unit of the product or none. Hence, our framework is the same as that of Lombardini-Riipinen (2005). We introduce a green network effect, assuming that the consumer of a product is aware of the number of people purchasing the same product.

Consumer preferences are represented by the following utility function $u_i(\theta)$:

$$u_i(\theta) = \theta q_i - p_i + \alpha_i n_i \quad i = l, h \tag{1}$$

with θ an ecological consciousness parameter which is uniformly distributed over $[\underline{\theta}, \bar{\theta}]$ with a unit density function ($\underline{\theta} = \bar{\theta} - 1$ and $\bar{\theta} > 1$), θq_i willingness-to-pay for quality q_i ($q_h \geq q_l$), p_i the price of product i, and n_i the number of consumers buying the product i. We assume that the network effect only works in a positive way for both products, each benefiting from a network effect $\alpha_i \geq 0$. Moreover, this effect plays linearly, since no analytical solution of the model could be provided with a more general form, which would be more realistic.

Faced with a "green" quality q_h and a "brown" quality q_l ($q_h > q_l$), only consumers with a parameter $\theta \geq \tilde{\theta} = p_1/q_1$ purchase. The consumer indifferent between buying the brown product ql at price p_l or the green product qh at price p_h is characterized by:

$$\hat{\theta} = \frac{p_h - p_l - \alpha_h \bar{\theta} - \alpha_l \left(\bar{\theta} - 1\right)}{q_h - q_l - \alpha_h - \alpha_l} \tag{2}$$

Through concern for simplicity, we assume that the market is covered and thus that $\tilde{\theta} \leq \underline{\theta}$.[4] Accordingly, the demand functions are defined by $n_h = \bar{\theta} - \hat{\theta}$ and $n_l = 1 - n_h$ such as:

$$n_h = \frac{\bar{\theta}\,(q_h - q_l) - (p_h - p_l) - \alpha_l}{q_h - q_l - \alpha_h - \alpha_l} \tag{3}$$

Both firms enjoy positive market shares[5] if $q_h - q_l > \alpha_h + \alpha_l$ and $p_h - p_l \in](\bar{\theta} - 1)(q_h - q_l) + \alpha_h, \bar{\theta}(q_h - q_l) - \alpha_l[$. Without network effect, the demand functions are

[4] The analytical results of this model are hugely more difficult to provide and to analyse when we assume that the market is not covered. Without network effect and with a cost parameter c equal to one, Motta (1993) only succeeds in giving a numerical solution of the game.

[5] See Appendix A1.

the same as in Lombardini-Riipinen (2005). All other things being equal, the introduction of α_i tends to increase the demand for product i. Accordingly, the global impact of the network effect depends on the relative size of α_h and α_l.

The ecological quality of the product i is defined by the abatement effort of firm i: $q_i = \bar{e} - e_i$, where $\bar{e}$ is the emissions per unit of output when no abatement investments are carried out and e_i is the actual emissions per unit, after abatement, of firm i. Quality is then defined over the interval $[0, \bar{e}]$. Furthermore, the firms' unit production costs are assumed, in line with Cremer and Thisse (1994, 1999), to be independent of quantity, strictly increasing and convex in quality, with the quadratic form $c(q_i) = \frac{1}{2}cq_i^2$. We also assume, following Cremer and Thisse (1999), Amacher et al. (2004), Eriksson (2004), Conrad (2005) and Lombardini-Riipinen (2005) that abatement is achieved through a variable production cost, so that firms' profits are defined by:

$$\pi_i = (p_i - c(q_i))\, n_i \quad i = h, l \tag{4}$$

The competition between firms takes place in a two-stage game. In the first stage, the environmental quality, q_i, to produce is decided on. In the second stage, prices, p_i, are chosen.

Here the economy is characterized by three market failures: imperfect competition, a network effect and pollution. The issue of behavior optimality is thus particularly relevant. In order to analyze this question, we define welfare as the sum of the consumers' surpluses and the firms' profits less the environmental damage. Note that the welfare function should not necessarily include the network effect.[6] Indeed, the diffusion of a green (brown) product will both increase its intrinsic value, through greater perceived quality and usefulness (wastefulness) for the environment of the green product, and its extrinsic value, through the "warm glow" effect arising from greater recognition by others. Whereas the intrinsic value must be included in welfare, the "warm glow" effect should be excluded according to Andreoni (2006) and Diamond (2006). Since we do not distinguish between these two value types in our model, we include the network effect in the welfare function. This assumption is usual in models with network effects in line with the seminal paper of Katz and Shapiro (1985), surveyed by Shy (2011), including those dealing with social network effects (Friedman and Grilo 2005; Lambertini and Orsini 2005). Accordingly, welfare is defined as:

$$W = CS_h(q_h, q_l) + CS_l(q_h, q_l) + \pi_h(q_h, q_l) + \pi_l(q_h, q_l) - D(E) \tag{5}$$

The surplus of consumers of a product i is defined, as usual, by $CS_i(q_h, q_l) = \int_{\hat{\theta}_i}^{\bar{\theta}_i} u_i(\theta)\, df(\theta)$, with $\hat{\theta}_l = \bar{\theta} - 1$, $\bar{\theta}_l = \hat{\theta}_h = \hat{\theta}$ and $\bar{\theta}_h = \bar{\theta}$. Environmental damage is the monetary equivalent of the consequences of polluting emissions from society in its entirety. It is defined in a linear function of overall emissions E: $D(E) = \delta E$, with $\delta \geq 0$ and $E \equiv e_h n_h + e_l(1 - n_h)$. The regulator role consists of guiding the economic actors towards optimal behavior, i.e. behavior which maximizes social welfare. The introduction of corrective fiscal policies in the fourth section of the paper will lead us to add state revenue to the welfare components.

In order to ensure the existence of a sub-game perfect equilibrium and of a first-best optimum, we will assume thereafter that the network effect fulfills conditions (C1): $\alpha_i \leq 1/(16c)$ for $i = h, l$.[7]

[6] We thank an anonymous reviewer for bringing this issue to our attention. For a discussion on the issue of the definition of welfare in behavioral economics, see Bernheim and Rangel (2005) and Atkinson (2011).

[7] We will show in the appendix that these conditions allow the existence of a unique unregulated equilibrium ($\alpha_i < 9/(16c)$) and of the first best optimum ($\alpha_i < 1/(16c)$).

3 The unregulated equilibrium

In this section, we examine the game equilibrium in the case of *laissez-faire* and focus on the analysis of the green network effect, which distinguishes this model from the Lombardini-Riipinen (2005)'s one.

The game is solved using backward induction in order to provide the sub-game perfect equilibrium. Conditions (C1) ensure the existence of a unique regulated equilibrium and positive market shares for both firms. We also assume that $\bar{\theta}$ is sufficiently high to ensure full market coverage (see Appendix A1).

In the second stage, firms compete on price knowing the product qualities decided on in the first stage. Maximization of profit (4) with respect to price induces the following equilibrium prices of the sub-game:

$$p_h = \frac{(q_h - q_l)\left(\bar{\theta}+1\right) - (\alpha_h + 2\alpha_l)}{3} + \frac{1}{3}cq_h^2 + \frac{1}{6}cq_l^2$$
$$p_l = \frac{(q_h - q_l)\left(2-\bar{\theta}\right) - (2\alpha_h + \alpha_l)}{3} + \frac{1}{6}cq_h^2 + \frac{1}{3}cq_l^2 \quad (6)$$

All other things being equal, the higher network effect α_h is, the lower the willingness-to-pay for both products of the indifferent consumer $\hat{\theta}$ will be, through the substitution effect between $\hat{\theta}q_h$ and $\alpha_h n_h$ in utility function $u_h(\hat{\theta})$. Accordingly, the brown firm must reduce its price in order to curb its loss in market share and profit, whereas the green firm's reaction function is independent of α_h. The impact of network effect α_l is, the lower the willingness a higher $\hat{\theta}$ which leads to a defensive price strategy of the green firm. In other words, a rise in α_h shifts the brown firm's reaction function towards the left while a rise in α_h shifts the green firm's reaction function downward. This induces a decrease in both prices, reinforced by the property of strategic complementarity in prices.

In the first stage, firms decide on quality levels by maximizing their profits (4) and anticipating the prices (6) of the second stage. We show in appendix A1 that, when condition (C1) is fulfilled, the only equilibrium of the quality game is defined by[8]

$$q_h^* = \frac{4\bar{\theta}+1}{4c} - \frac{\alpha_h - \alpha_l}{\Phi}$$
$$q_l^* = \frac{4\bar{\theta}-5}{4c} - \frac{\alpha_h - \alpha_l}{\Phi} \quad (7)$$

with $\Phi \equiv 3 - 4c\,(\alpha_h + \alpha_l)$ and, according to (C1), $\Phi > 0$.

The green network effect generates two contradictory impacts on qualities: whereas a rise in α_h shifts the green firm's reaction function downward and the brown firm's one to the left of the quality space, leading to lower qualities, a rise in α_l shifts the curves in the other directions, leading to better qualities. Accordingly, a large $\alpha_i\,(i = h, l)$ induces, all other things being equal, a fall in prices, which involves a firm trade-off between a lower production cost, requiring a poorer quality, and a larger market share, entailing a better quality (for a given rival quality). The first effect dominates the second one when α_h grows, whereas the second effect is predominant when α_l grows. Qualities being strategic complements, the effect of α_h and α_l on the abatement effort is reinforced. As a consequence, equilibrium qualities decrease

[8] Note that $q_h^{**} > 0$ and $q_l^{**} > 0$, since, for the highest $\alpha_h = 1/16c$ and the lowest $\alpha_l = 0$, qualities are minimal and equal to $q_h^* = (22\bar{\theta}+5)/22c$ and $q_h^* = (11\bar{\theta}-14)/22c$, with $\bar{\theta} > 14/11$ under market coverage condition (see Appendix A.3).

with α_h and increase with α_l but qualities are unaffected by the network effect when $\alpha_h = \alpha_l$. Moreover, product differentiation is independent of the externality ($q_h^* - q_l^* = 3/2c$).[9]

According to (6) and (7), the prices, the demand for the green product and the firms' profits are defined by:

$$p_h^* = \frac{16\bar{\theta}^2 + 8\bar{\theta} + 25}{32c} - \frac{\alpha_h + \alpha_l}{2} + \frac{c\left(\alpha_h - \alpha_l\right)^2}{2\Phi^2} - \frac{\left(\alpha_h - \alpha_l\right)\left(12\bar{\theta} - 9 + 8c\left(\alpha_h + \alpha_l\right)\right)}{12\Phi}$$

$$p_l^* = \frac{16\bar{\theta}^2 - 40\bar{\theta} + 49}{32c} - \frac{\alpha_h + \alpha_l}{2} + \frac{c\left(\alpha_h - \alpha_l\right)^2}{2\Phi^2} - \frac{\left(\alpha_h - \alpha_l\right)\left(12\bar{\theta} - 3 - 8c\left(\alpha_h + \alpha_l\right)\right)}{12\Phi} \quad (8)$$

$$n_h^* = \frac{1}{2} + \frac{2c\left(\alpha_h - \alpha_l\right)}{3\Phi} \quad (9)$$

$$\pi_h(q_h^*, q_l^*) = \left(\frac{3}{2c} - \left(\alpha_h + \alpha_l\right)\right) n_h^* 2$$

$$\pi_l(q_h^*, q_l^*) = \left(\frac{3}{2c} - \left(\alpha_h + \alpha_l\right)\right) \left(1 - n_h^*\right)^2 \quad (10)$$

The green network effect influences prices, qualities and market shares differently according to the size of α_h compared with that of α_l. Insofar as product differentiation remains the same whatever the extent of the green network effect, the intensity of price competition remains constant. However, a large α_h (respectively α_l) reduces (resp. increases) prices because of the network effect itself and also the lower (resp. higher) product quality. Although, without a network effect, firms share the demand equitably, α_h (resp. α_l) favors the green (resp. brown) product firm, by increasing its market share and its profit. In contrast, the brown (resp. green) product firm is penalized by the externality, which reduces its market share. It is worth noting that, when $\alpha_h = \alpha_l$, denoted α, the green network effect does not affect the qualities but reduces both prices from amount α and profits from amount $\alpha/2$ with regard to the situation without network externality, described by Lambertini and Orsini (2005).

When the products are sold at prices (8) with equilibrium qualities (7), welfare, defined by the equation (5), is written:[10]

$$W^* = \frac{\bar{\theta}\left(\bar{\theta} - 1\right)}{2c} + \frac{9}{32c\Phi^2} + \frac{\left(\alpha_h + \alpha_l\right)\left(9 - 8c\left(\alpha_h + \alpha_l\right)\right)}{18\Phi} - \frac{4c\alpha_h\alpha_l\left(39 - 40c\left(\alpha_h + \alpha_l\right)\right)}{18\Phi^2} - \delta\left(\bar{e} - \frac{\delta\left(2\bar{\theta} - 1\right)}{2c}\right) \quad (11)$$

Main results of the green network effect are summarized in proposition 1 below.

Proposition 1 *At the sub-game perfect equilibrium, a larger α_h tends to decrease environmental qualities and prices and to raise the market share and the profit of the green firm, to*

[9] Lambertini and Orsini (2005) obtain a similar result with the assumption of consumer vanity. In their model and ours, the fall in both qualities induced by a rise in α_h arises from the positive externality from which high-quality consumers benefit. Although the origin of the externality is different, vanity in one case, conformity in the other, this effect allows the high-quality firm to decrease the quality of its product while enjoying an unchanged demand (all other things being equals).

[10] According to several simulations with a range of suitable values for $\bar{\theta}$, c, α_l and α_h, welfare rises with α_h and α_l, which favor the global consumers' surplus and reduces, to a lesser extent, the global firms' profits, without affecting pollution.

the detriment of the brown firm, whereas the impact of a larger α_l *is opposite. When* $\alpha_h = \alpha_l$*, qualities are unaffected by the network externality, while prices and profits decrease in response of a higher network effect. In all cases, the product differentiation is independent of* α_h *and* α_l*.*

Proof See Appendix A1. □

4 The first-best optimum

The first-best optimum is reached when, for each product, the marginal benefit of consumption is equal to the marginal social cost of production, and also when the allocation of consumers between both qualities is optimal (see Cremer and Thisse 1999; Lombardini-Riipinen 2005). The three green market failures (imperfect competition, network effect and pollution) lead us to give new definitions for product prices and for the environmental consciousness parameter for the consumer indifferent to both products, compared to those used for the equilibrium.

The optimal product prices correspond here to the marginal social cost net of the positive consumption externality, i.e. the marginal production cost plus the marginal environmental damage, minus the marginal benefit of the network effect.[11] Hence, the "fair prices" are the following (see appendix A2):

$$\begin{aligned} p_h^o &= \frac{c}{2} q_h^o 2 + \delta\left(\bar{e} - q_h^o\right) - \alpha_h n_h^o \\ p_l^o &= \frac{c}{2} q_l^o 2 + \delta\left(\bar{e} - q_l^o\right) - \alpha_l\left(1 - n_h^o\right) \end{aligned} \tag{12}$$

Welfare is defined, as in equation (5), as the sum of the consumers' surpluses and the firms' profits less the environmental damage, but here firms sold their products at their optimal prices. Since the optimal prices reflect the social cost of production net of the network effect, the welfare at the first best optimum can be reduced to the following equation:

$$W = \int_{\bar{\theta}-1}^{\hat{\theta}^\circ} \left[\theta q_l - p_l^o\right] d\theta + \int_{\hat{\theta}^\circ}^{\bar{\theta}} \left[\theta q_h - p_h^o\right] d\theta \tag{13}$$

$$\text{with} \quad \hat{\theta}^\circ = \frac{p_h^o - p_l^o - \alpha_h \bar{\theta} - \alpha_l\left(\bar{\theta} - 1\right)}{q_h - q_l - \alpha_h - \alpha_l} \tag{14}$$

The optimal qualities of the green and brown products are defined by:

$$\begin{aligned} q_h^O &= \frac{\bar{\theta} + \delta}{c} - \frac{1 - 16c\alpha_l}{4c\left(1 - 8c\left(\alpha_h + \alpha_l\right)\right)} \\ q_l^O &= \frac{\bar{\theta} + \delta}{c} - \frac{3 - 16c\left(\alpha_h + 2\alpha_l\right)}{4c\left(1 - 8c\left(\alpha_h + \alpha_l\right)\right)} \end{aligned} \tag{15}$$

At the optimum, differentiation is lower than at the unregulated equilibrium ($q_h^o - q_l^o = 1/2c$). This is explained by the behavior of the firms that want to raise product differentiation in order to relax price competition. Differentiation remains at the optimum independent of the

[11] We could have defined the optimal price of a product as its marginal social cost (the production cost plus the environmental damage) and explicitly kept marginal social benefits from consumption (the willingness to pay for a product plus the network effect) in the welfare function. This would have provided the same results for the first-best optimum.

extent of the network effect. The equilibrium green quality is too low (resp. high) when the marginal damage, δ, is higher (resp. lower) than given thresholds, whereas the brown quality is always too low.[12] In addition, the optimal allocation of consumers corresponds to a demand for the green (resp. brown) product higher than that at equilibrium when $\alpha_h > \alpha_l$ (resp. $\alpha_h < \alpha_l$):[13]

$$\hat{\theta}^o = \bar{\theta} - \frac{1}{2} - \frac{4c(\alpha_h - \alpha_l)}{1 - 8c(\alpha_h + \alpha_l)} \tag{16}$$

This difference in demand arises from the network effect alone.

Welfare at the first-best optimum is therefore defined by:

$$W^o = \frac{16\bar{\theta}\left(\bar{\theta} - 1\right) - 32c(\alpha_h + \alpha_l)\left(2\bar{\theta} - 1\right)^2 - 256c^2\alpha_h\alpha_l + 5}{32c(1 - 8c(\alpha_h + \alpha_l))} + \frac{\delta\left(2\bar{\theta} - 1 + \delta\right)}{2c} - \delta\bar{e} \tag{17}$$

Obviously, first-best optimal welfare is higher than welfare at the equilibrium. This is due, in particular, to an overall optimal pollution lower than that at the game equilibrium:

$$E^o = \bar{e} - \frac{2\bar{\theta} - 1}{2c} - \frac{\delta}{c} \leq E^* = \bar{e} - \frac{2\bar{\theta} - 1}{2c} \tag{19}$$

We therefore deduce Proposition 2 below.

Proposition 2 *In comparison with the unregulated equilibrium, the first-best optimum is characterized by: a higher abatement effort of the brown firm, a stronger abatement effort of the green firm when the marginal damage is sufficiently high, a higher green demand when $\alpha_h > \alpha_l$ and a higher brown demand when $\alpha_l > \alpha_h$, and a lower product differentiation. That always entails less pollution and greater social welfare.*

5 Optimal taxation

We envisage three fiscal policies: a pollution tax in order to limit excessive environmental damage, an *ad valorem* tax in order to reduce product differentiation, and a subsidy or tax for the green product[14] in order to favor network externality. Doing this, we draw on a framework close to the one proposed by Lambertini and Orsini (2005). However, the introduction of the green network effect means a corrective policy including three instruments rather than two.

With consumers of the green product benefiting from the subsidy,[15] $s_h \geq 0$, or paying a tax, $s_h \leq 0$, the net price of the green product is $p_h - s_h$ and, according to equation (3), the demand for the green product becomes:

$$n_h = \frac{\bar{\theta}(q_h - q_l) - (p_h - p_l - s_h) - \alpha_l}{q_h - q_l - \alpha_h - \alpha_l} \tag{20}$$

[12] This threshold is defined by: $\tilde{\delta} = \frac{1}{2} + \frac{5c(\alpha_h - \alpha_l)}{(1-8c(\alpha_h+\alpha_l))\Phi}$. For the brown quality, we can show that $q_l^o > q_l^*$ when $\delta > -\frac{1}{2} + \frac{5c(\alpha_h - \alpha_l)}{(1-8c(\alpha_h+\alpha_l))\Phi}$, which is always negative when $\alpha_h - \alpha_l \leq 1/16c$.

[13] At the equilibrium, $\hat{\theta} = \bar{\theta} - \frac{1}{2} - \frac{2c(\alpha_h - \alpha_l)}{3\Phi}$.

[14] We could, alternatively, assume a subvention for both products. In all results of the game, the subvention s_h would be replaced by $s_h - s_l$.

[15] The subsidy s_h is here different from the one assumed by Lambertini and Orsini (2005), who weights the subsidy by the gap between both qualities $(q_h - q_l)$.

The firms are subject to an emission tax and a product tax. Their profits are thus rewritten as follows (with $i = h, l$):

$$\pi_i = ((1 - t_v)\, p_i - c\,(q_i) - \tau_e\,(\bar{e} - q_i))\, d_i = \frac{1}{\tau_v}\,(p_i - \tau_v c\,(q_i) - \tau_v \tau_e\,(\bar{e} - q_i))\, d_i \quad (21)$$

with t_v the *ad valorem* tax defined over [0, 1], $\tau_v = 1/(1 - t_v)$ an index of the *ad valorem* tax defined over $[1, +\infty)$, and τ_e the pollution tax defined over $[0, +\infty)$. In order to ensure the existence of a regulated game equilibrium, we assume that the network effect fulfills conditions (C2): $2\alpha_h + \alpha_l < 9/(8c\tau_v) - s_h$ and $\alpha_h + 2\alpha_l < 9/(8c\tau_v) + s_h$, and that $\bar{\theta}$ is sufficiently large to guarantee full market coverage (see Appendix A.3).

Following the same game solution process as in Sect. 3, we show in Appendix A.3 that there exists a unique sub-game perfect equilibrium. The equilibrium qualities are the following[16]:

$$q_h^{**} = \frac{12\bar{\theta} + 3}{4\tau_v c \Phi_v} - \frac{2\left(2\bar{\theta}\,(\alpha_h + \alpha_l) + \alpha_h + s_h\right)}{\Phi_v} + \frac{\tau_e}{c}$$
$$q_l^{**} = \frac{12\bar{\theta} - 15}{4\tau_v c \Phi_v} - \frac{2\left(2\bar{\theta}\,(\alpha_h + \alpha_l) - 2\alpha_h - 3\alpha_l + s_h\right)}{\Phi_v} + \frac{\tau_e}{c} \quad (22)$$

with $\Phi_v \equiv 3 - 4c\tau_v\,(\alpha_h + \alpha_l)$ and $\Phi_v > 0$.

The environmental tax motivates firms to enhance the quality of their products, whereas the subsidy (resp. tax) encourages them to reduce (resp. increase) quality. Notwithstanding this, neither of them affects product differentiation ($q_h^{**} - q_l^{**} = 3/(2\tau_v c)$). This is only influenced by the *ad valorem* tax, which, as showed by Cremer and Thisse (1994), tends to decrease differentiation. This effect brings about a reduction of the ecological quality and lower deterioration, or an improvement, of the standard quality.[17]

The demand for the green product is given as:

$$n_h^{**} = \frac{1}{2} + \frac{2\tau_v c\,(2s_h + \alpha_h - \alpha_l)}{3\Phi_v} \quad (23)$$

It is stimulated by the subsidy for green purchases and the *ad valorem* tax and reduced by a tax on the green product, but is not affected by the environmental tax. Both firms enjoy positive demand since (C2) is fulfilled.

The firms' profits are defined by:

$$\pi_h(q_h^{**}, q_l^{*}) = \frac{1}{\tau_v}\left(\frac{3}{2\tau_v^c} - (\alpha_h + \alpha_l)\right) n_h^{**2}$$
$$\pi_l(q_h^{**}, q_l^{**}) = \frac{1}{\tau_v}\left(\frac{3}{2\tau_v^c} - (\alpha_h + \alpha_l)\right) \left(1 - n_h^{**}\right)^2 \quad (24)$$

The profits at the regulated equilibrium are independent of the level of the pollution tax, which affect qualities and prices of both firms in the same way. The *ad valorem* tax reduces the profits. The subsidy (resp. tax) increases the profits of the green (resp. brown) firm to the detriment of its competitor.

Only implementation of the three fiscal instruments can motivate firms to supply the optimal qualities at "fair prices" to consumers while leading demand for the green product to its optimal level. The optimal taxation is described in Proposition 3 below.

[16] The expression of equilibrium prices is relegated in Appendix A.3.

[17] The proof of the effects of τ_v on qualities, demand and profits are given in Appendix A.3.

Proposition 3 *When (C1) and (C2) are fulfilled, the first-best optimum can be reached through the combination of the following ad valorem tax, environmental tax and subsidy or tax of the green purchase:*

$$\left(\tau_v^o, \tau_e^o, s_h^o\right) = \left(3,\ \delta + \frac{2}{3}\left(\bar{\theta} - \frac{1}{2}\right),\ \frac{(\alpha_h - \alpha_l)\,(5 - 16c\,(\alpha_h + \alpha_l))}{2\,(1 - 8c\,(\alpha_h + \alpha_l))}\right)$$

Proof. The first best optimal taxation $\left(\tau_v^o, \tau_e^o, s_h^o\right)$ has to equalize the equilibrium values of qualities, prices and demand, and their optimal values. It is the single solution of the system of three equations $q_h^{**} = q_h^o$, $q_l^{**} = q_l^o$ and $n_h^{**} = n_h^o$.

The *ad valorem* tax and the environmental tax are the same as those given by Lombardini-Riipinen (2005). This result is not surprising insofar as the network effect affects neither the product differentiation nor the pollution at the equilibrium. The *ad valorem* tax is equal to 2/3 while the environmental tax is higher than the marginal damage, δ, in order to correct the harmful effect of the product tax on pollution levels. The optimal subsidy is null if the spillover doesn't come into play or if $\alpha_h = \alpha_l$. It is positive (resp. negative) when $\alpha_h > \alpha_l$ (resp. $\alpha_h < \alpha_l$); the greater α_h and the lower α_l, the greater (resp. lower) the optimal subsidy (resp. tax)[18] in order to stimulate the demand for the green (resp. brown) product.

When the regulator is only responsible for environmental policies, they cannot guide the economy towards the first best optimum. Therefore, we investigate how an environmental tax or subsidy for green purchase can lead to a second best optimum. We ignore the *ad valorem* tax because it has the propensity to increase pollution and, hence, is not suitable for an environmental policy (see Lambertini and Orsini 2005; Brecard 2008)

The second best optimum is characterized by maximum welfare when prices and qualities are those chosen by the firms at the regulated equilibrium. Welfare is thus defined by:

$$W^{**} = CS_h^{**} + CS_l^{**} + \pi_h^{**} + \pi_l^{**} + GR^{**} - \delta E^{**} \tag{25}$$

with $GR^{**} = \tau_e E^{**} - s_h n_h^{**}$ the government revenue coming from the environmental tax paid by the firms (redistributed to consumers as a lump sum) from which the subsidy (resp. tax) paid to green product consumers is deducted (resp. added) (financed by a lump sum tax or subsidy paid by the whole consumer base).

At the regulated game equilibrium, the pollution tax has no impact on product differentiation, firms' market share and profits. Nevertheless, it raises the qualities and the prices of the products. Without other corrective policies, welfare is defined by:

$$W_{\tau_e}^{**} = W^* + \tau_e \frac{2\delta - \tau_e}{2c} \tag{26}$$

Accordingly, the second best environmental tax $\hat{\tau}_e$ is here equal to the Pigouvian tax δ. This result is the same as that of Lombardini-Riipinen (2005) because the network effect has no effect on pollution and thus on the policy that aims at reducing it. Furthermore, because of the assumption of full market coverage, the tax does not induce any reduction in the firms' supply.

In case of the green purchase subsidy or tax, the welfare is characterized by:

$$W_s^{**} = W^* + 2cs_h \frac{(\alpha_h - \alpha_l)\,(21 - 16c\,(\alpha_h + \alpha_l)) + s_h\,(3 + 8c\,(\alpha_h + \alpha_l))}{18\Phi^2} \tag{27}$$

The subsidy (resp. tax) tends to improve welfare beyond that achieved without the environmental policy when $\alpha_h > \alpha_l$ (resp. $\alpha_l > \alpha_h$). Consequently, when $\alpha_h > \alpha_l$, the green

[18] $\partial s^o/\partial\alpha_h = (128c^2(\alpha_h + \alpha_l)^2 - 16c(2\alpha_h + 5\alpha_l) + 5)/2(1 - 8c(\alpha_h + \alpha_l))^2 \geq 0$ and $\partial s^o/\partial\alpha_l = -(128c^2(\alpha_h + \alpha_l)^2 - 16c(5\alpha_h + 2\alpha_l) + 5)/2(1 - 8c(\alpha_h + \alpha_l))2 \leq 0$.

purchase aid must be maximal. It is defined by $\hat{s}_h = \frac{9}{8c} - (2\alpha_h + \alpha_l)$ and leads to the disappearance of the brown product ($n_h^{**} = 1$). When $\alpha_l > \alpha_h$, the green tax is defined by $\hat{s}_h = -\frac{9}{8c} + \alpha_h + 2\alpha_l$ and leads to a brown monopoly ($n_h^{**} = 0$).

The joint use of the two fiscal instruments achieves an increase in welfare, without reaching the welfare level at the first best optimum.[19] When $\alpha_i > \alpha_j\,(i, j = h, l, i \neq j)$, the monopoly supplies the quality $\hat{q}_i = \left(2\bar{\theta} + 2\delta - 1\right)/2c$ at price $\hat{p}_i = \left(4\bar{\theta}^2 - 4\bar{\theta} + 13 - 4\delta^2\right)/(8c) - \alpha_h - \alpha_l + \delta\bar{e}$ and earns a profit $\hat{\pi}_i = 3/2c - \alpha_i$. The welfare reaches then the threshold $W^{**}_{s+\tau_e} = \left(2\bar{\theta} + 2\delta - 1\right)^2/(8c) + \alpha_i - \delta\bar{e}$.

The combination of the pollution tax and the green purchase subsidy is however likely to be subject to budget constraints when $\alpha_h > \alpha_l$. In this case, the subsidy arises from equality $\hat{\hat{s}}_h n_h = \tau_e E$. It is defined by:

$$\hat{\hat{s}}_h = \frac{-9 + 8c(\alpha_h + 2\alpha_l) + \sqrt{(9 - 8c(\alpha_h + 2\alpha_l))^2 + 96\delta(3 - 4c(\alpha_h + \alpha_l))(1 + 2c\bar{e} - 2\delta - 2\bar{\theta})}}{16c} \quad (28)$$

This subsidy is lower than the maximal one, $\hat{s}_h$. The equilibrium qualities are therefore lower and the green consumers are fewer. Welfare is also lower than with the maximal subsidy.

We sum up the results of second best taxation in Proposition 4 below.

Proposition 4 *When (C1) and (C2) are fulfilled, a second best optimum can be reached through the combination of the Pigouvian tax and a maximal green subsidy* $\hat{s}_h = \frac{9}{8c} - (2\alpha_h + \alpha_l)$ *when* $\alpha_h > \alpha_l$, *or a green tax* $\hat{s}_h = -\frac{9}{8c} + \alpha_h + 2\alpha_l$ *when* $\alpha_l > \alpha_h$. *The firm benefiting from the largest network effect becomes then a monopolist. When* $\alpha_h > \alpha_l$, *if the subsidy is entirely financed by the environmental tax, a second best optimum can arise from the combination of the Pigouvian tax and green subsidy* $\hat{\hat{s}}_h$, *lower than* $\hat{s}_h$.

It is worth noting that, when $\alpha_l > \alpha_h$, the correction of the consumption externality requires taxing the green product and favoring brown demand. This policy will not affect pollution, which is independent of the network effects and the subsidy or tax for the green product. However, since such a policy is not in accordance with the basic idea of an environmental policy, we could imagine that a regulator would like to change the environmental social norm in order to avoid the case where $\alpha_l > \alpha_h$. Consumer behavior could be oriented towards green consumption, through "green nudges", which consist of promoting environmental social norms and, in this way, inciting consumers to environmentally-friendly behavior, without being prescriptive or guilt-inducing (Centre d'Analyse Stratégique 2011). In our model, "green nudges" could entail a rise in α_{h} and a drop in α_{l} to such an extent that $\alpha_h > \alpha_l$.

6 Conclusion

Taking into account the effect that the number of consumers of a product has on their satisfaction on consuming that product has given new results about the workings of a green market.

Firm behavior is not only influenced by consumer willingness to pay for ecological quality, as shown by Lombardini-Riipinen (2005), but also by the green network effect. Paradoxically, when the green product network effect is stronger than that of the brown product, this effect

[19] $W^{**}_{s+\tau_e} = W^o - (1 - 16c\alpha_i)^2/(32c\,(1 - 8c\,(\alpha_h + \alpha_l)))$ *with* $\alpha_i > \alpha_j$, $i = h, l$, $i \neq j$.

pushes firms to decrease both the quality and the prices of their products, although product differentiation is not impacted by externality. It benefits the green firm, which sees its market share and its profit rise to the detriment of its competitor. Conversely, when consumers are more influenced by the number of brown consumers than by the number of green consumers, the network effect encourages firms to improve the qualities and the prices, but differentiation remains unchanged. Moreover, whatever the relative network effect of products, the network effect results in an improvement in welfare, although it doesn't affect total pollution.

The network externality cannot however alone compensate for the effects of pollution and imperfect competition on welfare. It doesn't change the tendency of firms to over-differentiate their products and to over-pollute in comparison with the first-best optimum. Nevertheless, the spillover effect is at the origin of inefficiency in the green product demand. The implementation of an appropriate taxation system allows the reconciliation of the equilibrium to the optimum. We have shown that the optimal combination of an *ad valorem* tax, a pollution tax and a subsidy for green purchase can achieve this when the green product network effect is higher than that of brown product. When the brown product network effect is the highest, the subsidy must be replaced by a tax on green products. When the regulator only has environmental policy tools, the optimal policy consists of imposing a Pigouvian tax, equal to the marginal damage, and a subsidy for the green purchase that eventually removes the brown product firm from the market or a tax on green product that leads to a brown monopoly.

This paper completes the analysis initiated by Cremer and Thisse (1999) and drawn out by Lombardini-Riipinen (2005). It takes advantage of recent literature dealing with the effects of the number of consumers of a product on the satisfaction arising from its consumption (Grilo et al. 2001). Even if our model has the merit of being relatively simple, it would undoubtedly gain from being generalized to the case of a partially covered market. The network effect could then influence total production and, in this way, total pollution. This would certainly modify optimal taxation, in particular the pollution tax. Furthermore, the way of introducing the network externality in consumers' utility function could be refined in order to investigate whether non-linear network effects would change our results.

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Appendix

A1 Proofs for the unregulated equilibrium

In order to prove results for the unregulated equilibrium, please set the taxation parameters as follows in Appendix A3: $\tau_v = 1$, $\tau_e = 0$ and $s_h = 0$.

Proof of Proposition 1.

Denoting $x_{\alpha_i} \equiv \partial x / \partial \alpha_i$ $(i = h, l)$, we deduce from (7) to (10) that, when (C1) and market coverage conditions are verified:

$$\begin{aligned}
q^*_{i\alpha h} &= -\frac{3 - 8c\alpha_l}{\Phi^2} < 0, \quad q^*_{i\alpha_l} = \frac{3 - 8c\alpha_h}{\Phi^2} > 0 \\
p^*_{h\alpha_h} &= -1 + 2cq_h q_{h\alpha_h} + cq_l q_{l\alpha_h}/3 \leq 0, \quad p^*_{h\alpha_l} = (-2 + 2cq_h q_{h\alpha_l} + cq_l q_{l\alpha_l})/3 \geq 0 \\
p^*_{l\alpha_h} &= (-2 + cq_h q_{h\alpha_h} + 2cq_l q_{l\alpha_h})/3 \leq 0, \quad p^*_{l\alpha_l} = (-1 + cq_h q_{h\alpha_l} + 2cq_l q_{l\alpha_l})/3 \geq 0 \\
n^*_{h\alpha} h &= \frac{2c\,(3 - 8c\alpha_l)}{3\Phi^2} > 0, \quad n^*_{h\alpha_l} = -\frac{2c\,(3 - 8c\alpha_l)}{3\Phi^2} < 0
\end{aligned}$$

$$\pi^*_{h\alpha_h} = \frac{9+36c(\alpha_h-\alpha_l)-32c^2\alpha_h(\alpha_h+\alpha_l)}{6\Phi^2}n_h > 0$$
$$\pi^*_{l\alpha_h} = \frac{-63+36c(3\alpha_h+5\alpha_l)-32c^2\left(2\alpha_h^2+5\alpha_h\alpha_l+3\alpha_l^2\right)}{6\Phi^2}(1-n_h) < 0$$
$$\pi^*_{h\alpha_l} = \frac{-63+36c(5\alpha_h+3\alpha_l)-32c^2\left(3\alpha_h^2+5\alpha_h\alpha_l+2\alpha_l^2\right)}{6\Phi^2}n_h < 0$$
$$\pi^*_{l\alpha_l} = \frac{9-36c(\alpha_h-\alpha_l)-32c^2\alpha_l(\alpha_h+\alpha_l)}{6\Phi^2}(1-n_h) > 0$$
$$W^*_{\alpha_h} = \frac{243-72c(7\alpha_h+20\alpha_l)+96c^2\left(6\alpha_h^2+19\alpha_h\alpha_l+29\alpha_l^2\right)-256c^3\left(\alpha_h^3+3\alpha_h^2\alpha_l+8\alpha_h\alpha_l^2+6\alpha_l^3\right)}{36\Phi^3} \geq 0$$
$$W^*_{\alpha_h} = \frac{243-72c(20\alpha_h+7\alpha_l)+96c^2\left(19\alpha_h^2+19\alpha_h\alpha_l+6\alpha_l^2\right)-256c^3\left(6\alpha_h^3+8\alpha_h^2\alpha_l+3\alpha_h\alpha_l^2+\alpha_l^3\right)}{36\Phi^3} \geq 0$$

The signs of $p^*_{i\alpha_l}, \pi^*_{i\alpha_j}$ and $W^*_{\alpha_i}$ have been verified by plotting numerators for $\alpha_i \in [0, 1/16c]$ for a range of suitable values for $\bar{\theta}$ and c, using *Mathematica* software.

A2 Proofs for the first-best optimum

Proof of existence and uniqueness of the first-best optimum

Let p_l^o be the optimal price of the standard product, the price of the green product maximizing the welfare defined by (13) is the solution of:

$$p_h^o = p_l^o + \frac{c}{2}\left(q_h^2-q_l^2\right)-\delta\left(q_h^- q_l\right)+\alpha_l + \frac{(\alpha_h+\alpha_l)\left(c\left(q_h^2+q_l^2\right)-2\left(\bar{\theta}+\delta\right)(q_h-q_l)+4\alpha_l\right)}{2\left(q_h-q_l-2(\alpha_h+\alpha_l)\right)} \quad \text{(A1)}$$

We deduce that the optimal number of consumers of green products is defined by:

$$n_h^o = \frac{2\left(\bar{\theta}+\delta\right)\left(q_h^- q_l\right)-c\left(q_h^2+q_l^2\right)-4\alpha_l}{2\left(q_h-q_l-2(\alpha_h+\alpha_l)\right)} \quad \text{(A2)}$$

Using (A2) and the definition of p_l^o in (12), (A1) can be rewritten as follows:

$$p_h^o = \frac{c}{2}q_h^2+\delta(\bar{e}-q_h)-\alpha_h n_h \quad \text{(A3)}$$

The definition of p_h^o in (A3) is the same as in (12). Therefore, our definitions of the optimal prices allow to maximizing the welfare.

By substituting the optimal prices in the welfare function (13) and solving the maximization conditions for optimal qualities, we can compute five candidates for the optimum, including only one solution satisfying the SOC and the stability condition. We can show that when the optimal qualities are defined by (15), the following second derivatives are definitely negative if (C1) are fulfilled:

$$\partial^2 W/\partial q_h^2\big|_{q_h^o,q_l^o} = -\frac{c(1-16c\alpha_l)\left(3-16c(3\alpha_h+2\alpha_l)+128c^2(\alpha_h+\alpha_l)^2\right)}{8(1-8c(\alpha_h+\alpha_l))^2(1-4c(\alpha_h+\alpha_l))} < 0 \quad \text{(A4)}$$

$$\partial^2 W/\partial q_l^2 = -\frac{c(1-16c\alpha_h)\left(3-16c(2\alpha_h+3\alpha_l)+128c^2(\alpha_h+\alpha_l)^2\right)}{8(1-8c(\alpha_h+\alpha_l))^2(1-4c(\alpha_h+\alpha_l))} < 0 \quad \text{(A5)}$$

The cross second derivatives are positive:

$$\partial^2 W/\partial q_h \partial q_l\big|_{q_h^o,q_l^o} = \partial^2 W/\partial q_l \partial q_h\big|_{q_h^o,q_l^o} = \frac{c\,(1-16c\alpha_h)\,(1-16c\alpha_l)}{8\,(1-8c\,(\alpha_h+\alpha_l))^2\,(1-4c\,(\alpha_h+\alpha_l))} \tag{A7}$$

and the determinant of the hessian matrix H is positive:

$$\text{Det } H = \frac{c^2\,(1-16c\alpha_h)\,(1-16c\alpha_l)}{8\,(1-8c\,(\alpha_h+\alpha_l))\,(1-4c\,(\alpha_h+\alpha_l))} \tag{A8}$$

A3 Proofs for the regulated equilibrium

Proof of the condition for positive market share

Positive market shares require $\hat{\theta}\ \in]\bar{\theta}-1,\bar{\theta}[$. Using the definition of $\hat{\theta}$, this condition comes down to $p_h - s_h - p_l\ \in](\bar{\theta}-1)(q_h-q_l)+\alpha_h, \bar{\theta}(q_h-q_l)-\alpha_l[$. Furthermore, $(\bar{\theta}-1)(q_h-q_l)+\alpha_h < \bar{\theta}(q_h-q_l)-\alpha_l$ requires $q_h - q_l > \alpha_h+\alpha_l$ □

Proof of the existence of the regulated equilibrium

At the price competition stage, the reaction functions resulting from maximization of profits (21) are:

$$\begin{cases} p_h^*\,(p_l) = \frac{1}{2}\left[p_l + s_h - \alpha_l + (q_h-q_l)\,\bar{\theta} + \tau_e\tau_v\,(\bar{e}-q_h)\right] + \frac{\tau_v}{4}cq_h^2 \\ p_l^*\,(p_h) = \frac{1}{2}\left[p_h - s_h - \alpha_h + (q_h-q_l)\left(1-\bar{\theta}\right) + \tau_e\tau_v\,(\bar{e}-q_l)\right] + \frac{\tau_v}{4}cq_l^2 \end{cases} \tag{A9}$$

Only one candidate for the equilibrium results from (A9). It is defined by:

$$\begin{aligned} p_h &= \frac{1}{3}\,(q_h-q_l)\left(\bar{\theta}+1\right) + \frac{\tau_e\tau_v}{3}\,(3\bar{e}-2q_h-q_l) + \frac{1}{3}\tau_v cq_h^2 + \frac{1}{6}\tau_v cq_l^2 + \frac{s_h-\alpha_h-2\alpha_l}{3} \\ p_l &= \frac{1}{3}\,(q_h-q_l)\left(2-\bar{\theta}\right) + \frac{\tau_e\tau_v}{3}\,(3\bar{e}-q_h-2q_l) + \frac{1}{3}\tau_v cq_l^2 + \frac{1}{6}\tau_v cq_h^2 - \frac{s_h-2\alpha_h-\alpha_l}{3} \end{aligned} \tag{A10}$$

The demand for products and the profits are then defined by:

$$n_h = \frac{2\,(q_h-q_l)\left(1+\tau_e\tau_v+\bar{\theta}\right) + 2s_h - 2\alpha_h - 4\alpha_l - \tau_v cq_h^2 + \tau_v cq_l^2}{6\,(q_h-q_l-\alpha_h-\alpha_l)} \tag{A11}$$

$$\pi_i(q_h,q_l) = \frac{q_h-q_l-\alpha_h-\alpha_l}{\tau_v}n_i^2 \quad i=h,l \tag{A12}$$

At the quality competition stage, maximization of profits (A12) leads to the following FOC:

$$\begin{aligned} \pi_{hq_h}\,(q_h,q_l) = \frac{n_h}{6\tau_v\,(q_h-q_l-\alpha_h-\alpha_l)} &\left[4\tau_v cq_h\,(q_l+\alpha_h+\alpha_l) + 2\,(q_h-q_l)\left(\bar{\theta}+1+\tau_v\tau_e\right)\right. \\ &\left. -\tau_v cq_l^2 - 3\tau_v cq_h^2 + 2\left(s_h+\alpha_h+2\tau_v\tau_e\,(\alpha_h+\alpha_l)+2\bar{\theta}\,(\alpha_h+\alpha_l)\right)\right] = 0 \end{aligned} \tag{A13a}$$

$$\begin{aligned} \pi_{lq_l}\,(q_h,q_l) = \frac{(1-n_h)}{6\tau_v\,(q_h-q_l-\alpha)} &\left[4\tau_v cq_l\,(-q_h+\alpha_h+\alpha_l) + 2\,(q_h-q_l)\left(\bar{\theta}-2+\tau_v\tau_e\right)\right. \\ &\left. +3\tau_v cq_l^2 + \tau_v cq_h^2 - 2s_h - 4\alpha_h\left(\bar{\theta}-1+\tau_v\tau_e\right) + \alpha_l\left(2\bar{\theta}-3+2\tau_v\tau_e\right)\right] = 0 \end{aligned} \tag{A13b}$$

Assuming $0 < n_h < 1$, this system of two polynomial functions of degree two in q_h and q_l has five candidates for the equilibrium (q_h^{**}, q_l^{**}). We keep only the solution, defined in Equation (22), which, without network effect and taxation, allows firms to earn positive profits and satisfies the second order conditions. In order to show that $q_h^{**} > 0$ and $q_l^{**} > 0$, note that qualities are minimal when $\alpha_l = 0, \alpha_h = 9/16c\tau_v - s_h/2$ and $\tau_e = 0$. Minimal qualities are then $q_h^{**} = (2\theta - 1)/2c\tau_v$ and $q_l^{**} = (\theta - 2)/2c\tau_v$, both being positive on condition of market coverage (see below).

The prices are then defined by:

$$\begin{aligned} p_h^{**} &= \frac{16\bar{\theta}^2 + 8\bar{\theta} + 25 - 16\tau_e^2\tau_v^2}{32c\tau_v} - \frac{s_h - \alpha_h - 2\alpha_l}{3} + \tau_e\tau_v\bar{e} - 1 \\ &\quad + \frac{(2s_h + \alpha_h - \alpha_l)\left(12\bar{\theta} - 3 - 2c\tau_v\left(2s_h - \alpha_h - 3\alpha_l + 8\bar{\theta}\left(\alpha_h + \alpha_l\right)\right)\right)}{4\Phi_v^2} \\ p_l^{**} &= \frac{16\bar{\theta}^2 - 40\bar{\theta} + 49 - 16\tau_e^2\tau_v^2}{32c\tau_v} - \frac{s_h + 2\alpha_h + \alpha_l}{3} + \tau_e\tau_v\bar{e} \\ &\quad + \frac{(2s_h + \alpha_h - \alpha_l)\left(12\bar{\theta} - 9 - 2c\tau_v\left(2s_h - 5\alpha_h - 7\alpha_l + 8\bar{\theta}\left(\alpha_h + \alpha_l\right)\right)\right)}{4\Phi_v^2} \end{aligned} \tag{A14}$$

with $\Phi_v = 3 - 4c\tau_v(\alpha_h + \alpha_l)$. Prices are non-negative since (C1) ensures that the last term of (A10) is lower than the first term, other terms being positive. The demand for the green product is characterized by (23) and the profits by (24).

The second derivatives of the profits are written:

$$\begin{aligned} \left.\frac{\partial^2\pi_h(q_h^{\cdot}q_l)}{\partial q_h^2}\right|_{q_h^{**},q_l^{**}} &= \frac{c(9+8c\tau_v(s_h-\alpha_h-2\alpha_l))\left(-32c^2\tau_v^2(\alpha_h+\alpha_l)^2+8c\tau_v(s_h+8\alpha_h+7\alpha_l)-27\right)}{36(3-2c\tau_v(\alpha_h+\alpha_l))\Phi_v^2} \le 0 \\ \left.\frac{\partial^2\pi_l(q_h^{\cdot}q_l)}{\partial q_l^2}\right|_{q_h^{**},q_l^{**}} &= \frac{c(9-8c\tau_v(s_h+2\alpha_h+\alpha_l))\left(-32c^2\tau_v^2(\alpha_h+\alpha_l)^2-8c\tau_v(s_h-7\alpha_h-8\alpha_l)-27\right)}{36(3-2c\tau_v(\alpha_h+\alpha_l))\Phi_v^2} \le 0 \end{aligned} \tag{A15}$$

The determinant of the hessian matrix is then defined by:

$$\text{Det}\, H = \frac{c^2\left(9 + 8\tau_v c\left(s_h - \alpha_h - 2\alpha_l\right)\right)\left(9 - 8\tau_v c\left(s_h + 2\alpha_h + \alpha_l\right)\right)}{162\left(3 - 2\tau_v c\left(\alpha_h + \alpha_l\right)\right)\Phi_v} \tag{A16}$$

with

$$\frac{\partial^2\pi_h}{\partial q_h\partial q_l} = \frac{\partial^2\pi_l}{\partial q_l\partial q_h} = \frac{c\left(9 + 8\tau_v c\left(s_h - \alpha_h - 2\alpha_l\right)\right)\left(9 - 8\tau_v c\left(s_h + 2\alpha_h + \alpha_l\right)\right)}{36\left(3 - 2\tau_v c\left(\alpha_h + \alpha_l\right)\right)\Phi_v^2} \tag{A17}$$

The second derivatives are negative and the determinant of the hessian matrix is positive if α_h and α_l fulfill (C1) and (C2): $2\alpha_h + \alpha_l < 9/(8c\tau_v) - s_h$ and $\alpha_h + 2\alpha_l < 9/(8c\tau_v) + s_h$.

The Nash Equilibrium must also satisfy the non-deviation conditions, i.e.

$$\begin{cases} \pi_h\left(q_h^{**}, q_l^{**}\right) \ge \pi_h\left(q_h^{\cdot}q_l^{**}\right) & q_h \in [0, \bar{e}] \\ \pi_l\left(q_h^{**}, q_l^{**}\right) \ge \pi_l\left(q_h^{**}, q_l\right) & q_l \in [0, \bar{e}] \end{cases} \quad \text{and} \quad q_h^{**} - q_l^{**} > \alpha_h + \alpha_l \tag{A18}$$

For $q_l = q_l^{**}$, $\pi_h(q_h, q_l^{**})$ takes its maximum in q_h^{**} and is positive when $n_h(q_h, q_l^{**}) \in]0, 1]$. We can show that $n_h(q_h, q_l^{**})$ is a decreasing function of q_h. There exist two thresholds $\underline{q}_h$ and $\bar{q}_h$ such as $n_h(q_h, q_l^{**}) \in [0, 1]$ when $q_h \in [\underline{q}_h, \bar{q}_h[$. There exist two other thresholds q_h^0 and q_h^1 such as $\pi_h(q_h^*, q_l^*) \ge \pi_h(q_h^{\cdot}q_l^*)$ for all $q_h \in [q_h^0, q_h^1]$. Values of $\underline{q}_h$, $\bar{q}_h$, q_h^0 and

q_h^1 have been computed using *Mathematica* software and can be obtained upon request from the author. Simulations with various suitable values of $\bar{\theta}$, c, τ_v, τ_e, s_h, α_h and α_l show that $q_h^0 < \underline{q}_h < q_h^{**} < \bar{q}_h < q_h^1$. The equilibrium qualities thus fulfill the non-deviation conditions. We apply the same methodology in order to provide the non-deviation conditions for the brown firm.

At the regulated equilibrium, since $q_h^{**} - q_l^{**} = 3/2c\tau_v$, the condition of positive market shares requires that $p_h^{**} - s_h - p_l^{**} \in]3(\bar{\theta}-1)/(2c\tau_v) + \alpha_h, 3\bar{\theta}/(2c\tau_v) - \alpha_l[$. According to (A14), we have:

$$\begin{aligned} p_h^{**} - s_h - p_l^{**} &= \frac{3\left(\bar{\theta}-1\right)}{2c\tau_v} + \alpha_h + \frac{(9 - 8c\tau_v\left(2\alpha_h + \alpha_l + s_h\right))\left(3 - 2c\tau_v\left(\alpha_h + \alpha_l\right)\right)}{12c\tau_v\Phi_v} \\ &= \frac{3\bar{\theta}}{2c\tau_v} - \alpha_l + \frac{(9 - 8c\tau_v\left(\alpha_h + 2\alpha_l - s_h\right))\left(3 - 2c\tau_v\left(\alpha_h + \alpha_l\right)\right)}{12c\tau_v\Phi_v} \end{aligned}$$

Duopoly existence thus only requires that (C2) is satisfied.

Proof of the condition for market coverage

The condition for market coverage ($\tilde{\theta} \leq \bar{\theta} - 1$) implies $p_l^{**}/q_l^{**} \leq \bar{\theta} - 1$. Using (22) and (A14) and rearranging terms, we find the minimal threshold of $\bar{\theta}$: $\bar{\theta} \geq 1 - \tau_e\tau_v + \vartheta$, with:

$$\begin{aligned} \vartheta = \Big[&\Big(675 - 16c\tau_v\left(32c^2\tau_v^2\left(\alpha_h + \alpha_l\right)^2\left(2\alpha_h + \alpha_l + s_h\right)\right. \\ &\left.-12c\tau_v\left(15\alpha_h^2 + 10\alpha_l^2 + 24\alpha_h\alpha_l + 6\alpha_h s_h + 4\alpha_l s_h + s_h^2\right)\right) \\ &+9\left(17\alpha_h + 14\alpha_l + 3s_h\right) - 6\tau_v\tau_e\bar{e}\Phi_v^2\Big)\Big]^{1/2} / \left[4\Phi_v\right] \end{aligned}$$

Without network effect and taxation, the coverage condition is fulfilled if $\bar{\theta} \geq 9/4$. The minimal threshold of $\bar{\theta}$ decreases with α_i until $\alpha_i = 1/16c$ $(i = h, l)$ for a given $\alpha_j (j \neq i)$. When $\alpha_h = \alpha_l = 1/16c, \bar{\theta}$ must be larger than 2.199. Through their effects on prices, taxes tend to raise this threshold, whereas the subvention tends to reduce it.

Proof of the effects of the product tax

$$\begin{aligned} q_{h\tau_v}^{**} &= -\bar{\theta}/c\tau_v^2 - \left[9 - 8c\tau_v\left(\alpha_h + \alpha_l\right)\left(3 - 4c\tau_v\left(\alpha_h + s_h\right)\right)\right]/\left[4c\tau_v^2\Phi_v^2\right] \leq 0 \\ q_{l\tau_v}^{**} &= -\left(\bar{\theta} - 3\right)/c\tau_v^2 - \left[63 - 8c\tau_v\left(\alpha_h + \alpha_l\right)\left(21 - 4c\tau_v\left(4\alpha_h + 3\alpha_l + s_h\right)\right)\right] \\ &\quad /\left[4c\tau_v^2\Phi_v^2\right] \leq 0 \\ n_{h\tau_v}^{**} &= 2c\left(2s_h + \alpha_h - \alpha_l\right)/\Phi_v^2 \geq 0 \\ \pi_{h\tau_v}^{**} &= -\frac{3 - \tau_v c\left(\alpha_h + \alpha_l\right)}{c\tau_v^3}n_h^2 + \frac{2\left(3 - 2\tau_v c\left(\alpha_h + \alpha_l\right)\right)\left(2s_h + \alpha_h - \alpha_l\right)}{\tau_v^2\Phi_v^2}n_h \leq 0 \\ \pi_{l\tau_v}^{**} &= -\frac{3 - \tau_v c\left(\alpha_h + \alpha_l\right)}{c\tau_v^3}\left(1 - n_h\right)^2 - \frac{2\left(3 - 2\tau_v c\left(\alpha_h + \alpha_l\right)\right)\left(2s_h + \alpha_h - \alpha_l\right)}{\tau_v^2\Phi_v^2}\left(1 - n_h\right) \\ &\leq 0 \end{aligned}$$

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