Environmental Policy to Foster a Green Differentiated Energy Market

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Abstract

Many products are made by technological processes that cause environmental damage. Current environmental concerns are affecting firms' technological processes as a result of government intervention in markets but also due to environmental awareness on the part of consumers. This paper assumes a spatial competition model where two firms sell a homogeneous product with input differentiation: the product is made by green and polluting inputs. In a two-stage game firms first decide what technology bundle to use (the ratio of green and polluting inputs) and then Bertrand competition takes place. First, it is shown that in the absence of government intervention both firms prefer to produce by using a bundle of green and polluting technologies which is not welfare maximizing. Second, the option of subsidizing green technology and the existence of a publicly-owned firm are analyzed. Overall, both policies yield a more environmentally-friendly technology bundle, except when costs of green energy technologies are high enough. Moreover, environmental social welfare is enhanced.

Keywords: Differentiated inputs · Environmental policy · Green market · Mixed duopoly · Subsidy

JEL Classification: D11 · D43 · L11

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1 Introduction

Environmental concerns have become relevant as economic issues for governments in recent years. In particular, evidence of global warming and an increase in consumers' environmental awareness have forced governments and international institutions to deploy active energy policies in order to minimize environmental damage caused by economic activities. In the last ten years a number of countries have signed the Kyoto protocol, which marks the start of a new era where the scarcity of certain energy sources, the improving of renewable energy technologies (hereinafter called RETs) and a growing consumer movement supporting green energy are the main drivers. For instance, the electricity sector has incorporated renewable sources into its technology mix, gasoline companies have investigated new feed-products and improved gasoline, and buildings and houses in isolated location have incorporated off-shore technologies (mainly wind generators and photovoltaic panels). However, new RETs have a great handicap when competing with traditional fossil-based technologies (hereinafter called FBTs): the average and marginal costs of RETs are higher than those of FBTs. To encourage research, development and deployment of RETs and bring them to a degree of sufficient technical maturity where they can compete with FBTs a number of economic measures have been implemented by governments. Sadly, encouraging profit-oriented firms to produce using RETs is costly and has no immediate effects in the short run.

This paper presents a spatial duopoly model of horizontal input differentiation with price competition in the output market. Two firms located à la Hotelling (Hotelling (1929)) sell an output produced using a combination of RETs and FBTs.[1] Energy markets can usually decide on the bases when designing the technology bundle to produce a given output. Electricity can be generated by using coal-burning units, combined-cycle plants and other traditional fossil-based technologies but also by mean of wind farms, photovoltaic panels and other renewable energy processes. The motor industry is also able to make hybrid vehicles, in which an internal-combustion engine is combined with an electric motor. The model presented here also takes into account the environmental awareness of consumers and a welfare function which includes the environmental damage that results from technological processes. It is assumed that the goal of government is twofold: (i) to increase the amount of RETs and decrease the amount of FBTs in firms' technology bundles; and (ii) to maximize an environmental social welfare function. We first present the market outcome in the absence of any government intervention and the first best environmental social welfare solution that a benevolent social planner would choose. Secondly, as the government's goal is to encourage RETs and enhance the environmental social welfare function two different policy measures are studied: (i) a subsidy for RETs; and (ii) a publicly-owned firm which competes with a profit-oriented firm.

In this setting, our study provides some insights into the debate ongoing concerning the effect of subsidies

[1] D'Aspremont et al. (1979) extend the Hotelling model by assuming quadratic costs and show that it is possible for both firms to locate outside the unit interval. In our model we use a quadratic cost specification but firms are constrained to locate within the unit interval. Thus, for certain parameter values it is possible to find corner and semi corner solutions (where one of the two firms locates at the very end).

and government intervention on energy markets. In the case of a subsidy aimed at encouraging RETs there is an *ex post* market distortion because relative prices are modified by the subsidy. In the case of a publicly-owned firm, there is an *ex ante* non negligible market distortion caused by the active role of the government in the market.

The literature describing markets where green and polluting products coexist has increased in recent years. Moreover, the effects of environmental regulation on market performance and social welfare are also of economic interest. In Conrad (2005) a horizontal product differentiation with respect to an environmental friendly product characteristic is used to model price-environmental quality competition. A trade-off between higher prices for better environmental quality and lower prices for poor environmental quality exists. A term to incorporate the feeling of guilt at not having purchased the environmentally friendliest product is added into individual preferences. In this setting, when firms simultaneously choose their respective characteristics and then they compete in prices, Conrand finds that the location of the social welfare maximizing characteristics is not the same as that chosen by private firms. Even if there is no real environmental damage, the social optimal location differs from that of the private solution. Erikson (2004) uses horizontal differentiation to examine the extent to which partial and voluntary internalization of negative environmental externalities by consumers can replace public intervention. Moraga-Gonzalez and Padrón-Fumero (2002) also measure the impact of different environmental policies on aggregate emissions and social welfare in a vertical product differentiation approach where consumers are willing to pay more for less polluting goods. They find that there is a trade-off between the willingness of consumers to pay and the unit emissions of firms. The studies in Porter (1990) and Porter and van der Linde (1995) conclude that environmental regulations by governments improve welfare because they can open up new investment opportunities, encourage firms to innovate and generate long term gains that can offset the costs of complying with them. Along these lines, André et al. (2009) show that firms profit from the existence of a rule penalizing any firm that refuses to produce an environmentally friendly good. In a recent paper Matsukawa (2012) studies the effects on welfare of subsidies and emission taxes in a green market where the product is environmentally differentiated. He concludes that an emission tax is always welfare dominant because it induces firms to improve the environmental qualities of their product as well as the environmental awareness of consumers. Kurtyka and Mahenc (2011) study optimal taxation on a pollutant variety in a duopoly where firms can either produce a green or a pollutant variety à la Hotelling. They specify an environmental function and find that firms switch from the pollutant to the green variety when the environmental externality is internalized. Taxation of polluting products is also analyzed in Cremer and Thisse (1999) for the case when firms cannot evade it and in Macho-Stadler and Pérez-Castrillo (2006) and Macho-Stadler (2008) for the case when they can.

The benefits and costs of privatizing a publicly-owned firm since the 80's have also been analyzed. Moreover, the literature on mixed oligopoly has studied the extent to which public firms can be used as a policy instrument to improve resource allocation in oligopolistic markets. In Cremer at al. (1989) and (1991) the authors speculate as to the possibility of using public firms to maximize social welfare in a Cournot setting when the product is homogeneous and when it is differentiated. Fraja and Delbono (1989) show that it is socially better for the government to privatize a publicly-owned firm if the market is competitive enough and the publicly-owned firm cannot have the advantage in moving otherwise the existence of a publicly-owned firm is socially desirable. In an environmental framework, Barcena-Ruíz and Garzón (2006) analyze government environmental policy in a mixed oligopoly where firms produce a homogeneous good. They show that the decision whether to privatize a public firm interacts with the environmental policy of governments.[2]

In our setting of horizontal input differentiation it is shown that in the absence of government intervention firms produce by using a bundle of technologies which strongly depends upon the difference in cost between RETs and FBTs and on the environmental awareness of consumers. Moreover, both firms prefer to produce by using a single technology instead of a bundle of technologies only if differences in costs are strong enough and consumers' environmental awareness is low. When the government intervenes the result is a more environmentally-friendly technology bundle regardless of the measures adopted, except when cost differences between RETs and FBTs are very high. In particular, the implementation of a subsidy programme reduces environmental damage and comes close to the first best environmental social welfare solution. A government intervention by mean of a publicly-owned firm fully internalizes environmental damage and force the private firm to take into account the amount of pollutant emitted into the atmosphere per additional unit of production. Thus, both policy measures are welfare-enhancing and by means of a publicly-owned firm the first best solution is reached. This is in keeping with Bárcena-Ruiz and Garzón (2006), who find that the public firm should not be privatized when market competition is low enough.

The rest of the paper is organized as follows. Section 2 describes the set up of the model and characterizes the market solution with no government intervention. Section 3 presents environmental policies. Section 4 discusses the implications of government intervention for welfare. Section 5 concludes.

2 The model

We consider a duopolistic market where a unit mass of uniformly distributed consumers indexed by x live in the interval $[0, \alpha]$ where $\alpha \in (0, 1]$. Each consumer buys at most one unit of a product of homogenous quality environmentally differentiated at the production stage. Firms produce by using RETs and FBTs.[3] It is assumed that firm g, located at t_g, is a technologically green-oriented firm which sells a product that causes pollution to the tune of et_g, where $e > 0$ accounts for the amount of pollutant emitted into the atmosphere per additional unit of production. Firm f, located at t_f, is a technologically fossil-fuel-oriented firm which sells a product that causes pollution to the tune of et_f. Without loss of generality, it is assumed that $t_g \leq t_f$ within

[2] See for instance Sanjo (2009) and Martínez-Sánchez (2011) for a more general discussion on mixed duopolies with horizontal differentiation and Bertrand competition.

[3] In the case of electricity generation it represent the bundle of RETs and FBTs per kilowatt produced. In the case of hybrid vehicles it represents the proportion of km powered by the electric motor and the proportion of km powered by a gasoline or diesel motor per 100 km.

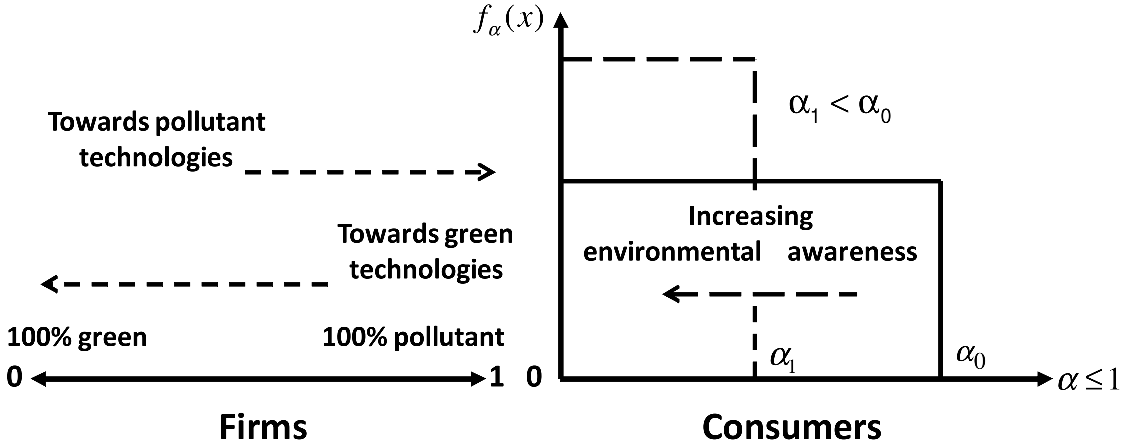

Figure 1: Firms' technology space and unit mass of consumers as a function of $\alpha \in (0, 1]$.

the unit interval. If the firms locate at the two extremes of the unit interval they make a 100% technologically green product and a 100% technologically polluting product, respectively. Thus, from the firms' point of view the unit interval stands for the environmental quality of the technology bundle, ranging from zero, which represents the highest environmental quality, to one, which is the lowest environmental quality and the greatest pollutant emissions. Hence, in our model the assumption of horizontal differentiation is related to the technology bundle chosen by firms. We also assume that the unit mass of consumers care about the pollutant emissions caused by FBTs and show some degree of awareness of environmental damage. We use the exogenous parameter α to capture this idea of environmental awareness at aggregate level. Even though consumers know that this effect is negligible at individual level they experiment some altruism that yields to this aggregate environmental awareness effect, which increases as it approaches zero (that is, as consumers' guilt at not purchasing a pure green-produced goods increases). Figure 1 depicts the *technological and environmental space* where firms and consumers *live*.

The net utility of a consumer located at x is:

$$U_i(x) = \begin{cases} \rho - (x - t_g)^2 - p_g & \text{if he/she buys from } i = g \\ \rho - (t_f - x)^2 - p_f & \text{if he/she buys from } i = f. \end{cases} \tag{1}$$

Parameter ρ represents the consumer's utility obtained from purchasing a product that complies with his/her ideal technology bundle and p_i $(i = g, f)$ is the price of the product. The disutility experienced by a consumer from not purchasing that technological bundle is assumed to be quadratic; hence it is $(x - t_g)^2$ and $(t_f - x)^2$ when a consumer located at x buys a unit of output from the green-oriented and fossil–fuel-oriented firm, respectively. Moreover, we also assume that ρ is large enough for full coverage of the market to be socially efficient. Firms' demand functions are,

$$D_i(\overline{x}) = \begin{cases} \int_0^{\overline{x}} f_\alpha(x)dx & \text{if } i = g \\ \int_{\overline{x}}^{\alpha} f_\alpha(x)dx & \text{if } i = f, \end{cases} \tag{2}$$

where $\overline{x}$ is the consumer who is indifferent between buying from g and f,

$$\overline{x} = \frac{t_f + t_g}{2\alpha} + \frac{p_f - p_g}{2\alpha(t_f - t_g)},$$

according to $U_g(\overline{x}) = U_f(\overline{x})$ and where $f_\alpha(x) = 1/\alpha$ is a density function in $0 \leq x \leq \alpha$. The cost incurred by a firm when it produces output by using a technology bundle t_i is $c_g(1 - t_i) + c_f t_i$. It is assumed that $c_g \geq c_f$. This means that a *pure* green product requires a more expensive technology. Firms' profit function is,

$$\pi_i = [p_i - c_g(1 - t_i) - c_f t_i] D_i(\overline{x}) \tag{3}$$

Note that firms' decisions take into account the cost incurred by using each technology but also depend on the environmental awareness of consumers. Here we introduce the notion of environmental social welfare,

$$ESW = \textstyle\sum_{i=g,f} \pi_i + \rho - CD - E_T \tag{4}$$

which is defined as the sum of industry profits and the maximum consumer utility (ρ) minus the consumer disutility (CD) from not purchasing the preferred technological bundle and the total emissions (the environmental damage) caused by aggregate pollution, E_T,[4]

$$CD = \int_0^{\overline{x}} (p_g + (x - t_g)^2) f_\alpha(x)dx + \int_{\overline{x}}^{\alpha} (p_f + (t_f - x)^2) f_\alpha(x)dx, \qquad E_T = e \sum_{i=g,f} t_i D_i(\overline{x}).$$

Consumer disutility is minimized at $x = (t_g + t_f)/2$ provided that $CD'(x) = (t_g + t_f - 2x)(t_g - t_f)$. This means that the extra cost of an extra consumer buying from g (f) is positive for all $x > (t_g + t_f)/2$ ($x < (t_g + t_f)/2$). It is immediately apparent from ESW that for the technology bundle (given the uniform distribution of consumers) for each firm to be efficient it must hold that $(c_f + e - c_g)(t_f - t_g) = CD'(x)$; i.e., the cost saving from producing by FBTs plus the environmental damage must be equal to the consumer disutility (or the marginal social cost of not purchasing the preferred technological variety). Hence, from the social point of view the market should be split such that $x^* = \min\{\alpha, [t_g + t_f + (c_f + e - c_g)]/2\}$.

Assumption 1: It is socially efficient for both firms to supply the product so that $0 < x^* < \alpha$.

Assumption 2: The market supplies output by using both RETs and FBTs according to

$$(c_g - c_f - e) \leq t_g + t_f \leq 2(c_g - c_f - e).$$

The timing of the model is as follows. At the first stage (the *production stage*) firms decide on their technology bundle. At the second stage (the *retailing stage*) firms engage in Bertrand competition. The model is solved by backward induction to find the set of subgame perfect equilibria.

[4] Moraga-González and Padrón-Fumero (2002) and Bárcena-Ruiz and Garzón (2006) define social welfare (W), as the sum of the consumer surplus (CS) and firms' profits minus the social valuation of environmental damage caused by aggregate pollution, E_T.

As a benchmark we analyze the model with no government intervention. Then we study the effect that two environmental policies have on the firms' technology bundles and the implications for ESW. First, a private duopoly is analyzed where the government subsidizes RETs. Second, a mixed duopoly is analyzed where a publicly-owned firm (either a green or fossil-fuel-oriented firm) maximizes ESW.

2.1 Market performance under no government intervention

This section presents the market solution with no government intervention. For comparison purposes and without loss of generality c_f is normalized to unity hereinafter. Hence, as $c_g > 1$ it measures cost differences between RETs and FBTs. In our setting firms are able to produce either by choosing a bundle of technologies (thus locating within the unit interval) or to produce with a single technology (thus locating at the ends of the unit interval).

At the *retailing stage* first order conditions are found by differentiating (3) with respect to p_i,

$$(p_i - c_g(1-t_i) - t_i)\frac{\partial D_i(\overline{x})}{\partial p_i} + D_i(\overline{x}) = 0, \qquad i = g, f.$$

yielding reaction functions $p_i(p_j)$,

$$p_g(p_f) = \frac{p_f + (t_f^2 - t_g^2) - t_g(c_g - 1) + c_g}{2}, \qquad p_f(p_g) = \frac{p_g + (t_g^2 - t_f^2) - t_b(c_g - 1) + c_g}{2} + \alpha(t_f - t_g). \qquad (5)$$

It is easy to check that second order conditions are also satisfied. Notice that $\partial p_f(p_g)/\partial\alpha$ is always positive. This accounts for the consumer awareness of the environment: as α decreases the fossil-fuel-oriented firm loses the capacity to charge a higher price in response to a price increase by the green-oriented firm.

By solving the above equation system contingent retail prices $p_i(t_i, t_j)$ are found as a function of the technological strategy at the *production stage*,

$$\widehat{p}_g(t_g, t_f) = \frac{(t_f^2 - t_g^2) - (c_g - 1)(t_f + 2t_g) + 2\alpha(t_f - t_g)}{18} + c_g \qquad \widehat{p}_f(t_g, t_f) = \frac{(t_g^2 - t_f^2) - (c_g - 1)(2t_f + t_g) + 4\alpha(t_f - t_g)}{18} + c_g.$$

A further inspection of the above contingent retail prices gives some interesting insights. Assume firms' technological strategy at the *production stage* as given. Then, for a given pair (t_g, t_f) contingent retail prices have the following properties: (i) there is a positive relationship between RETs costs and retail prices, i.e. $\partial\widehat{p}_i(t_g, t_f)/\partial c_g > 0$; (ii) there is an inverse relationship between consumer awareness of the environment and retail prices, i.e. $\partial\widehat{p}_i(t_g, t_f)/\partial\alpha > 0$; (iii) a change in RETs costs strongly affects the retail price of the green firm, $\partial\widehat{p}_g(t_g, t_f)/\partial c_g - \partial\widehat{p}_f(t_g, t_f)/\partial c_g > 0$; and (iv) a change in the environmental awareness of consumers strongly affects the retail price of firm f, $\partial\widehat{p}_f(t_g, t_f)/\partial\alpha - \partial\widehat{p}_g(t_g, t_f)/\partial\alpha > 0$.

As this is a perfect information game, contingent retail prices are assumed to be common knowledge. Firms incorporate these insights at the *production stage* in order to choose an optimal technological strategy.[5] Hence, at the *production stage* firms choose the technology bundle aimed to maximize

$$\pi_i(t_i, t_j) = [p_i(t_i, t_j) - c_g(1 - t_i) - t_i]D_i(\overline{x}(t_i, t_j)).$$

[5] In Appendix 1 we report *retailing stage* profits under each market configuration: no government intervention, subsidy on RETs and a publicly-owned firm, respectively.

First order conditions $\partial\pi_i(t_i,t_j)/\partial t_i = 0$ are

$$[\frac{\partial p_i(t_i,t_j)}{\partial t_i} + c_g - 1]D_i\left(\overline{x}(t_i,t_j)\right) + [p_i(t_i,t_j) - c_g(1-t_i) - t_i]\,\frac{\partial D_i\left(\overline{x}(t_i,t_j)\right)}{\partial t_i} = 0,$$

yielding firms' reaction functions $t_i(t_j)$,

$$t_g\left(t_f\right) = \tfrac{t_f+c_g-1}{3} - \tfrac{2\alpha}{3}, \quad \text{and} \quad t_f\left(t_g\right) = \tfrac{t_g+c_g-1}{3} + \tfrac{4\alpha}{3}. \tag{6}$$

The solution of the above system of equations provides a characterization for interior solutions (i.e., when both firms choose a technology bundle)

$$\widehat{t}_g(c_g,\alpha) = \tfrac{2(c_g-1)-\alpha}{4}, \quad \text{and} \quad \widehat{t}_f(c_g,\alpha) = \tfrac{2(c_g-1)+5\alpha}{4}. \tag{7}$$

However, the set of possible technology configurations may include the use of single technologies (corner solutions) and a combination of them (semi-corner solutions). Proposition 1 and Figure 2 characterize firms' technologies as a function of consumer awareness of the environment and RETs costs.

Proposition 1 *Firms' technology bundle depends on the cost differences between the green-oriented and fossil-fuel-oriented firm and the environmental awareness of consumers,*

(i) Case I: Firms produce using a bundle of technologies in accordance with (7);

(ii) Case IIa: Firm g produces using a bundle of technologies in accordance with (6) which is a best response to firm f choosing pure FBTs, $(\widehat{t}_g,\widehat{t}_f) = (\frac{c_g-2\alpha}{3}, 1)$;

(iii) Case IIb: Firm f produces using a bundle of technologies in accordance with (6) which is a best response to firm g choosing pure RETs, $(\widehat{t}_g,\widehat{t}_f) = (0, \frac{c_g-1+4\alpha}{3})$;

(iv) Case III: Firm g produces using RETs and firm f produces using FBTs solely, $(\widehat{t}_g,\widehat{t}_f) = (0,1)$.

P roof. See appendix. ■

In order to characterize this set of optimal production technologies we define functions T_i, $i = g, f$ as

$$T_g = \{(c_g,\alpha) \in \mathbb{R}^2 \text{ such that } t_g(c,\alpha) = 0\}, \quad \text{and} \quad T_f = \{(c_g,\alpha) \in \mathbb{R}^2 \text{ such that } t_f(c,\alpha) = 1\}.$$

Along T_i firms produce by a single technology. Hence, T_g and T_f define regions where both firms prefer to produce by a bundle of technologies or to use a single technology process.

Equilibrium configurations strongly depend on the environmental awareness of consumers: as α decreases the market share of firm g increases and thus price competition is enhanced. This yields an increase in welfare via a reduction in environmental damage. A lower unit cost c_g has the same effect. In Table 1 we report market shares, price-cost margin differences, and differences in firms' profits under each market configuration.[6]

[6] Table 1 reports only the market share of firm g: the market share of firm f is obtained by $1 - D_g(\widehat{x})$.

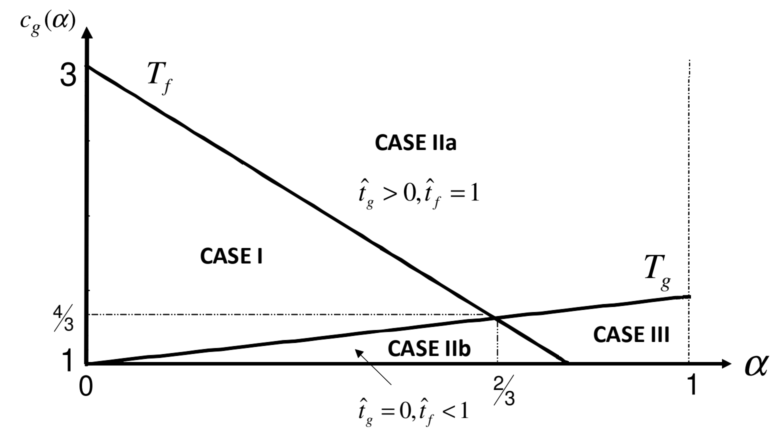

Figure 2: Firms' technology bundle as a function of α and $c_g(\alpha)$.

Table 1. Market performance under no government intervention.				
	Case I	*Case IIa*	*Case IIb*	*Case III*
$D_g(\widehat{x})$	$\frac{1}{2}$	$\frac{(1+5\alpha-c_g)}{9\alpha}$	$\frac{(3+2\alpha-c_g)}{9\alpha}$	$\frac{(2(1+\alpha)-c_g)}{6\alpha}$
$\widehat{pcm}_f - \widehat{pcm}_g$	0	$\frac{(4(1-c_g)+\alpha)(1-4\alpha-c_g)}{27}$	$\frac{(2(3-c_g)+2\alpha)(-6+5\alpha+2c_g)}{27}$	$\frac{2(-2+\alpha+c_g)}{3}$
$\widehat{\pi}_f - \widehat{\pi}_g$	0	$\frac{(4(1-c_g)+\alpha)(1-4\alpha-c_g)}{27}$	$\frac{(2(3-c_g)+2\alpha)(-6+5\alpha+2c_g)}{27}$	$\frac{2(-2+\alpha+c_g)}{3}$

When firms produce using mixed technologies (*Case I*) the market is split down the middle. As cost differences are not great the strategic effect (i.e. the incentive of firms to move away from each other) and the demand effect (i.e. the incentive of firms to remain close to each other) are quite similar yielding to the interior solution. Moreover, firms are equally affected by α and c_g; thus, the ability of firms to charge prices above their marginal cost is the same. As a result, the difference in profits is zero. If firms produce using single technology processes (*Case III*) market shares are affected by α and c_g in opposite directions. In particular, this case is possible when the environmental awareness of consumers and cost differences are relatively low. The underlying intuition is related to the fact that those consumers located closer to zero have a strong preference for buying from g because this firm has a strong incentive to produce using RETs because c_g is relatively low. By contrast, there are also consumers located closer to one who buy from f, which may charge a better price when producing using FBTs. However, as the price advantage is relatively low the strategic effect strongly dominates the demand effect. Hence, in this case the demand of firm f and its price cost margin are always larger than those of firm g, giving the former a profit advantage. Finally, in semi corner cases (*Case IIa* and *Case IIb*) the demand effect strongly dominates the strategic effect for the firm that uses a bundle of technologies. In the case of firm g when consumers have a high level of environmental awareness of the environment it is possible that there may be a large cost disadvantage but it is necessary to produce partly with FBTs in order to capture demand. When consumers are also spread closer to one, RETs costs become more important so that firm g also needs to produce using FBTs in order to capture demand. The semi corner case for firm f is symmetric. When consumers have a high level of environmental awareness and RETs costs are closer to FBTs costs it is necessary for firm f to produce partly with RETs in order to capture demand. Finally, when consumers are also spread closer to one but RETs costs are virtually the same as FBTs costs firm f also needs to produce using RETs in order to capture demand.

2.2 Welfare analysis under no government intervention

This section analyzes welfare. In our environment market failure means that firms choose a technology bundle other that that preferred by a benevolent social welfare maximizer. In our framework market failures come from three forces: (i) cost differences between technologies; (ii) pollutant emissions measured by E_T; and (iii) consumer disutility from not purchasing a product underlying the preferred technology bundle. In order to maximize ESW a benevolent social maximizer takes $\partial ESW/\partial t_i = 0$, $(i = g, f)$, which yields a socially optimal allocation of technology bundles,

$$t_g^* = \tfrac{c_g - e - 1}{2} + \tfrac{\alpha}{4} \qquad t_f^* = \tfrac{c_g - e - 1}{2} + \tfrac{3\alpha}{4}$$

Notice that in the particular case where environmental concerns are equal to zero $(e = 0)$, consumers are spread along the unit interval $(\alpha = 1)$ and the cost of RETs is the same as that of FBTs the above expressions resemble the well-knows solution $(t_g, t_f) = (1/4, 3/4)$. By replacing optimal technology bundles at ESW the following is obtained

$$ESW^* = \rho - \frac{e\alpha + (e - \alpha)(c_g - 1)}{2} - \frac{c_g(6 - c_g) - 1}{4} + \frac{12e^2 - \alpha^2}{48}.$$

In the case of an interior solution when there is no government intervention in the market routine calculations yield the following:

$$\widehat{ESW} = \rho - \frac{e\alpha + (e - \alpha)(c_g - 1)}{2} - \frac{c_g(6 - c_g) - 1}{4} - \frac{13\alpha^2}{48}$$

Now we measure welfare differences for the case when both firms produce using a bundle of technologies. As corner and semi corner cases strongly depend on parameter values we perform a further inspection after the analysis of environmental policies in order to establish relevant comparisons. Thus, for the interior market solution

$$ESW^* - \widehat{ESW} = \frac{(e^2 + \alpha^2)}{4},$$

so differences come only from environmental concerns, namely e and α. It is straightforward to check that $\partial(ESW^* - \widehat{ESW})/\partial e > 0$ and $\partial(ESW^* - \widehat{ESW})/\partial \alpha > 0$, which means that a reduction in pollutant emissions and increases in the environmental awareness of consumers enhance $\widehat{ESW}$, which yields $ESW^* - \widehat{ESW}$ to zero. It is important to note that c_g does not affect ESW differences because both firms use both technologies: it means that the role of the social planner is to internalize e and α because c_g has the same effect on welfare regardless of the solution considered. The rest of the paper is devoted to investigating how government intervention may approach ESW^* by encouraging a greener energy market.

3 Environmental policies

In this section we investigate the effects of two alternative environmental policies. We assume that the government behaves as a benevolent social maximizer. First, it decides to grant a subsidy s on RET technologies. Second, the effects of government acquisition of either the green-oriented or the fossil-fuel-oriented firm are studied. The timing of the model remains the same as in the absence of government intervention.

3.1 Subsidizing RETs

Here we investigate the effect of a subsidy s per unit of green input ($0 < s \leq c_g - 1$) to reallocate RETs and FBTs. In other words, each firm i is granted s for the set amount of RETs in its technology bundle. The maximization problem of firm i is

$$\pi_i = [p_i - \delta_g(s)(1-t_i) - c_f t_i]\, D_i(\overline{x}) \tag{8}$$

where $\delta_g(s) = c_g - s$ accounts for the net cost that a firm incurs when using RETs. At the *retailing stage* each firm chooses prices p_i as a function of the locations chosen at the *production stage*. By differentiating (8) with respect to p_i $(i = g, f)$ the following first order conditions are obtained:

$$(p_i - \delta_g(s)(1-t_i) - t_i)\frac{\partial D_i(\overline{x})}{\partial p_i} + D_i(\overline{x}) = 0.$$

Reaction functions $p_i(p_j)$ at the *retailing stage* are found,

$$p_g(p_f) = \tfrac{p_f + (t_f^2 - t_g^2) - t_g(\delta_g(s)-1) + \delta_g(s)}{2}, \qquad p_f(p_g) = \tfrac{p_g + (t_g^2 - t_f^2) - t_b(\delta_g(s)-1) + \delta_g(s)}{2} + \alpha(t_f - t_g). \tag{9}$$

The above expressions are the same as those in (5) except for the term $\delta_g(s)$, which accounts for the cost saving as a result of the subsidy s. By solving the above equation system contingent retail prices $p_i(t_i, t_j)$ are found as a function of the technology strategy at the *production stage,*

$$p_g(t_g, t_f) = \tfrac{(t_f^2 - t_g^2) - (\delta_g(s)-1)(t_f + 2t_g) + 2\alpha(t_f - t_g)}{18} + \delta_g(s) \qquad p_f(t_g, t_f) = \tfrac{(t_g^2 - t_f^2) - (\delta_g(s)-1)(2t_f + t_g) + 4\alpha(t_f - t_g)}{18} + \delta_g(s).$$

Notice that these contingent prices are equivalent to those with no any government intervention when $s = 0$. Thus, the effect of c_g in $p_i(t_g, t_f)$ is now reduced as s increases, $\partial p_i(t_g, t_f)/\partial c_g > \partial p_i(t_g, t_f)/\partial \delta_g(s) > 0$ whereas the effect of α remains the same. Finally, regardless of the level of s, a decrease in RETs costs strongly affects the retail price of the green-oriented firm.[7].

[7] This is because $\partial \widehat{p}_i(t_g, t_f)/\partial \delta_g(s) = \partial \widehat{p}_i(t_g, t_f)/\partial c_g$, $i = g, f$.

At the *production stage* firms choose their technology by incorporating the information $p_i(t_i, t_j)$ into their profit function,

$$\pi_i(t_i, t_j) = [p_i(t_i, t_j) - \delta_g(s)(1 - t_i) - t_i]\, D_i\left(\overline{x}(t_i, t_j)\right)$$

with first order conditions $\partial \pi_i(t_i, t_j)/\partial t_i = 0$, $(i = g, f)$

$$t_g(t_f) = \tfrac{t_f + \delta_g(s) - 1}{3} - \tfrac{2\alpha}{3}, \quad \text{and} \quad t_f(t_g) = \tfrac{t_g + \delta_g(s) - 1}{3} + \tfrac{4\alpha}{3}. \tag{10}$$

Solving the simultaneous system given by (10) the characterization for a pair of technology bundles is found,

$$\widetilde{t}_g = \tfrac{2(\delta_g(s) - 1) - \alpha}{4}, \quad \text{and} \quad \widetilde{t}_f = \tfrac{2(\delta_g(s) - 1) + 5\alpha}{4}. \tag{11}$$

An interior solution $\widetilde{t}_g \geq 0$ requires $\delta_g(s) \geq (2 + \alpha)/2$ and for $\widetilde{t}_f \leq 1$ it is needed that $\delta_g(s) \leq (6 - 5\alpha)/2$. Thus, firms produce using technology bundles only for certain parameter values. Proposition 2 characterizes equilibria depending on $\delta_g(s)$.

Proposition 2 *Firms' technologies depend on the cost differences between the green-oriented and fossil-fuel-oriented firms, the environmental awareness of consumers, and the level of the subsidy,*

(i) Case I: Firms produce using both types of technology (interior solution) in accordance with (11);

(ii) Case IIa: Firm g produces using a technology bundle as indicated in (10) which is a best response to firm f choosing a pure FBTs, $(\widetilde{t}_g, \widetilde{t}_f) = (\frac{\delta_g(s) - 2\alpha}{3}, 1)$*;*

(iii) Case IIb: Firm f produces using a technology bundle as indicated in (10) which is a best response to firm g choosing a pure RETs, $(\widetilde{t}_g, \widetilde{t}_f) = (0, \frac{\delta_g(s) - 1 + 4\alpha}{3})$*;*

(iv) Case III: Firm g produces using RETs and firm f produces using FBTs solely, $(\widetilde{t}_g, \widetilde{t}_f) = (0,1)$.

P roof. See appendix. ■

In comparison with Proposition 1, as $\delta_g(s)$ decreases both firms increase the proportion of RETs in their technology bundles resulting in an increase in welfare via a reduction in environmental damage. An objection to the RETs subsidy is that s lowers firms' incentives to invest in RETs as net cost decreases. Figure 3 represents the situations summarized in Proposition 2. As can be seen in Figure 3 the effect of s is to re-scale the technology space so that now there is more opportunity for RETs.

In Table 2 we report market shares, price-cost margin differences, and differences in firms' profits under each market configuration.

Table 2. Market performance with a subsidy.

	Case I	*Case IIa*	*Case IIb*	*Case III*
$D_g(\widetilde{x})$	$\frac{1}{2}$	$\frac{(1+5\alpha-\delta_g(s))}{9\alpha}$	$\frac{(3+2\alpha-\delta_g(s))}{9\alpha}$	$\frac{(2(1+\alpha)-\delta_g(s))}{6\alpha}$
$\widetilde{pcm}_f - \widetilde{pcm}_g$	0	$\frac{(4(1-\delta_g(s))+\alpha)(1-4\alpha-\delta_g(s))}{27}$	$\frac{(2(3-\delta_g(s))+2\alpha)(-6+5\alpha+2\delta_g(s))}{27}$	$\frac{2(-2+\alpha+\delta_g(s))}{3}$
$\widetilde{\pi}_f - \widetilde{\pi}_g$	0	$\frac{(4(1-\delta_g(s))+\alpha)(1-4\alpha-\delta_g(s))}{27}$	$\frac{(2(3-\delta_g(s))+2\alpha)(-6+5\alpha+2\delta_g(s))}{27}$	$\frac{2(-2+\alpha+\delta_g(s))}{3}$

When firms produce using a technology bundle (*Case I*) market shares, price cost margins differences and

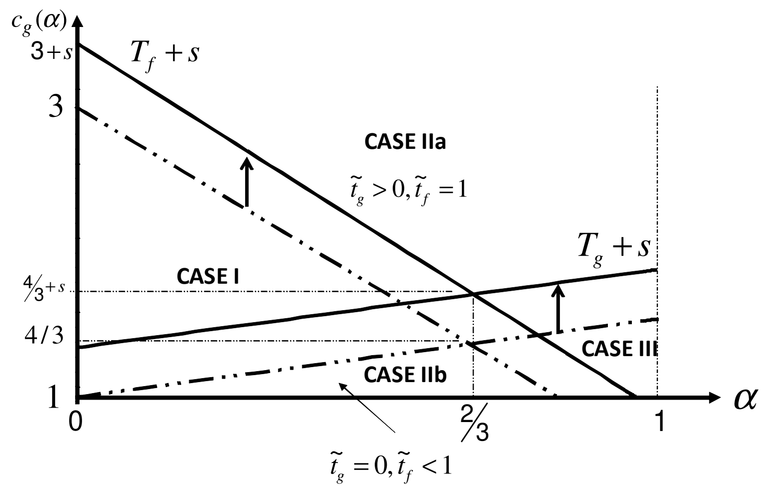

Figure 3: Firms' technology bundle as a function of α, s and $c_g(\alpha)$.

profits differences are the same as when there is no government intervention. Moreover, as it will be shown in Section 3, welfare is enhanced. If firms produce using single technology processes (*Case III*) market shares are affected by α and $\delta_g(s)$ in opposite directions. As $\delta_g(s) < c_g$ firm g gets a bigger market share than in the case of no government intervention because now consumers have a strong preference for buying from g as RETs costs have decreased. In the opposite direction, consumers who buy from f obtain a smaller price advantage as this firm has a technology bundle that is FBTs intensive. As a result, although the strategic effect still dominates the demand effect, it results in a reduction in market share for firm f. Hence, in this case the demand of firm g increases and price cost margin differences and profits differences are reduced. Finally, in semi corner cases (*Case IIa* and *Case IIb*) the strategic effect has more impact as the subsidy increases, so it reinforce its dominance over the demand effect for the firm that uses a single technology.

3.2 A publicly-owned firm

In this section, we consider that the government owns either the green-oriented firm or the fossil-fuel-oriented firm). The publicly-owned firm maximizes environmental social welfare while the private one maximizes profits. Assume that the government owns the green-oriented firm. The case in which the government owns the fossil-fuel-oriented firm is symmetric and provides the same qualitative results.[8] At the *retailing stage* the first order conditions for the publicly-owned firm are obtained by differentiating (4) with respect to p_g,

$$(p_g - \delta_g(s)(1-t_g) - t_g)\frac{\partial D_g(\overline{x})}{\partial p_g} + D_g(\overline{x}) - \frac{\partial CD}{\partial p_g} - \frac{\partial E_T}{\partial p_g} = 0,$$

while the first order condition for the private firm are obtained by differentiating (3) with respect to p_f,

$$(p_f - \delta_g(s)(1-t_f) - t_f)\frac{\partial D_f(\overline{x})}{\partial p_f} + D_f(\overline{x}) = 0.$$

[8] Interested readers can find retailing-stage and production-stage equilibria for this case in Appendix 2.

The reaction function for the publicly-owned firm is

$$p_g^W(p_f) = p_f + (t_f - t_g)(c_g - 1 - e),$$

while that for the private firm f coincides with (5). Solving the system equation *retailing stage* prices are set,

$$p_g^W = (2t_g - t_f) - (t_f - t_g)(2e + t_g + t_f) + c_g(1 + t_f - 2t_g) + 2\alpha(t_f - t_g),$$

$$p_f = t_g - (t_f - t_g)(e + t_g + t_f) + c_g(1 - t_g) + 2\alpha(t_f - t_g).$$

At the *production stage* the government and the profit-oriented firm incorporate this information in order to choose an optimal technological strategy aimed at maximizing $ESW_g(t_g, t_f)$ and $\pi_f(t_g, t_f)$, where ESW_g stands for government intervention in firm g. First order conditions $\partial ESW_g(t_g, t_f)/\partial t_g = 0$ and $\partial \pi_f(t_g, t_f)/\partial t_f = 0$ provide the following reaction functions:

$$t_g(t_f) = \tfrac{t_f + c_g - (1+e)}{3}, \quad \text{and} \quad t_f(t_g) = \tfrac{t_g + c_g - (1+e)}{3} + \tfrac{2\alpha}{3}. \tag{12}$$

No matter whether the government owns the green-oriented firm or the fossil-fuel-oriented firm the reaction functions are the same. This is because government ownership of the green-oriented firm forces the private firm to take into account the amount of pollution emitted per additional unit of production. The solution of the above system of equations provides a characterization for interior solutions (i.e. when firms choose a technology bundle),

$$t_g^* = \tfrac{c_g - e - 1}{2} + \tfrac{\alpha}{4} \quad \text{and} \quad t_f^* = \tfrac{c_g - e - 1}{2} + \tfrac{3\alpha}{4} \tag{13}$$

which coincides with that which maximizes ESW. As in the previous cases, the set of possible technology configurations is not restricted to an interior solution. In this case semi-corner solutions are also possible. We present the results under this market configuration in Proposition 3.

Proposition 3 *The optimal technological strategy when the government owns either the green-oriented firm or the fossil-fuel-oriented firm is characterized as follows,*

(i) Case I: Firms prefer to produce using a bundle of technologies (interior solution) as in (13).

(ii) Case IIa: Firm g produces using a technology bundle which is a best response to firm f choosing a pure FBTs, $(t_g^*, t_f^*) = (\frac{c_g - e}{3}, 1)$;

(iii) Case IIb: Firm f produces using a technology bundle which is a best response to firm g choosing a pure RETs, $(t_g^*, t_f^*) = (0, \frac{c_g - e - (1 - 2\alpha)}{3})$.

P roof. See appendix. ■

Figure 4 graphically describes government and private firm technology decisions as implied by the relationship between α and c_g.

An interesting observation is that, in contrast with the previous sections, it is not an equilibrium for both firms to use a single technology. Semi corner cases are found when RETs costs are too high or too

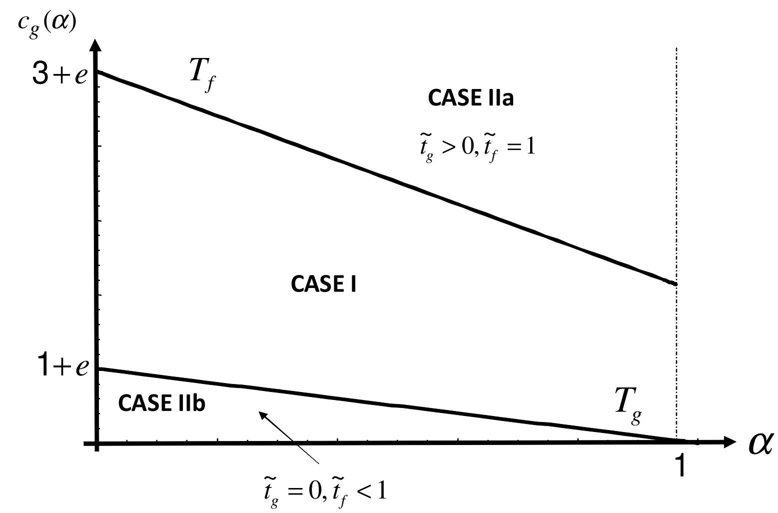

Figure 4: Firms' technology bundle as a function of α, e and $c_g(\alpha)$.

low for a given pollution level e. When RETs costs are relatively closer to FBTs costs, for a given pollution level e, both firms prefer to produce using a bundle of technologies. This is because RETs costs are not too high (low) compared with the environmental damage caused by the fossil-fuel-oriented firm. Thus, as the government also cares for the environment it decides to produce using a bundle of technologies in this *average* case; that is, it internalizes environmental damage caused by the use of FBTs. Notice that this depends crucially on the level of environmental awareness of consumers, α. Moreover, changes in c_g and e affect both firms in the same way. In particular, $\partial t_i/\partial e < 0$ and $\partial t_i/\partial c_g > 0$. The market is split at $x^* = \alpha/2$. Table 3 summarizes the interior solution and both semi corner cases.

Table 3. Market performance when government owns a firm.

	Case I	*Case IIa*	*Case IIb*
$D_g(x^*)$	$\frac{1}{2}$	$\frac{3+e-c_g}{3\alpha}$	$\frac{1+\alpha+e-c_g}{3\alpha}$
$pcm_f^* - pcm_g^*$	$\frac{\alpha e}{2}$	$\frac{e(3+e-c_g)}{3}$	$\frac{e(2\alpha-(1+e)-c_g)}{3}$

For the case of interior solutions (*Case I*) the demand and strategic effects are again roughly balanced so both firms produce using a bundle of technologies. Indeed, this solution is the first best as a result of the intervention by the government, which internalizes environmental damage. It is interesting to note that in the case of semi corner solutions (*Case IIa* and *Case IIb*) there are two extreme cases in which both firms produce using the same single technology. On one hand, when $3(1-\alpha/2) \leq c_g - e$ and $\alpha \to 1$ both firms prefer to produce using FBTs. This is because consumers are spread over the unit interval so there is a significant group of them that does not care so much about the environment. As a result, as RETs costs are so high compared with e, firms are forced to behave in a completely *polluting fashion*. On the other hand, when $c_g - e \leq 1-\alpha/2$ and $\alpha \to 0$ both firms prefer to produce using RETs solely. This is because consumers are so highly aware of the environment and RETs costs are so small compared with e that firms prefer to behave in a completely *green fashion*. These two special cases are in line with the well-known principle of minimum differentiation where the demand effect completely offsets the strategic effect.

4 Welfare analysis

In this section we analyze the effect of the two policy measures on ESW. First we focus on the case where both firms produce using a bundle of technologies. This case is of particular interest because parameters are assumed to be at *normal or expected levels*.

When the government grants a subsidy s on RET technologies ESW is

$$\widetilde{ESW} = \rho - \frac{e\alpha + (e-\alpha)(\delta_g(s)-1)}{2} - \frac{\delta_g(s)(6-\delta_g(s))-1}{4} - \frac{13\alpha^2}{48}$$

The difference with the first best solution is

$$ESW^* - \widetilde{ESW} = \frac{e^2+\alpha^2}{2} - \frac{s[2(c_g+\alpha-e-3)-s]}{2}. \tag{14}$$

Along this section ESW difference with respect the first best solution is called *welfare differences*.The term on the right hand side in (14) is positive and $\partial(ESW^* - \widetilde{ESW})/\partial s = (c_g + \alpha - e - s - 3)/4 < 0$. Thus, as s increases the difference with the optimal ESW decreases. Intuitively, as α decreases and c_g decreases a low level of subsidy becomes necessary: as long as consumers' environmental awareness increases and RET costs decrease the gap is minimized. The effect of the level of pollutant emissions merely a further inspection. By taking the partial derivative, $\partial(ESW^* - \widetilde{ESW})/\partial e = (e-s)/2$ it is observed that when the level of subsidy does not offset the pollutant emissions the gap increases. The intuition behind this is that the government may improve welfare by inducing firms to pollute less *ex ante*, for instance by setting emission quotas, or *ex post*, by subsidizing RET. In both cases it moves firms' locations towards zero making the technology mix more *green*. These observations suggest that it is very important to reduce c_g and e and to encourage environmental awareness among consumers in order to reduce total government expenditure $s(\widetilde{t}_g D_g(\widetilde{x}) + (1-\widetilde{t}_f) D_f(\widetilde{x}))$ arising from the subsidy.

When the government owns either the green-oriented or the fossil-fuel-oriented firm the first best solution is reached. The reason is that the government takes into account environmental damage but also the level of consumer awareness of the environment. Thus, by efficiently choosing the technology bundle of its own firm it encourages its rival also to choose an efficient technology bundle in order to behave competitively.

Finally, we study welfare implications when one or both firms produce using a single technology (i.e. the semi corner and corner cases). In order to reach interesting insights we assume two particular values of environmental awareness on the part of consumers: $\alpha = 1/2$ and $\alpha = 1$ which correspond to the average case and the usual assumption of consumers spread over the unit interval, respectively. We also fix RETs cost at $c_g = \{1, 3\}$. It allows us to study two extreme cases: (i) no cost differences between RETs and FBTs, and (ii) a significant inefficiency in cost by part of RETs. Inside Table 4 we report partial derivatives of welfare differences with respect s and e, depending on the market environment considered.

Table 4. Welfare differences for some values of α and c_g.[9]

Values of α	1/2		1	
Values of c_g	$c_g = 1$	$c_g = 3$	$c_g = 1$	$c_g = 3$
No intervention	semi-corner left $\frac{\partial(ESW^* - \widehat{ESW})}{\partial e} > 0$	semi-corner right $\frac{\partial(ESW^* - \widehat{ESW})}{\partial e} = \frac{e}{2} - 0.32 \gtreqless 0$	corner $\frac{\partial(ESW^* - \widehat{ESW})}{\partial e} > 0$	semi-corner right $\frac{\partial(ESW^* - \widehat{ESW})}{\partial e} = \frac{e}{2} - 0.1 \gtreqless 0$
Subsidy	semi corner left $\frac{\partial(ESW^* - \widetilde{ESW})}{\partial s}\rfloor_{s=0} < 0$	semi corner left $\frac{\partial(ESW^* - \widetilde{ESW})}{\partial s}\rfloor_{s>3/2} < 0$ semi corner right $\frac{\partial(ESW^* - \widetilde{ESW})}{\partial s}\rfloor_{s<5/4} < 0$	corner $\frac{\partial(ESW^* - \widetilde{ESW})}{\partial s} < 0$ semi corner left $\frac{\partial(ESW^* - \widetilde{ESW})}{\partial s}\rfloor_{s>1/2} < 0$	corner $\frac{\partial(ESW^* - \widetilde{ESW})}{\partial s}\rfloor_{s>3/2} < 0$ semi corner left $\frac{\partial(ESW^* - \widetilde{ESW})}{\partial s}\rfloor_{s>5/2} < 0$ semi corner right $\frac{\partial(ESW^* - \widetilde{ESW})}{\partial s}\rfloor_{s<3/2} < 0$
Mixed duopoly	semi corner left $\frac{\partial(ESW^* - ESW_i^*)}{\partial e} > 0$	semi corner left $\frac{\partial(ESW^* - ESW_i^*)}{\partial e}\rfloor_{e>9/4} > 0$ semi corner right $\frac{\partial(ESW^* - ESW_i^*)}{\partial e}\rfloor_{e>3/4} > 0$	semi corner left $\frac{\partial(ESW^* - ESW_i^*)}{\partial e}\rfloor_{e>1/2} > 0$	semi corner left $\frac{\partial(ESW^* - ESW_i^*)}{\partial e}\rfloor_{e>5/2} > 0$ semi corner right $\frac{\partial(ESW^* - ESW_i^*)}{\partial e}\rfloor_{e>3/2} > 0$

[9] Inside Table 4 ESW_i^* stand for Environmental Social Welfare when the government owns either firm g or f, for $i = g, f$.

In a market without any govenment intervention it is straigforward that, no matter the value of α, when there is no cost differences a reduction in e enhance welfare (thus, approaching ESW^*). However, this effect is not clear when cost differences are high. Indeed, when consumers are more concious about environment ($\alpha = 1/2$) a relative low level of e ($e < 0.64$) reduce welfare differences. This is because FBTs becomes more efficient than RETs but also because FBTs produce relative low pollutan emissions. Indeed, firm f produce only using FBTs and firm g moves towards the center and thus, replace RETs by FBTs. This effect is relaxed when consumers spread on the unit interval ($\alpha = 1$).The maximum level of e that reduce welfare differences is lower ($e < 0.21$). This is because consumers are less concious about environment so that the green-oriented firm is relative more intensive on FBTs (and firm f is at 1). The effect of a subsidy is clearly welfare enhancing and thus, reducing welfare differences. However, the level of s induce firms to behave *green* intensive or *pollutant* intensive. For instance, for the case when $\alpha = 1/2$ and $c_g = 1$ any level of s induce firm g to produce by a 100% RETs and firm f to be intensive in RETs. Contrary to this, for the case when $\alpha = 1$ and $c_g = 3$ the level of s yields to different technologies configurations. Indeed, if the aim of the government is to get the most green technology mix (semi corner solution with $t_g = 0$) at any cost it needs at least a level of $s > 5/2$; a corner solution only requires a level $s > 3/2$; and if the government goal is only to enhance welfare at the cost of a more pollutant technology configuration it requires $s < 3/2$. Finally, when the government owns either firm g or f welfare differences depend on e. Overall, semi corner solutions require a higher e as α and c_g increase. For instance, when $\alpha = 1/2$ and $c_g = 1$ it yields to semi corner case where $t_g = 0$ and $t_f < 1$. Contrary to this, when $\alpha = 1$ and $c_g = 3$ semi corner cases take place only when e is higher enough. The reason is that when consumers are less environmentaly concious and RETs inefficiency is large the relative weigh of pollutant emissions becomes less important and thus its impact on welfare is reduced.

5 Conclusions

In this paper we study the effect of technological processes that involve environmental damage in a green differentiated market. We assume a spatial duopoly competition model where firms sell a homogeneous product with input differentiation: the product is made using RETs and FBTs. In a two-stage game firms first decide on their technology bundles (the ratio of green and polluting inputs) and secondly Bertrand competition takes place.

In this setting, we first characterize optimal technology bundles, price cost margins and market shares in the absence of government intervention, and the environmentally optimal social welfare solution. It is shown that in the absence of government intervention both firms prefer to produce using a bundle of RETs and FBTs except in the case when RETs are extremely costly or consumer awareness of the environment is sufficiently high. In that case firms prefer to produce using a single technology instead of a bundle of technologies.

Second, the option of subsidizing RETs and the existence of a publicly-owned firm to foster a green differentiated energy market aimed at approaching the environmentally optimal social welfare solution are analyzed. Overall, both policies yield a more environmentally-friendly technology bundle except when RETs costs are too high. Moreover, environmental social welfare is enhanced. In particular, it is shown that the fossil-fuel-oriented firm reduces its market share as long as the cost difference decrease. When the government introduces a subsidy it encourages both firms to produce using more RETs. The cases in which both firms prefer to produce using a single technology become more difficult to achieve because the subsidy allows strong differences in costs for all levels of environmental awareness on the part of consumers. Thus, it could be a negative policy measure if the aim is to encourage firms to invest in order to decrease RETs costs.

When we focus on the case when the government owns either the green-oriented firm or the fossil-fuel-oriented firm it is shown that firms prefer to produce using a bundle of technologies as the demand and strategic effects are roughly balanced. Moreover, this solution is the first best as a result of the government intervention which internalizes environmental damage. There are also two extreme cases where one firm produces using a single technology as a result of a low cost difference (there is a pure green firm) or when that cost difference is very high (there is a pure fossil-fuel-oriented firm) for a given level of pollutant emissions.

Finally, it is important to note that in the case of a subsidy there is an *ex post* market distortion because relative prices are modified by the subsidy, whereas in the case of a publicly-owned firm there is a non negligible *ex ante* market distortion caused by the active role of the government in the market.

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Appendix 1: retailing stage profits.

- No government intervention.

$$\pi_g\left(t_g,t_f\right)=\frac{(t_f-t_g)(1+t_g+t_f+2\alpha-c_g)^2}{18}, \qquad \pi_f\left(t_g,t_f\right)=\frac{(t_f-t_g)(1+t_g+t_f-4\alpha-c_g)^2}{18}.$$

- Implementation of a subsidy.

$$\pi_g\left(t_g,t_f\right)=\frac{(t_f-t_g)(1+t_g+t_f+2\alpha-\delta_g(s))^2}{18}, \qquad \pi_f\left(t_g,t_f\right)=\frac{(t_f-t_g)(1+t_g+t_f-4\alpha-\delta_g(s))^2}{18}.$$

- Mixed duopoly. Retailing stage welfare and retailing stage private firm's profits.

$$ESW_i\left(t_g,t_f\right)=\rho+\frac{t_f^3-t_f^2(2\theta-t_g-2\delta_g(s)-4\alpha)-t_f(1+e-t_g-\delta_g(s)-2\alpha)(\theta-\delta_g(s)-2\alpha)-t_g(\theta^2+\delta_g(s))}{4\alpha}+$$

$$+\frac{\delta_g(s)(lt_g\theta-2\alpha)}{2\alpha}-\frac{\alpha^2}{3};$$

$$\pi_g^f(t_g,t_f)=\frac{(t_f-t_g)(\theta+t_g-\delta_g(s))^2}{2\alpha}, \quad \text{and} \quad \pi_f^g(t_g,t_f)=\frac{(t_f-t_g)(\theta+t_g-\delta_g(s)-2\alpha)^2}{2\alpha}.$$

where $\theta = 1 + e + t_g$, and $i, j = g, f$. Superscripts on profit functions stand for that firm owned by the state.

Appendix 2: government owns the fossil-fuel-oriented firm.

- Retailing stage: Government chooses the p_f that maximizes ESW, for which the reaction function is:

$$p_f^W(p_g) = p_g + (t_g - t_f)(c_g - 1 - e),$$

while the private firm g chooses the p_g which maximizes profits, for which the reaction function coincides with (5). By solving this system equation retailing stage prices are set,

$$p_f^W = (2t_f - t_g) - (t_g - t_f)(2e + t_f + t_g) + c_g(1 + t_g - 2t_f),$$

$$p_g = t_f - (t_g - t_f)(e + t_f + t_g) + c_g(1 - t_f).$$

- Production stage: First order conditions $\partial ESW_f(t_g, t_f)/\partial t_f = 0$ and $\partial \pi_g(t_g, t_f)/\partial t_g = 0$ provide firms' reaction functions, which coincide with those obtained in (12) in Subsection 3.2. Thus, the same equilibrium is obtained.

Appendix 3: proof of propositions.

- Proof of proposition 1. By taking the expressions in (7) we can characterize interior solutions. Assume $t_g(c_g, \alpha) = 0$ and $t_f(c_g, \alpha) = 1$. This yields functions T_i, $i = g, f$. An examination the gradient vector $\nabla t_g(c_g, \alpha) = (+, -)$ and $\nabla t_f(c_g, \alpha) = (+, +)$ reveals that values $t_g > 0$ and $t_f < 1$ exist below T_f and over T_g. As T_f meets T_g at $\alpha = 2/3$ and $c_g = 4/3$ (see Figure 2) four types of can be defined. (i) Case I (Interior solution) requires $0 < \alpha < 2/3$ where $T_f > T_g$. Accordingly, $t_g(c_g, \alpha) > 0$ and $t_f(c_g, \alpha) < 1$ implies that $c_g \in ((2 + \alpha)/2, (6 - 5\alpha)/2)$. (ii) Case III (corner solution). Taking the information of the gradient vectors, this requires $T_f < T_g$ which in turn yields $2/3 < \alpha \leq 1$. Start by setting $t_f = 1$ as t_f cannot exceed one. The best response of firm g is $t_g(1) = (c_g - 2\alpha)/3$. The best response of firm f on $t_g(1)$ is then $t_f[t_g(1)] = (10\alpha + 4c_g - 3)/9$ which is larger than one for $c_g > (6 - 5\alpha)/2$. Now assume that $t_g = 0$ as t_g cannot be negative. The best response of firm f is $t_f(0) = (c_g + 4\alpha - 1)/3$. The best response of firm g on $t_f(0)$ is then $t_g[t_f(0)] = (4(c_g - 1) - 2\alpha)/3$ which is always negative for $c_g < (2 + \alpha)/2$. (iii) Semi corner solutions. Case IIa: As $\nabla t_f(c_g, \alpha) = (+, +)$ firm f always chooses pure FBT when $t_f \geq 1$. Using the information contained in (i) and (ii) firm g produces using a technology bundle as indicated in (7) when T_f is active, that is, when $0 < \alpha < 2/3$ which implies $c_g > (6 - 5\alpha)/2$, and also when T_g is active, that is, when $2/3 < \alpha \leq 1$ which implies $c_g > (2 + \alpha)/2$. Case IIb: Analogously, as $\nabla t_g(c_g, \alpha) = (+, -)$ firm g always chooses pure RET when $t_g \leq 1$. Firm f produces using a technology bundle as indicated in (7) when T_g is active, that is, when $0 < \alpha < 2/3$ which implies $c_g < (2 + \alpha)/2$, and also when T_f is active, that is, when $2/3 < \alpha \leq 1$ which implies $c_g < (6 - 5\alpha)/2$. This completes the proof.

- Proof of Proposition 2. The proof of this proposition is analogous to Proposition 1, replacing c_g by $\delta_g(s)$.

- Proof of proposition 3. We proceed in three steps. (i) Case I (interior solution): By taking (13) we have to find values of e and α which provide $0 < \{t_g, t_f\} < 1$. First, $t_g > 0$ implies that $2c_g + \alpha - 2(1+e) > 0 \Rightarrow c_g - e > 1 - \alpha/2$. Second, $t_f < 1$ implies that $2c_g + 3\alpha - 2(1+e) < 4 \Rightarrow c_g - e < 3(1-\alpha/2)$. (ii) Case IIa (semi corner solution) with $t_g > 0$ and $t_f = 1$ as t_f cannot exceed one. The best response is $t_g(1) = c_g - e > 0$ as we assume that $c_g - e > 3(1-\alpha/2)$. The best response of firm f on $t_g(1)$ is then $t_f[t_g(1)] = [4(c_g - e) - 3(1-2\alpha)]/9 > 1$ as $c_g - e > 3(1-\alpha/2)$. We thus conclude that $t_g = (c_g - e)/3$ and $t_f = 1$. (iii) Case IIb (semi corner solution) with $t_f < 1$ and $t_g = 0$ as t_g cannot be negative. The best response is $t_f(0) = [c_g + 2\alpha - (1+e)]/3 < 1$ as we assume that $c_g - e < 1 - \alpha/2$. The best response of firm g on $t_f(0)$ is then $t_g[t_f(0)] = [4(c_g - e) - (1-2\alpha) - 3]/9$ which is lower than zero as long as $c_g - e < 1 - \alpha/2$. We thus conclude that $t_g = 0$ and $t_f = [(c_g - e) - (1-2\alpha)]/3$. This completes the proof.

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