Emission Taxes and the Adoption of Cleaner Technologies: The Case of Environmentally Conscious Consumers

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Abstract

We model a market with environmentally conscious consumers and a duopoly in which firms consider the adoption of a clean technology. We show that as pollution increases, consumers shift more resources to the environmental activities, thereby affecting negatively the demand faced by the duopoly. This effect generates incentives for firms to adopt the clean technology even in the absence of emissions taxes. When such taxes are considered, our results indicate that the benefit of adopting the clean technology is initially increasing and then decreasing in the emission tax. The range of values for which the emission tax increases this benefit becomes narrower when the consumers' environmental awareness is stronger.

Keywords: Environmentally Conscious Consumers; Technology Choice; Environmental Taxation

JEL Classification: L13, Q55, Q58

1 Introduction

Recent years have witnessed an increased awareness for issues pertaining to the impact of economic activity on environmental degradation. As a result, both policy makers and the wider public have intensified their efforts and actions towards pollution reduction. On the one hand, policy makers have attempted to encourage firms' investments in environmental R&D using a variety of instruments such as taxes on emissions, caps or R&D subsidies. On the other hand, environmentally conscious consumers have not only shifted their preferences towards goods with environmentally friendly attributes (e.g., recyclable packaging, organic produce, certification of environmentally friendly production techniques etc.) but they have also increased the resources they devote to general activities that mitigate the extent of environmental degradation.

There are many ways through which consumers can contribute resources to improve the environment. One example is the participation in carbon offsetting schemes. These schemes are supported by firms in a variety of industries, from aviation (British Airways, for example) to energy generation (Eon). Through these schemes, individuals contribute financially to the purchase of carbon credits to compensate for their own emissions. Another example is the individuals' donations to certain NGOs who purchase permits from emissions trading systems on their behalf, thereby reducing the amount of available permits and therefore effective emissions. Examples of such NGOs are the Acid Retirement Fund and the Clean Air Conservancy Trust in the US or Sandbag in the UK. Finally, individuals can take part in environmental volunteering, which often involves not only the supply of unpaid work (with its associated opportunity cost) but an additional financial contribution.[1]

At the same time, it seems that firms are aware of the potential effects of their environmental characteristics on their demand. The concept of 'green marketing' describes a well-known business practice that, according to Coddington (1993), "takes into account consumer concerns about promoting preservation and conservation of the natural environment" (Coddington 1993; p. 3). Polonsky (1994) argues that 'green marketing' is not solely associated to the promotion of products with environmentally-friendly characteristics. Instead, it incorporates a much broader range of practices that include, among others,

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[1] For example, Global Vision International is an organisation which runs a number of projects related to climate change and conservation all over the world. Volunteers pay a financial contribution and work on their chosen project for a certain amount of time.

changes to the processes of product creation, in order to reduce pollutant emissions and thus render them less harmful to environmental quality. Indeed, there has been an increasing trend in firm participation in voluntary environmental programs since the early 1990s both in the US and Europe. One of the reasons why firms choose to take part in these programs is public perception (Taiyab 2005; Estrada *et al.* 2008), which may be argued to have an effect on demand. In some cases, organised citizens have achieved the right-to-know about emissions and toxic exposures in local communities in the US through the Toxic Release Inventory. In Massachusetts, the Toxic Use Reduction Act (TURA henceforth), an extended version of the TRI, has led firms to reduce their toxic releases substantially (for example, over the period 2000 to 2005, there was a reduction of 9% in toxic chemicals and 21% in toxic by-products). Interestingly, there are no penalties associated to pollution in either the TURA or in the TRI. Thus, one of the main reasons behind firms' environmental effort in these frameworks is their worry about the market-related consequences of their actions (Sabel *et al.* 1999).[2] In a way, extreme examples of consumer behaviour affecting firms' actions can be seen in boycotts, some of which have been successful in making firms produce in a more environmentally friendly manner. For example, Shell announced its decision to dispose of its Brent Spair oil tanker in the North Sea after a massive consumer boycott of Shell petrol stations led by Greenpeace. Of course, such boycotts are not costless for the consumers. They require time and effort for their organisation, as well as monetary resources (e.g., campaigns on the media etc.).[3]

So far, the literature has contemplated the existence of heterogeneous consumers, where their preferences for the environment motivate competing firms to endogenously differentiate their goods in terms of their environmental attributes (e.g., Bansal and Gangopadhyay 2003; Conrad 2005; Deltas *et al.* 2008; Andre *et al.* 2009). Thus, in equilibrium some firms specialise in the production of a greener variety of the good. This arises in the context of horizontal differentiation (Conrad 2005); vertical differentiation (Bansal and Gangopadhyay 2003; Andre *et al.* 2009); and where two dimensions of differentiation, environmental and intrinsic characteristics of the goods, are considered (Deltas *et al.* 2008).

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[2] These inventories do not require firms to do anything else then reporting their releases or reduction plans. In principle, they do not carry penalties for pollution. Thus, the reaction of firms to being listed in this Inventory stems, at least in first instance, from its effects on consumer behaviour.

[3] In the particular example of the Shell boycott, consumers must have driven and queued in other petrol stations with its consequent cost in terms of time/effort.

However, such frameworks fail to capture the essential features of other empirically relevant arrangements such as the ones we alluded to earlier (carbon-offsetting programmes; donations to charities; volunteering; boycotts etc.). What all the aforementioned examples and anecdotal evidence reveal is that firms are willing to revert to environmentally-friendly production methods in response to the various manifestations of consumers' environmental awareness. Moreover, evidence suggests that this awareness appears to become stronger in situations where environmental problems and their repercussions become more notable (see van Birgelen et al. 2011). Naturally, it is safe to think that firms' respond in this way as a result of their understanding that a failure to react could have adverse consequences for the demand of their products. This may be because demand is shifted away as a result of the perception and concern that environmentally conscious consumers have about the polluting production methods of an industry. It may also be because the amount of resources that consumers are becoming more and more willing to devote for pro-environmental activities are diverted away from the resources available of the consumption of firms' products. Or, given that these two issues are certainly interlinked, it may be because of a combination of both. In any case, the preceding discussion shows that the analysis of environmental technology choice, in a scenario where firms consider the adverse effect that is generated by the reaction of consumers to their polluting production methods is a venture that is certainly worth pursuing. What is more, such an analysis may have important policy implications in the sense that the relative strength of consumers' environmental consciousness, and its corresponding implications for demand, could impinge on the effectiveness of policy instruments designed to induce the implementation of less pollution production methods, for example emission taxes.

In this paper, our aim is to fill the current void in the literature. Particularly, we move away from consumer heterogeneity and its implications for product design to focus on issues that impact on production methods. We begin our analysis with the description of a market where consumers have preferences over the consumption of a homogeneous good and environmental quality, which is affected by firms' choice of technology.[4] These consumers

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[4] With regards to the homogeneity assumption, we could think about the example of electricity, which can be generated with either more or less polluting methods (e.g., renewable sources). From the point of view of the consumer, the electricity supply to her household is the same whichever technology has been used in its generation.

can also devote resources towards environmental improvements. We show that, in response to an increase in pollution, consumers shift their resources away from the consumption of goods and towards activities that mitigate the extent of environmental degradation. Subsequently, we analyse a Cournot duopoly in which this negative demand effect impinges on both firms' decisions concerning output production and the cleanliness of the technologies they employ. The latter is characterised by the pollutants emitted per unit of production and its choice may entail positive technology spillovers across firms. There is substantial evidence on the existence of technological spillovers across firms and/or industries (Griliches 1992) including environmental technology spillovers (Buonanno *et al.* 2001; Clarke *et al.* 2006).

In this context, we derive and discuss the implications of the negative demand effect of pollution for firms' optimal choices. Furthermore, we show how the relative strength of this effect may impinge on the effectiveness of emission taxes as policy tools designed to motivate the adoption of cleaner production techniques by firms.[5]

The remaining of the paper is structured as follows. In Section 2, we analyse a market in which environmentally conscious consumers devote resources towards environmental improvements and derive the implications of higher pollution for consumer demand. In Section 3, we use these implications in a Cournot duopoly model with endogenous technology choice and derive equilibria in both the absence and the presence of emission taxes. Section 4 shows how the negative demand effect from pollution affects the scope of emission taxes as incentive mechanisms for the adoption of cleaner production methods. Section 5 provides some further discussion on some of the model's basic assumptions and Section 6 concludes.

2 A Market with Environmentally Conscious Consumers

The objective of this section is to demonstrate that the activities of environmentally conscious consumers may have a negative effect on the total demand faced by firms. In particular, we are going to derive a demand function whose linear approximation, with the

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[5] In addition to the more mainstream instruments of environmental policy (i.e., emission taxes; subsidies to environmental innovation) the use of informational campaigns to raise environmental awareness as a policy instrument has become the focus of a number of studies (see Petrakis *et al.* 2005; Garcia-Gallego and Georgantzis 2009, 2011). Our decision to focus on emission taxes lies on the importance of (environmental) technology choice in our setting.

same qualitative properties, is going to form the basis of our subsequent analysis of output and environmental technology choice by firms.

Consider a market which consists of $k > 1$ identical consumers and $N > 1$ firms that produce and sell quantities of a homogeneous product. The price of this product is denoted P. Each consumer $i = 1,...,k$ is endowed with an (exogenous) income of $y_i > 0$ and her preferences are defined over the consumption of the homogeneous product, denoted C_i, and environmental quality, captured by the variable E, according to

$$u_i = \delta \ln(C_i) + (1-\delta)\ln(E), \tag{1}$$

where $\delta \in (0,1)$ weights the two arguments of the consumer's utility.

Environmental quality is composed of two parts. Firstly, we assume that firms' production activities degrade the environment due to pollution. Secondly, we also assume that each consumer is environmentally aware and active in the sense that she is willing to devote resources to activities that support the environment. Formally, we capture these two effects by assuming that

$$E = e(M) + \sum_{i=1}^{k} x_i , \tag{2}$$

where x_i denotes the amount of a consumer's endowment devoted to environmentally friendly activities, M denotes pollution or total emissions, while the function $e(M)$ satisfies $e'(M) < 0$.

The assumption inherent in our set-up is that consumers can internalise the benefit of their activities on the quality of the environment. A similar assumption has been employed in the existing literature (see Mariani *et al.* 2010). However, there are other interpretations that can describe a more or less identical set-up. For example, one could think of x_i as a lump-sum tax which is chosen under majority voting and whose proceeds are used for environmentally-friendly activities. Alternatively, we could rewrite (2) as $E = e(M) + x_i$ and interpret it as the amenity value of environmental quality, in which x_i describes a 'joy-of-giving' (or 'warm glow') argument.[6] In both cases, apart from the presence of scale factors, the results would be qualitatively identical to those in our current formulation.[7]

Each consumer's problem is to choose C_i and x_i to maximise the utility function in (1) subject to (2) and her budget constraint

$$PC_i + x_i = y_i . \tag{3}$$

Naturally, when maximising her utility, the consumer takes P, M, and her exogenous income y_i as given.

Assuming interior solutions, we can reformulate the problem by substituting (2) and (3) in (1) to write

$$x_i^* = \arg\max_{x_i} \delta \ln\left(\frac{y_i - x_i}{P}\right) + (1-\delta)\ln\left[e(M) + \sum_{i=1}^{k} x_i\right], \tag{4}$$

and

$$C_i^* = \frac{y_i - x_i^*}{P} . \tag{5}$$

The first-order condition for the problem is

$$\frac{\partial U_i}{\partial x_i} = \frac{-\delta}{y_i - x_i} + \frac{1-\delta}{e(M) + \sum_{i=1}^{k} x_i} = 0 . \tag{6}$$

The second-order condition is

$$\frac{\partial^2 U_i}{\partial x_i^{\,2}} = \frac{-\delta}{(y_i - x_i)^2} - \frac{1-\delta}{\left[e(M) + \sum_{i=1}^{k} x_i\right]^2} < 0 \ . \tag{7}$$

Recall that consumers in the market are assumed to be identical – an assumption that applies to both their preferences and their endowments. Thus, we have $y_i = y \ \forall i$. Given this, it is obvious that $x_i = x \ \forall i$ holds as well. Therefore, we obtain x^* after solving (6). It is straightforward to establish that

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[6] See the seminal work by Andreoni (1989, 1990). There has been ample experimental evidence of this behaviour in public good games (see for example, Palfrey and Prisbey 1996, 1997; and Goeree *et al.* 2002).

[7] The relative strength of the warm glow effect could also be captured by the use of an appropriate preference parameter a_i so that $E = e(M) + a_i x_i$. Obviously, this effect would be more important for higher values of a_i. When $a_i = 0$, a consumer cares about the environmental quality but she does not wish to contribute in any way. Again, such a formulation would introduce a scale effect in the optimal solutions, but it would leave their qualitative nature unaffected.

$$x^* = \frac{(1-\delta)y - \delta e(M)}{1+\delta(k-1)}, \tag{8}$$

where we assume that the consumer's endowment is sufficiently high to guarantee an interior solution $x^* > 0$.[8] Substituting (8) in (5) and using hat $x_i = x \ \forall i$ results in

$$C^* = \delta \frac{ky + e(M)}{P[1+\delta(k-1)]}. \tag{9}$$

Now, we can use (9) to obtain the aggregate demand function, denoted $\tilde{C}^*$, for the homogeneous consumption good according to

$$\tilde{C}^* = \sum_{i=1}^{k} C^* = k\delta \frac{ky + e(M)}{P[1+\delta(k-1)]}. \tag{10}$$

Equation (10) reveals a standard, negatively sloped demand function with respect to the price (i.e., $\partial \tilde{C}^* / \partial P < 0$). Interestingly, equation (10) also implies that pollution affects aggregate demand. The next proposition formalises this claim.

Proposition 1. *In the interior solution an increase in pollution will result, ceteris paribus, in a reduction of the consumption good's aggregate demand.*

Proof. Using equation (10), we can see that $\partial \tilde{C}^* / \partial M < 0$. **QED**

The intuition for this result is straightforward. The increase in pollution will stimulate the consumers' desire to devote resources towards environmentally oriented activities – an effect that is manifested in the increase of the marginal utility from such activities (see equation 6). The equilibrium can only be restored if this marginal utility falls back to its original level; thus, each consumer will optimally choose to increase her spending on x. However, with a given amount of income available, this shift has to materialise at the expense of consumption. Hence, the demand for the consumption good will ultimately decline as, for a given price level, the demand curve shifts downwards.

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[8] It can be easily established that a sufficient condition for an interior solution is $y > \frac{\delta e(M)}{1-\delta}$. Henceforth, we assume that income is sufficiently high to satisfy this condition.

The preceding analysis has shown a link between aggregate demand and pollution in an economy with environmentally conscious consumers. More importantly, the mechanism we have described implies that this link may be pertinent to various aspects of a firm's decision making process. To see this, recall that pollution is a negative side-effect of firms' production activities. Now, let us assume that each firm $j = 1,\ldots,N$ produces and supplies a quantity q_j by accessing a technology that emits μ_j units of pollutants per unit of production. In this case pollution will amount to

$$M = \sum_{j=1}^{N} \mu_j q_j \,. \tag{11}$$

The expression in (11), combined with the demand function in (10), reveals how and why the mechanism summarised in Proposition 1 can be an important characteristic of firms' choices concerning production, technology adoption etc. As such, it may have significant implications for policies designed to induce the implementation of environmentally friendlier production methods by firms. Our purpose is to utilise the main point from the preceding discussion in order to provide a formal analysis of these implications. This is a task we undertake in the following sections of the paper.

3 Emission Taxes and Environmental Technology Choice

The preceding analysis has demonstrated a scenario that supports an aggregate demand function $\tilde{C}^* = c(P,M)$, where $c_P, c_M < 0$. Now, let us consider an industry whose firms face such a demand function. When doing so, we shall restrict our attention to a duopoly, henceforth $N = 2$. The equilibrium in the market where the good is sold requires that $\tilde{C}^* = \sum_{j=1}^{2} q_j$. Therefore, the market clearing condition can be written as

$$\sum_{j=1}^{2} q_j = c(\underset{(-)}{P}, \underset{(-)}{M}) \,. \tag{12}$$

The demand component on the RHS of equation (12) has the same qualitative properties as (10), that is, it is decreasing in the price (P) and the level of pollution (M). To ensure analytical tractability, we simplify matters by following the standard approach of working under a linear approximation of an aggregate demand function that possesses the same qualitative properties. Otherwise, the lack of closed-form solutions would complicate the analysis unnecessarily and blur the intuition, thus obscuring the main message and the transparency of the results. Hence, the remaining analysis will be making use of

$$c(P,M) = a - \Gamma(M) - P, \quad a > 0, \tag{13}$$

where $\Gamma'(M) > 0$. A linear approximation is also employed to capture the negative effect of pollution on the demand for the good. That is

$$\Gamma(M) = \gamma M, \tag{14}$$

where $\gamma > 0$ quantifies the relative strength of this negative effect.[9]

Since firms produce a homogeneous product, it is helpful to think of them as operating under Cournot competition. Therefore, our formal analysis will be undertaken on the basis of an inverse demand function which we can get after combining equations (11)-(14). That is

$$P = a - \sum_{j=1}^{2}(1+\gamma\mu_j)q_j . \tag{15}$$

Each firm faces a constant marginal cost of production $m > 0$. Furthermore, it may be liable to a penalty (or tax) of $\tau \geq 0$ per unit of emissions. Given that a firm emits $\mu_j q_j$ units of pollution, its variable costs are

$$(m + \tau\mu_j)q_j . \tag{16}$$

All in all, firms' variable profits can be written as follows:

$$v_j = \left[a - \sum_{j=1}^{2}(1+\gamma\mu_j)q_j \right] q_j - (m+\tau\mu_j)q_j . \tag{17}$$

Firms can choose the type of technology they employ in their production process. In particular, we assume that each firm can choose between two alternative technologies ('dirty' or 'clean') which differ in their associated emissions per unit of output and adoption costs – the latter assumed to be fixed. We assume that there is a trade-off between the level of emissions and the adoption cost. That is, the dirty technology entails an emission rate $\overline{\mu}$ and can be adopted at zero cost while the clean technology is associated with a lower emission rate $\underline{\mu} < \overline{\mu}$ but a higher adoption cost. In what follows, we shall be assuming that $\overline{\mu} < 2\underline{\mu}$ holds. This restriction is sufficient, albeit not necessary, to ensure the stability of the

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[9] Introducing non-separability between the price level and pollution in the demand function would eliminate the tractability of the model, without offering any major additional insights given that both M and P still have a negative effect on demand, as they do in equation (13)-(14).

equilibrium that we will derive after solving the system of best response functions later in our analysis.[10]

Before we proceed, we would like to justify our use of discrete technology choice. Firstly, such an idea is empirically relevant and there is nothing alien to this approach. For example, we can think of the provision of transport services, where companies can employ either electric (clean) or petrol (dirty) vehicles. Secondly, this approach also minimises the complexity of the model's solution, without undermining the understanding of the intuition and the mechanisms involved in the choice of environmental technology.

We also introduce the possibility of positive spillovers associated with the design and implementation of the cleaner production method. It is less costly for a firm to develop and adopt the clean technology if its competitor is also using this clean technology. Formally, firm j faces a fixed cost Φ_j such that, for $j \neq j'$,

$$\Phi_j = \begin{cases} 0 & \text{if} \quad \mu_j = \overline{\mu} \\ \overline{\varphi} & \text{if} \quad \mu_j = \underline{\mu},\ \mu_{j'} = \overline{\mu} \\ \underline{\varphi} & \text{if} \quad \mu_j = \underline{\mu},\ \mu_{j'} = \underline{\mu} \end{cases}, . \tag{18}$$

where $\underline{\varphi} < \overline{\varphi}$.

Given (17) and (18), each firm's total profits, π_j, are given by

$$\pi_j = \left[a - \sum_{j=1}^{2} (1 + \gamma\mu_j) q_j \right] q_j - (m + \tau\mu_j) q_j - \Phi_j . \tag{19}$$

The objective of the firm is to maximise profits by the appropriate choices of q_j and μ_j. We assume that firms will choose their technologies first. Once firms' technology choices are observed, firms choose their output levels. Thus, the game has two stages: during the first stage, firms choose their technologies whereas during the second stage firms choose their output levels. We assume that firms choose simultaneously in each of these stages. As

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[10] Notice that this notion of stability differs from the one applied to variables that display an explicit dynamic pattern. In this case, an equilibrium is said to be stable if, starting from any point in its neighbourhood, the adjustment process in which players take turns myopically playing a best response to each other's current strategies converges to the equilibrium. Formally, using π_j to denote profits, the stability condition is $\frac{\partial^2 \pi_j}{\partial q_j^{\,2}} > \frac{\partial^2 \pi_j}{\partial q_j \partial q_{j'}}$, where $j = \{1, 2\}$. See Martin (2001).

usual, we solve this game by backwards induction and use subgame perfection as our equilibrium concept.

3.1 The Second Stage: Output Choices

In this stage, firms set their output levels to maximise profits. The first order condition for maximisation is given by

$$\frac{\partial \pi_j}{\partial q_j} = \left[a - \sum_{j=1}^{2} (1+\gamma\mu_j) q_j \right] - q_j(1+\gamma\mu_j) - m - \tau\mu_j = 0. \tag{20}$$

Notice that the second order condition for a maximum is fulfilled $(\partial^2 \pi_j / \partial q_j^{\ 2} = -2(1+\gamma\mu_j) < 0)$. Thus, we can solve (20) for q_j to obtain the best response function for each firm, which is

$$q_j^* = \frac{[a - m - \tau\mu_j - q_{j'}(1+\gamma\mu_{j'})]}{2(1+\gamma\mu_j)}. \tag{21}$$

As expected, firms' outputs are strategic substitutes since $\partial q_j^* / \partial q_{j'} < 0$. An increase in the competitor's output will put a downward pressure on the good's price, thus reducing the firm's marginal revenue. Given that the marginal cost of production is unchanged, the firm will find it profitable to reduce its production in order to restore the marginal revenue back to its original level. It is worth noting that the magnitude of this effect is reinforced by the presence of the parameter γ. The intuition for this is that firm j's output adds to the total level of emissions, triggering a shift of the consumers' demand away from the good and, as a response, a lower level of output by firm j. The same intuitive mechanism more or less applies when we try to explain the inverse relation between the firm's production and its own emission rate. Notice, however, that this adverse effect is reinforced by the presence of the emission tax which, effectively, adds to the cost of production.

Solving the system of best response functions for $j = \{1, 2\}$, we find the equilibrium levels of output, which are

$$q_1^* = \frac{a - m - \tau(2\mu_1 - \mu_2)}{3(1+\gamma\mu_1)}, \tag{22}$$

and

$$q_2^* = \frac{a - m - \tau(2\mu_2 - \mu_1)}{3(1+\gamma\mu_2)}. \tag{23}$$

Given these results, we are now able to formalise our analysis on the equilibrium output responses, associated with different technology choices. The following proposition summarises the corresponding qualitative effects.

Proposition 2. *A firm's optimal production is, ceteris paribus, decreasing in its own emission rate but increasing in its competitor's emission rate. The effect of the competitor's technology choice (i.e., the competitor's emission rate) on the firm's output exists if and only if* $\tau > 0$.

Proof. Using equations (21) and (22), it is straightforward to establish that $\partial q_1 / \partial \mu_1, \partial q_2 / \partial \mu_2 < 0 \ \forall \tau \geq 0$ and $\partial q_1 / \partial \mu_2, \partial q_2 / \partial \mu_1 > 0$ iff $\tau > 0$. **QED**

A few points merit discussion here. On the one hand, the firm's own emission rate has a negative effect on its own output through two different mechanisms. First, a higher emission rate means more pollution and therefore a higher shift in demand, leading to a reduction in output. Second, the own emission rate will positively affect the effective marginal cost of production of firms as long as emissions are taxed ($\tau > 0$). The higher this cost, the lower the output will be. The competitor's emission rate will affect positively the firm's own output as long as emissions are taxed. Although this result may seem at odds with the effects we discussed earlier, it can be explained as follows. When a competitor chooses a more polluting technology, there are two conflicting effects on the firm's output. The direct effect works as follows: a higher emission rate by the competitor will reduce the total demand for output as long as $\gamma > 0$. Consequently, the firm will react by reducing its own production. There is an indirect effect, however, which works in exactly the opposite direction. In particular, the competitor will combine her choice of a higher emission rate with a lower level of output – an effect partially attributed to the presence of the parameter γ, but also amplified by the fact that the emission tax exacerbates the overall cost of production. It is this latter effect that renders the indirect impact to the competitor's output dominant and, given that output levels are strategic substitutes, makes it profitable for the firm to increase its output. Moreover, this is precisely why taxation is crucial for the materialisation of technology choice interactions when firms determine their output levels.

Substituting (22) and (23) in (19), we can write each firm's total profits as

$$\pi_1 = v_1 - \Phi_1 = \frac{[a - m - \tau(2\mu_1 - \mu_2)]^2}{9(1+\gamma\mu_1)} - \Phi_1, \tag{24}$$

and

$$\pi_2 = v_2 - \Phi_2 = \frac{[a - m - \tau(2\mu_2 - \mu_1)]^2}{9(1+\gamma\mu_2)} - \Phi_2. \tag{25}$$

These expressions, together with (22) and (23), reveal that, in terms of equilibrium output and, therefore, variable profits, the choice of technology across firms is subject to strategic substitutability: other things being equal, a firm's choice to implement a cleaner technology reduces the other firm's output and therefore variable profits, lowering the incentives for the implementation of the cleaner technology. Nevertheless, the technology choice entails fixed costs whose presence introduces a strategic complementarity according to (18): other things being equal, a firm's decision to implement a less polluting technology makes it less costly for the other firm to do the same because of the positive spillover effect.

Given that the profits of each firm depend on their own and their competitor's technology choices, four scenarios arise: one where both firms choose the cleaner technology, $(\underline{\mu},\underline{\mu})$; another where both firms choose the dirtier technology, $(\overline{\mu},\overline{\mu})$; and two asymmetric ones, where firm 1 chooses the clean technology and firm 2 the dirty one, $(\underline{\mu},\overline{\mu})$, as well as the opposite case where $(\overline{\mu},\underline{\mu})$. Thus, the variable profits in each of these scenarios can be written as follows:

$$v_j^{\underline{\mu},\underline{\mu}} = \frac{(a - m - \tau\underline{\mu})^2}{9(1+\gamma\underline{\mu})}, \tag{26}$$

$$v_j^{\overline{\mu},\overline{\mu}} = \frac{(a - m - \tau\overline{\mu})^2}{9(1+\gamma\overline{\mu})}, \tag{27}$$

$$v_j^{\underline{\mu},\overline{\mu}} = \frac{[a - m - \tau(2\underline{\mu} - \overline{\mu})]^2}{9(1+\gamma\underline{\mu})}, \tag{28}$$

$$v_j^{\overline{\mu},\underline{\mu}} = \frac{[a - m - \tau(2\overline{\mu} - \underline{\mu})]^2}{9(1+\gamma\overline{\mu})}. \tag{29}$$

Note that in the above equations, we use the first superscript to identify firm j's own technology choice and the second superscript to identify its competitor's technology choice. Bringing together equations (26) to (29) and equation (18), we complete the payoff matrix in Table 1. In the next section we will identify under which conditions each of the above mentioned four scenarios may arise as equilibrium outcomes.

		Firm 2	
		$\overline{\mu}$	$\underline{\mu}$
Firm 1	$\overline{\mu}$	$v_1^{\overline{\mu},\overline{\mu}}$, $v_2^{\overline{\mu},\overline{\mu}}$	$v_1^{\overline{\mu},\underline{\mu}}$, $v_2^{\underline{\mu},\overline{\mu}} - \overline{\varphi}$
	$\underline{\mu}$	$v_1^{\underline{\mu},\overline{\mu}} - \overline{\varphi}$, $v_2^{\overline{\mu},\underline{\mu}}$	$v_1^{\underline{\mu},\underline{\mu}} - \underline{\varphi}$, $v_2^{\underline{\mu},\underline{\mu}} - \underline{\varphi}$

Table 1. Payoff matrix

3.2 The First Stage: Technology Choices

In this stage, firms seek to maximise profits through the appropriate choice of technology. Our preceding analysis indicates that firms have an incentive to implement a cleaner technology even in the absence of taxation due to the effect of pollution on the aggregate demand of environmentally conscious consumers, captured by the parameter γ. We will start by analysing the case without environmental policy ($\tau = 0$).

3.2.1 Technology Choice without Emission Taxes

Let us go back to equations (24) and (25) and set $\tau = 0$ to get

$$\pi_1 = \frac{(a-m)^2}{9(1+\gamma\mu_1)} - \Phi_1 , \tag{30}$$

and

$$\pi_2 = \frac{(a-m)^2}{9(1+\gamma\mu_2)} - \Phi_2 . \tag{31}$$

These equations reveal that the choice of a cleaner technology (i.e., $\underline{\mu}$ as opposed to $\overline{\mu}$) can only be optimal for the firm if $\gamma > 0$, that is if pollution entails the type of aggregate demand effects that we identified in Section 2. If $\gamma = 0$, and in the absence of environmental taxes, there is no incentive by neither firm to incur a cost for an activity that has no benefit whatsoever. However, insofar as $\gamma > 0$, such benefit clearly exists: a firm may be willing to incur the fixed cost of environmental innovation, anticipating that this will induce environmentally conscious consumers to shift their resources towards the consumption of goods. In fact, such motive exists even in the absence of spillovers. Nevertheless, if spillovers exist, they will create a further incentive for firms to adopt the cleaner technology.

Let us discuss now the conditions under which each combination of strategies may arise as an equilibrium. Note that here, the variable profit is solely a function of the own emission rate. Thus, the net benefit in terms of variable profits of implementing a cleaner technology is the same irrespectively of the competitors' choice, since $v_j^{\underline{\mu},\underline{\mu}} - v_j^{\overline{\mu},\underline{\mu}} = v_j^{\underline{\mu},\overline{\mu}} - v_j^{\overline{\mu},\overline{\mu}}$. In fact, in both cases this difference yields

$$\omega = \frac{(a-m)^2 \gamma(\overline{\mu} - \underline{\mu})}{9(1+\gamma\overline{\mu})(1+\gamma\underline{\mu})}. \tag{32}$$

It is evident from (32) that, in the absence of emission taxes, a benefit exists if and only if $\gamma > 0$ – that is, only if pollution results in aggregate demand effects. Next, we need to compare this net benefit with the difference in fixed cost of adopting each technology.[11] The result of this comparison will determine the equilibrium of the game. They are presented in the next proposition.

Proposition 3. *Suppose that* $\tau = 0$. *Then the following are equilibria:*

- *i.* $(\overline{\mu}, \overline{\mu})$ *if* $\omega \leq \underline{\varphi}$;
- *ii.* $(\overline{\mu}, \overline{\mu})$ *and* $(\underline{\mu}, \underline{\mu})$ *if* $\underline{\varphi} < \omega \leq \overline{\varphi}$;
- *iii.* $(\underline{\mu}, \underline{\mu})$ *if* $\omega > \overline{\varphi}$.

Proof. See the Appendix. □

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[11] As a tiebreaking rule, we assume that if a firm is indifferent between the two technologies, it will choose $\overline{\mu}$.

Proposition 3 states that the only equilibria that arise are symmetric (either both firms choose the clean technology or both firms choose the dirty one). In particular, when the net benefit of choosing the clean technology is very small (too small to be profitable to adopt it even when there are spillovers), the only equilibrium is $(\overline{\mu},\overline{\mu})$. Conversely, when this benefit is very high (high enough to make adoption profitable even without spillovers), the only equilibrium is $(\underline{\mu},\underline{\mu})$. For intermediate levels, both $(\overline{\mu},\overline{\mu})$ and $(\underline{\mu},\underline{\mu})$ arise as equilibria since adopting the clean technology is only profitable if the competitor adopts it too; that is when there is a possibility of benefiting from spillovers. In this case, however, this outcome is not guaranteed as firms face a coordination problem due to the multiplicity of equilibria.[12] For values satisfying $\omega \in (\underline{\varphi},\overline{\varphi}]$ although the positive spillovers would make it mutually advantageous for both firms to choose the clean technology, the expectation that the competitor may not choose $\underline{\mu}$ (hence, eliminating the benefits emanating from the spillover effect) may discourage firms from a choice of $\underline{\mu}$.

3.2.2 Technology Choice in the Presence of Emission Taxes

In this section, we analyse the first stage in the presence of emission taxes and try to identify the equilibrium outcomes that transpire in this scenario. For subsequent purposes, we begin this part by defining

$$\overline{\omega} = v_j^{\underline{\mu},\overline{\mu}} - v_j^{\overline{\mu},\overline{\mu}} = \frac{[a-m-\tau(2\underline{\mu}-\overline{\mu})]^2}{9(1+\gamma\underline{\mu})} - \frac{(a-m-\tau\overline{\mu})^2}{9(1+\gamma\overline{\mu})}, \tag{33}$$

and

$$\underline{\omega} = v_j^{\underline{\mu},\underline{\mu}} - v_j^{\overline{\mu},\underline{\mu}} = \frac{(a-m-\tau\underline{\mu})^2}{9(1+\gamma\underline{\mu})} - \frac{[a-m-\tau(2\overline{\mu}-\underline{\mu})]^2}{9(1+\gamma\overline{\mu})}. \tag{34}$$

The interpretation of (33) and (34) is similar to the corresponding one in equation (32). Here, however, the increase in variable profits from implementing the cleaner technology depends on whether the competitor chooses the dirty or the clean technology. We label with $\underline{\omega}$ this increase in the latter case and with $\overline{\omega}$ in the former. If $\overline{\omega}$ is higher than $\overline{\varphi}$, a firm's

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[12] Effectively, the existence of spillovers introduces a strategic complementarity in the choice of technology. See Cooper and John (1988) for a detailed discussion on the implications of coordination failures in models with strategic complementarities.

best response to its competitor choosing the dirty technology is to adopt the clean technology. Analogously, if $\underline{\omega}$ is higher than $\underline{\varphi}$, its best response to the clean technology is to adopt the clean technology too. Some tedious, but straightforward, algebra reveals that $\bar{\omega} > \underline{\omega}$ holds. In other words, the net benefit from implementing the less polluting technology is higher when the competitor actually implements the more polluting one. Recalling that the presence of the emission tax introduces some strategic substitutability in the optimal choice of technology (as opposed to the strategic complementarity emerging from the presence of spillover effects), the intuition behind this result is clear: when the competitor chooses the cleaner technology, and as long as the government taxes emissions, it becomes more competitive in the product market, as its marginal cost is lower than it would be if it chose the dirty technology. In turn, this affects negatively firm j's output and therefore the (variable) profitability of adopting the cleaner technology.

With these in mind, we can use the two propositions that follow in order to summarise the equilibrium outcomes that materialise during the first stage of the competition (when $\tau > 0$).

Proposition 4. *Suppose that* $\tau > 0$ *and* $\bar{\omega} - \underline{\omega} < \bar{\varphi} - \underline{\varphi}$. *Then, the following are equilibria:*

i. $(\bar{\mu}, \bar{\mu})$ *if* $0 \geq \underline{\omega} - \underline{\varphi} > \bar{\omega} - \bar{\varphi}$;

ii. $(\bar{\mu}, \bar{\mu})$ *and* $(\underline{\mu}, \underline{\mu})$ *if* $\underline{\omega} - \underline{\varphi} > 0 \geq \bar{\omega} - \bar{\varphi}$;

iii. $(\underline{\mu}, \underline{\mu})$ *if* $\underline{\omega} - \underline{\varphi} > \bar{\omega} - \bar{\varphi} > 0$.

Proof. See the Appendix. □

Proposition 5. *Suppose that* $\tau > 0$ *and* $\bar{\omega} - \underline{\omega} \geq \bar{\varphi} - \underline{\varphi}$. *Then, the following are equilibria:*

i. $(\bar{\mu}, \bar{\mu})$ *if* $0 \geq \bar{\omega} - \bar{\varphi} \geq \underline{\omega} - \underline{\varphi}$;

ii. $(\bar{\mu}, \underline{\mu})$ *and* $(\underline{\mu}, \bar{\mu})$ *if* $\bar{\omega} - \bar{\varphi} > 0 \geq \underline{\omega} - \underline{\varphi}$;

iii. $(\underline{\mu}, \underline{\mu})$ *if* $\bar{\omega} - \bar{\varphi} \geq \underline{\omega} - \underline{\varphi} > 0$.

Proof. See the Appendix. □

The scenarios described in Proposition 4 and Proposition 5 differ with respect to the relative strength of the spillover effect $\overline{\varphi}-\underline{\varphi}$ which is larger in the scenario in Proposition 4. Nevertheless, there are some common outcomes in both scenarios. Particularly, when the net benefit of choosing the clean technology is very small or very high, the equilibria are analogous to the equilibria arising in the absence of taxes; that is, $(\overline{\mu},\overline{\mu})$ in the former case and $(\underline{\mu},\underline{\mu})$ in the latter.

However, a major difference across scenarios arises for intermediate values of this benefit. In the first scenario, the relatively strong spillovers make the adoption of the clean technology profitable if and only if the competitor adopts it too. If the competitor uses the dirty technology, the benefit in terms of variable profits is not enough to make the adoption of the clean technology profitable. This is reflected in the equilibrium outcomes described in Proposition 4 (ii); in such a case, both $(\overline{\mu},\overline{\mu})$ and $(\underline{\mu},\underline{\mu})$ are Nash equilibria. However, when the spillover effect is not so strong, it may be profitable for a firm to adopt the clean technology as a reply to the competitor's adopting the dirty technology. In such a case, the competitor is in disadvantage in the output market due to the higher marginal cost. For the same reason, it is optimal for the competitor to adopt the dirty technology as a reply to the clean technology, as its less competitive position in the market and therefore lower output makes it less profitable to incur in the higher fixed costs of the clean technology. Thus, two asymmetric equilibria arise, $(\overline{\mu},\underline{\mu})$ and $(\underline{\mu},\overline{\mu})$, as Proposition 5 (ii) shows. Consequently, firms face a coordination problem due to the multiplicity of equilibria in both scenarios for intermediate values of the benefit of adopting the clean technology.

4 Environmental Awareness, Policy and Incentives for Pro-Environment Innovation

In this section, our purpose is to examine the effectiveness of environmental policy on increasing the incentive of firms in adopting the less polluting production method. Our previous analysis has made clear that the emission tax τ will affect this incentive through its impact on variable profits. In particular, it will do so through the effect it has on the net benefit of introducing the cleaner technology. That is, the increase in variable profits when a firm shifts from the dirty (i.e., $\overline{\mu}$) to the clean technology (i.e., $\underline{\mu}$).

The previous section has revealed that the increment in variable profits from introducing a cleaner technology varies depending on whether the competitor chooses to innovate ($\underline{\omega}$) or not ($\overline{\omega}$). We also know that the higher $\underline{\omega}$ and $\overline{\omega}$ are, the more likely that a firm will choose to adopt the clean technology as a reply to its competitor respectively adopting the clean technology or the dirty technology. Here we will use comparative statics to check whether τ has a positive, negative or non-monotonic effect on $\underline{\omega}$ and $\overline{\omega}$. Furthermore, we want to check whether γ, i.e., the parameter describing consumers' environmental awareness, impinges on the effectiveness of environmental policy. This will allow us to establish whether emissions taxation makes the adoption of the clean technology more likely to happen in equilibrium. To this aim, we shall examine $\underline{\omega}$ and $\overline{\omega}$ separately, beginning with the former.

As it is evident from our previous analysis and discussion, we are interested on the effect of τ on the composite term $\underline{\omega}$ in (34). Prior to undertaking the formal analysis, however, we need to impose an upper bound on the emission tax. This is necessary to ensure that variable profits are non-negative under any possible scenario concerning technology choice by the firm. A look at (34) reveals that the tax must satisfy $\tau \in \left(0, \frac{a-m}{2\overline{\mu}-\underline{\mu}}\right)$. Given this, the following proposition summarises our result.

Proposition 6. *There exists* $\tau^* \in \left(0, \frac{a-m}{2\overline{\mu}-\underline{\mu}}\right)$ *such that*

$$\frac{\partial \underline{\omega}}{\partial \tau}\begin{cases} >0 & \text{for} \quad \tau < \tau^* \\ =0 & \text{for} \quad \tau = \tau^* \\ <0 & \text{for} \quad \tau > \tau^* \end{cases}.$$

Furthermore, it is $\frac{\partial \tau^*}{\partial \gamma} < 0$.

Proof. See the Appendix. □

One implication of Proposition 6 is that there is a tax rate that maximises the incentive to adopt a clean technology when the competitor is expected to act similarly. Additionally, we can see that when the negative aggregate demand effect from pollution is more pronounced (i.e., when γ is higher) then the tax rate that maximises the incentive for pro-environment R&D becomes lower.

In terms of intuition, the non-monotonic effect of the emission tax is due to the conflicting effects on variable profits. On the one hand, the emission tax motivates the firm to choose a cleaner technology in order to reduce its overall tax obligation. On the other hand, however, excessively high taxation makes the overall tax burden so high and the reduction in variable profits so strong, that it eliminates any incentive for the adoption of the cleaner technology. Naturally, the tax rate where these marginal benefits and costs are equal, is the one that will provide the highest incentive for pro-environment innovation. A similar result has been found, in a different framework, by Perino and Requate (2012). What is different in our analysis is the impact of the negative demand effect of pollution, as this is captured by the parameter γ. Given that this effect already provides an incentive for the adoption of a cleaner production method (see Section 3.2.1), the parameter γ exemplifies the potential negative effect of the emission tax on the incentive to implement the cleaner technology. In fact, it is possible that the same increase in taxation that would raise the incentive for the adoption of the cleaner technology when $\gamma = 0$, may actually decrease this incentive for $\gamma > 0$. In terms of Figure 1, this scenario is depicted for values of the emission tax that lie on the interval $(\tau^*_{\gamma>0}, \tau^*_{\gamma=0})$.

Next, we undertake a similar analysis for the case where the firm expects its competitor not to adopt the cleaner production technique – that is, we focus on the composite term $\overline{\omega}$ in (33). In order to ensure that variable profits remain non-negative in this case, we use equation (33) to identify a proper range of values for the emissions tax which turns out to be $\tau \in \left(0, \frac{a-m}{\overline{\mu}}\right)$. The following proposition summarises our result.

Proposition 7. *There exists* $\tau^{**} \in \left(0, \frac{a-m}{\overline{\mu}}\right)$ *such that*

$$\frac{\partial \overline{\omega}}{\partial \tau}\begin{cases} >0 & \mathit{for} \quad \tau < \tau^{**} \\ =0 & \mathit{for} \quad \tau = \tau^{**} \\ <0 & \mathit{for} \quad \tau > \tau^{**} \end{cases}.$$

Furthermore, it is $\frac{\partial \tau^{**}}{\partial \gamma} < 0$.

Proof. See the Appendix. □

As we can see, the possibility of non-monotonic effects from environmental policy emerges in this scenario as well – as does the impact of the preference parameter γ on the tax rate that maximises the incentive to use the clean technology. Consequently, the intuition for these results is exactly the same with the one discussed in the analysis of Proposition 6. Given that both $\underline{\omega}$ and $\overline{\omega}$ are inverted U-shapes in τ, it is clear that the likelihood that a firm adopts the clean technology in equilibrium is initially increasing in the tax rate but will eventually turn decreasing. The turning point will take place earlier, i.e. for a lower level of the tax rate, if consumers have some preference for the environment which makes them shift resources from consumption to environmental activities. This is illustrated in Figure 1 in which we draw the relation between $\underline{\omega}$ and taxation for $\gamma = 0$ and $\gamma > 0$. An analogous figure can depict the relation between the emission tax rate and $\overline{\omega}$.

Before concluding this section, it is worth discussing the role of the tax rate in determining which combination of strategies arises in equilibrium. Thus, we need to consider jointly the effects that τ has on both $\overline{\omega}$ and $\underline{\omega}$. Figure 2 provides an illustration of $\overline{\omega}$ and $\underline{\omega}$ for arbitrary levels of fixed costs and spillovers. One can see that five regions emerge with correspondingly different equilibrium outcomes. In the first region (between 0 and τ_1), the best reply to both $\overline{\mu}$ and $\underline{\mu}$ is $\overline{\mu}$. This implies that the arising equilibrium will be ($\overline{\mu}$, $\overline{\mu}$). If the tax rate is set at a higher level (in the region between τ_1 and τ_2), the best response to $\overline{\mu}$ is $\overline{\mu}$ and to $\underline{\mu}$ is $\underline{\mu}$. Thus, it may occur that either ($\overline{\mu}$, $\overline{\mu}$) or ($\underline{\mu}$, $\underline{\mu}$) arise in equilibrium. In contrast, if the tax rate was set in the third region (between τ_2 and τ_3), the only equilibrium would be ($\underline{\mu}$, $\underline{\mu}$), as $\underline{\mu}$ is the best reply to both $\overline{\mu}$ and $\underline{\mu}$. Increasing the tax even further to be in the fourth region (between τ_3 and τ_4) reduces the profitability of adopting the clean technology and may induce asymmetric equilibria where only one of the firms adopts the clean technology, that is ($\underline{\mu}$, $\overline{\mu}$) or ($\overline{\mu}$, $\underline{\mu}$), since the best reply to $\overline{\mu}$ is $\underline{\mu}$ and *vice versa*. Increasing the tax rate even further (to be higher than τ_4) will lead to an equilibrium where the two firms adopt the polluting technology ($\overline{\mu}$, $\overline{\mu}$). Thus, setting the tax rate to be in the intermediate region (between τ_2 and τ_3) would be the only way in which the policy maker can warrant an outcome where both firms adopt the clean technology in equilibrium.[13]

Some important implications for policy making can be drawn from the above results. The first and perhaps counterintuitive implication is that increasing the tax rate on emissions does not necessarily create further incentives for the adoption of clean technologies. In fact, a higher tax rate may actually reduce the incentives to adopt the clean technology and therefore reduce the likelihood of this adoption in equilibrium, particularly if the original tax rate on emission is already relatively high. Secondly, the policy maker should be particularly aware of such an effect in situations where consumers are environmentally conscious. In such situations, the benefit of adopting the clean technology turns decreasing in the emissions tax rate for lower levels of taxation. Thus, the policy maker should take into account the behaviour of consumers when designing its environmental policy. For example, if carbon offsetting schemes are introduced in a given industry and consumers are actively participating in them, it may be optimal for the government to reduce its level of emissions taxation in that industry, especially if this level is initially high; otherwise, the incentives of firms in that given industry to adopt clean methods of production may be damaged.

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[13] Note that Figure 2 is presented as an illustrative example only. We could in fact find that the second and the fourth regions are switched over, or even that they do not arise. This would depend on the specific combination of parameters in each case. What is generally true is that as τ increases, there is a transition from less adoption of clean technologies to more adoption of clean technologies and then again to less adoption of clean technologies.

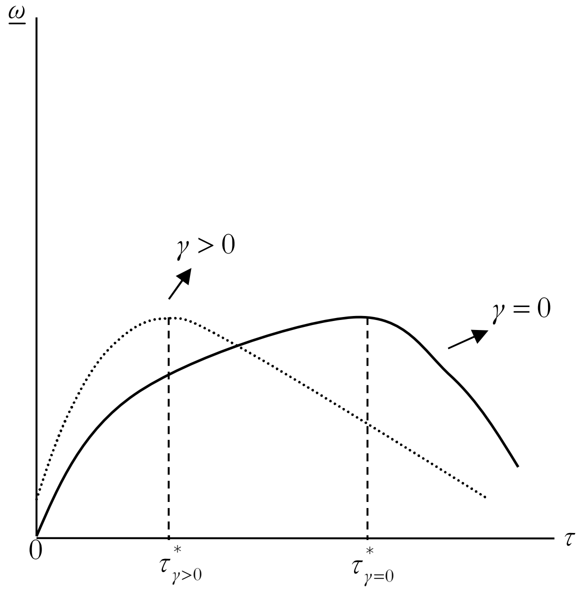

Figure 1

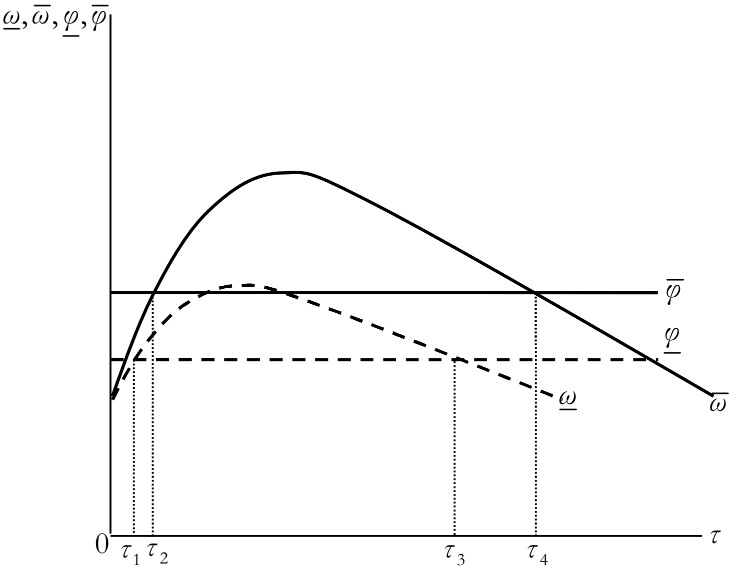

Figure 2

5 Discussion

Our framework has been constructed with the purpose of providing clear intuition that is made possible through the analytically tractable solution. Given that our model is streamlined, the reader may wonder whether some of our assumptions are crucial for our subsequent results. In this section, we will discuss and comment on the implications of some of our assumptions.

Firstly, let us consider equation (2) that determines environmental quality. One could wonder whether the assumption that the two terms affecting environmental quality are additive separable – implying that consumer resources can compensate perfectly for the environmental damage due to pollution – is crucial for Proposition 1. We can show that this is not the case. The results in (8) and (10) would be qualitatively the same if we were to assume a more general case where E is determined through a CES aggregator. Formally, if $E=\left[(e(M))^{\frac{\theta-1}{\theta}}+\left(\sum_{i=1}^{k}x_i\right)^{\frac{\theta-1}{\theta}}\right]^{\frac{\theta}{\theta-1}}$ then, after some tedious algebra, it is straightforward to establish that the solution for x^* can only be implicitly characterised through

$$(e(M))^{\frac{\theta-1}{\theta}}=k\left(x^*\right)^{-\frac{1}{\theta}}\left[\frac{1-\delta}{\delta}(y-x^*)-x^*\right].$$

Given this, we can use implicit differentiation to show that $\partial x^*/\partial M>0$ (and, therefore, $\partial\tilde{C}^*/\partial M<0$), as long as $\theta>1$. These are exactly the result obtained in Proposition 1.

Secondly, as we clearly stated in our Introduction, we are not concerned with a distinction between 'green' and polluting products. Instead, we want to analyse the aggregate demand effects of environmental spending and the corresponding implications for environmental technology choice. Adding a non-polluting good in a constant returns utility function like (1) would simply generate a scale effect in the optimal consumption of the polluting good – an effect related to the relative weights in the utility function. Qualitatively, the demand function for the polluting goods would remain the same, thus leaving the subsequent analysis on technology choice unaffected.

Thirdly, we need to emphasise that our model is not a general equilibrium one. For this reason we do not consider the use of tax revenues for such purposes as, for example, subsidies; transfers; or spending on public goods and services. Actually, this same approach is used by existing analyses that aim at focusing on the effect of emission taxes on environmental technology choice (e.g., van Soest 2005; Baker and Shittu 2006; Perino and Requate 2012; Bréchet and Meunier 2012). Had we assumed that such revenues are returned to consumers in the form of transfers, then the purpose of environmental policy as a tool to induce the use of cleaner technologies would probably be self-defeating. The reason is that consumers purchase normal goods, therefore total emissions would have an indirect positive effect on demand through income, in addition to the direct negative effect that has been the focus of our paper. As long as the latter effect dominates the former, then one would expect that the qualitative nature of the results would be similar to what we have obtained in our current framework. Nevertheless, if the former effect dominates the latter then the purpose of environmental policy becomes blurred as a higher tax rate would increase demand through the resulting income effect that emerges due to the subsidies. As the focus of our paper is quite different, we have chosen to abscond from this scenario. In any case, one could say that the use of government revenues can be widespread and not only limited to transfers. Our scenario, for example, could be relevant to a case where such revenues are used for government consumption purposes.

The need for analytical tractability also dictates two additional assumptions of our framework – the use of a discrete (as opposed to continuous) technology choice and the restriction of the industry's size to a duopoly. With regards to the former, allowing for a continuum of technologies makes the maximisation problem rather complicated and it eliminates the possibility of closed-form solutions. It does this, without adding any additional insights because the qualitative effects of structural parameters on the choice of a lower μ is the same, irrespective of whether the emission rate is a discrete or continuous variable. With regards to the use of a duopolistic industry, this restriction allows us to analyse how the interactions among competitors are affected by the main ideas of our paper, in a simple and straightforward manner. Allowing for more firms in the industry would generate (i) some scale effects manifested by a parameter that would indicate the number of firms, and (ii) more equilibria in Propositions 3-5 given the discrete nature of environmental technology choice. However, there is no reason to presume that the qualitative effect of the emission tax on the choice of μ and more importantly, the importance of γ for this effect would change drastically if we increase the size of the industry. Still the study of these issues under different market structures is a potentially interesting avenue for future research.

Finally, we need to justify the use of adoption spillovers in our framework. Although adoption spillovers are not crucial for the main results concerning the effectiveness of environmental policy to appear, having such spillovers allows for richer equilibrium outcomes. For example, if $\bar{\varphi} = \underline{\varphi}$, Proposition 5 would describe the only relevant equilibrium results of the game with positive taxation. As a result, the presence of spillovers entails a richer set of possible equilibria under environmental policy. Given the empirical relevance of spillovers, and in particular environmental ones (e.g., Buonanno *et al.* 2001; Clarke *et al.* 2006), this allows us to identify additional implications and possibilities when it comes to the effects of environmental policy. The reason for this is that the presence of spillovers introduces strategic complementarities in the decision making by firms, that may counteract the strategic substitutability derived from emission taxes. Furthermore, this allows us to verify that the effect of consumers' environmental awareness (described the parameter γ) on the effectiveness of environmental policy can survive into a more richer set of possible equilibria - a set that the presence of adoption spillovers allows to emerge.

6 Conclusions

We have analysed how the existence of environmentally conscious consumers affects firms' adoption of cleaner manufacturing technologies. Although, in recent years the literature has introduced the presence of environmentally conscious consumers in models of product differentiation, such models are not suitable for the analysis of situations where consumers are involved in environmental activities such as participation in carbon offsetting schemes; environmental volunteering; donations; boycotts etc.

In this paper we propose a framework of analysis for this alternative type of environmental conscious consumers. In particular, we have assumed that consumers' utility is a function of both their level of consumption of a good and environmental quality. Environmental quality is affected both by the amount of resources which consumers devote to environmental activity and by total emissions. As for the technology choice, we have assumed that firms have two technologies at their disposal which differ in their associated emissions per unit of output ratio and fixed costs.

We have shown that following an increase in pollution, consumers will channel resources away from consumption and towards environmental activities, thereby reducing the demand for the good which firms face and the subsequent levels of output produced by firms in equilibrium. This reduction in demand due to consumers' environmental activities generates incentives for firms to adopt the clean technology even in the absence of emissions taxes or technology spillovers.

Our results also indicate that increasing the tax rate on emissions does not necessarily lead to the adoption of clean technologies. In fact, the benefit of adopting the clean technology follows an inverted U-shape in the tax rate, which implies that after a threshold value of the emission tax rate, further tax increases make less likely the adoption of the clean technology in equilibrium. This counterintuitive effect is more prevalent in situations where consumers are environmentally conscious.

All in all, the main policy lesson that can be extracted from our model is that any environmental policy aimed at improving the technological profile of firms should take into account the behaviour of environmentally conscious consumers where relevant (for example, in markets where environmental activities such as the ones described above take place); otherwise, the policy may have undesirable effects on firms' decisions to invest in cleaner technologies. A word of caution is needed here: Our results have been derived in a streamlined model. The introduction of different market structures or more general demand or cost conditions would constitute a potentially interesting direction for future research.

Appendix

Proof to Proposition 3

From Table 1 and equation (32), we know that that firm 1's best response to firm 2 choosing $\underline{\mu}$ is $\overline{\mu}$ ($\underline{\mu}$) if $\omega \leq (>)$ $\underline{\varphi}$. Likewise, its best response to firm 2 choosing $\underline{\mu}$ is $\overline{\mu}$ ($\underline{\mu}$) if $\omega \leq (>)$ $\overline{\varphi}$. Recall that $\underline{\varphi} \leq \overline{\varphi}$. Thus, if $\omega \leq \underline{\varphi}$, firm 1 has a dominant strategy which is $\overline{\mu}$. Moreover, if $\omega > \overline{\varphi}$, its dominant strategy is $\underline{\mu}$ instead. As the game is symmetric, the same applies to firm 2. Hence, $(\overline{\mu}, \overline{\mu})$ and $(\underline{\mu}, \underline{\mu})$ are the equilibria in dominant strategies if $\omega \leq \underline{\varphi}$ and $\omega > \overline{\varphi}$ respectively.

Now assume that $\underline{\varphi} < \omega \leq \overline{\varphi}$. In such a case, firm 1's best response to firm 2 choosing $\overline{\mu}$ is $\overline{\mu}$ whereas its best response to firm 2's choice of $\underline{\mu}$ is $\underline{\mu}$. Again, due to symmetry, the same applies to firm 2. Thus, if $\underline{\varphi} < \omega \leq \overline{\varphi}$, two Nash equilibria arise: $(\overline{\mu}, \overline{\mu})$ and $(\underline{\mu}, \underline{\mu})$. **QED**.

Proof to Proposition 4

Consider the scenario where $\tau > 0$ and $\bar{\omega} - \underline{\omega} < \bar{\varphi} - \underline{\varphi}$ or $\bar{\omega} - \bar{\varphi} < \underline{\omega} - \underline{\varphi}$ after rewriting. From Table 1 and equations (33) and (34) we know that that firm 1's best response to $\bar{\mu}$ is $\underline{\mu}$ $(\bar{\mu})$ if $\bar{\omega} - \bar{\varphi} > (\leq)$ 0 and to $\underline{\mu}$ is $\underline{\mu}$ $(\bar{\mu})$ $\underline{\omega} - \underline{\varphi} >$ $(\leq)$ 0. Due to symmetry, the same applies to firm 2. Given these conditions and $\bar{\omega} - \underline{\omega} < \bar{\varphi} - \underline{\varphi}$, three cases may emerge:

(i) $\bar{\omega} - \bar{\varphi} \leq 0$ and $\underline{\omega} - \underline{\varphi} \leq 0$;

(ii) $\bar{\omega} - \bar{\varphi} \leq 0$ and $\underline{\omega} - \underline{\varphi} > 0$;

(iii) $\bar{\omega} - \bar{\varphi} > 0$ and $\underline{\omega} - \underline{\varphi} > 0$.

In case (i) both firms have a dominant strategy in $\bar{\mu}$ (it is their best response in both $\bar{\mu}$ and $\underline{\mu}$). Thus, $(\bar{\mu}, \bar{\mu})$ is an equilibrium in dominant strategies. In case (iii) both firms have a dominant strategy in $\underline{\mu}$ (it is their best response in both $\bar{\mu}$ and $\underline{\mu}$). Therefore, $(\underline{\mu}, \underline{\mu})$ is an equilibrium in dominant strategies. In case (ii), firm 1's best response to $\bar{\mu}$ is $\underline{\mu}$ $(\bar{\mu})$ if $\bar{\omega} - \bar{\varphi} > (\leq)$ 0 and to $\underline{\mu}$ is $\underline{\mu}$ $(\bar{\mu})$ $\underline{\omega} - \underline{\varphi} >$ $(\leq)$ 0. Of course, the same applies to firm 2 due to symmetry. Thus, two Nash equilibria emerge in this case; that is, $(\bar{\mu}, \bar{\mu})$ and $(\underline{\mu}, \underline{\mu})$.

To complete the proof, note that the conditions in (i), (ii), and (iii) can be written respectively as and $0 > \underline{\omega} - \underline{\varphi} > \bar{\omega} - \bar{\varphi}$, $\underline{\omega} - \underline{\varphi} > 0 > \bar{\omega} - \bar{\varphi}$ and $\underline{\omega} - \underline{\varphi} > \bar{\omega} - \bar{\varphi} > 0$ since $\bar{\omega} - \bar{\varphi} < \underline{\omega} - \underline{\varphi}$ applies in this scenario. **QED**.

Proof to Proposition 5

Consider the scenario where $\tau > 0$ and $\bar{\omega} - \underline{\omega} > \bar{\varphi} - \underline{\varphi}$ or $\bar{\omega} - \bar{\varphi} > \underline{\omega} - \underline{\varphi}$ after rewriting. From Table 1 and equations (33) and (34) we know that that firm 1's best response to $\bar{\mu}$ is $\underline{\mu}$ $(\bar{\mu})$ if $\underline{\omega} - \underline{\varphi} >$ $(\leq)$ 0. Due to symmetry, the same applies to firm 2. Given these conditions and $\bar{\omega} - \underline{\omega} > \bar{\varphi} - \underline{\varphi}$, three cases may emerge:

(i) $\bar{\omega} - \bar{\varphi} > 0$ and $\underline{\omega} - \underline{\varphi} \leq 0$;

(ii) $\bar{\omega} - \bar{\varphi} > 0$ and $\underline{\omega} - \underline{\varphi} \leq 0$;

(iii) $\bar{\omega} - \bar{\varphi} > 0$ and $\underline{\omega} - \underline{\varphi} > 0$.

In case (i) both firms have a dominant strategy in $\overline{\mu}$ (it is their best response in both $\overline{\mu}$ and $\underline{\mu}$). Thus, in this case $(\overline{\mu},\overline{\mu})$ is an equilibrium in dominant strategies. In case (iii) both firms have a dominant strategy in $\underline{\mu}$ (it is their best response in both $\overline{\mu}$ and $\underline{\mu}$). Therefore, $(\underline{\mu},\underline{\mu})$ is an equilibrium in dominant strategies. In case (ii), firm 1's best response to $\overline{\mu}$ is $\underline{\mu}$ and its best response to $\underline{\mu}$ is $\overline{\mu}$. Of course, the same applies to firm 2 due to symmetry. Thus, two Nash equilibria emerge in this case; that is, $(\overline{\mu},\underline{\mu})$ and $(\underline{\mu},\overline{\mu})$.

To complete the proof, note that the conditions in (i), (ii), and (iii) can be written respectively as and $0>\overline{\omega}-\overline{\varphi}>\underline{\omega}-\underline{\varphi}$, $\overline{\omega}-\overline{\varphi}>0>\underline{\omega}-\underline{\varphi}$ and $\overline{\omega}-\overline{\varphi}>\underline{\omega}-\underline{\varphi}>0$ since $\overline{\omega}-\overline{\varphi}>\underline{\omega}-\underline{\varphi}$ applies in this scenario. **QED**.

Proof to Proposition 6

Using the expression in (34), we can calculate the first derivative as

$$\frac{\partial\underline{\omega}}{\partial\tau}=\frac{2}{9}\left\{-\frac{(a-m-\tau\underline{\mu})\underline{\mu}}{(1+\gamma\underline{\mu})}+\frac{[a-m-\tau(2\overline{\mu}-\underline{\mu})](2\overline{\mu}-\underline{\mu})}{9(1+\gamma\overline{\mu})}\right\}. \tag{A1}$$

Obviously, the sign of (A1) will be dictated by the sign of the expression incised brackets. After some tedious algebra, we can reduce this expression to

$$J(\tau)=(\overline{\mu}-\underline{\mu})\{2(a-m-\tau\overline{\mu})+\gamma\underline{\mu}[a-m-\tau(4\overline{\mu}-\underline{\mu})]\}. \tag{A2}$$

We can use (A2) to check that $J(0)=(\overline{\mu}-\underline{\mu})(2++\gamma\underline{\mu})(a-m)>0$ and $J\left(\frac{a-m}{2\overline{\mu}-\underline{\mu}}\right)=(\overline{\mu}-\underline{\mu})(a-m)\left[2\left(1-\frac{2\overline{\mu}}{2\overline{\mu}-\underline{\mu}}\right)+\gamma\underline{\mu}\left(1-\frac{4\overline{\mu}-\underline{\mu}}{2\overline{\mu}-\underline{\mu}}\right)\right]<0$. Now, we can use (A1) to calculate the second derivative. This is

$$\frac{\partial^2\underline{\omega}}{\partial\tau^2}=\frac{2}{9}(\overline{\mu}-\underline{\mu})[-4\underline{\mu}-\gamma\underline{\mu}(4\overline{\mu}-\underline{\mu})]<0. \tag{A3}$$

Thus, we verify that there is a unique $\tau^*\in\left(0,\frac{a-m}{2\overline{\mu}-\underline{\mu}}\right)$ that maximises $\underline{\omega}$ and can be found by setting $J(\tau^*)=0$ in (A2). Eventually, this leads to

$$\tau^*=\frac{(a-m)(2+\gamma\underline{\mu})}{4\overline{\mu}+\gamma\underline{\mu}(4\overline{\mu}-\underline{\mu})}. \tag{A4}$$

To complete the proof, we use (A4) to calculate

$$\frac{\partial \tau *}{\partial \gamma} = \frac{-2\underline{\mu}(a-m)(2\overline{\mu}-\underline{\mu})}{[4\overline{\mu}+\gamma\underline{\mu}(4\overline{\mu}-\underline{\mu})]^2} < 0. \tag{A5}$$

QED.

Proof to Proposition 7

The expression in (33) allow us to derive

$$\frac{\partial \overline{\omega}}{\partial \tau} = \frac{2}{9}\left\{\frac{(a-m-\tau\overline{\mu})\overline{\mu}}{(1+\gamma\overline{\mu})} - \frac{[a-m-\tau(2\underline{\mu}-\overline{\mu})](2\underline{\mu}-\overline{\mu})}{9(1+\gamma\underline{\mu})}\right\}. \tag{A6}$$

The sign of (A6) depends on the sign of the expression incised brackets. This expression can be reduced to

$$J(\tau) = (\overline{\mu}-\underline{\mu})\{2(a-m-\tau\underline{\mu})+\gamma\overline{\mu}[a-m-\tau(4\overline{\mu}-\overline{\mu})]\}. \tag{A7}$$

From (A7) we can see that $J(0) = (\overline{\mu}-\underline{\mu})(2++\gamma\overline{\mu})(a-m) > 0$ and $J\left(\frac{a-m}{\overline{\mu}}\right) = -\frac{(\overline{\mu}-\underline{\mu})(a-m)(2\underline{\mu}-\overline{\mu})(1+\gamma\overline{\mu})}{\overline{\mu}} < 0$. Next, we compute the second derivative from (A6) which is

$$\frac{\partial^2 \overline{\omega}}{\partial \tau^2} = \frac{2}{9}(\overline{\mu}-\underline{\mu})[-4\underline{\mu}-\gamma\overline{\mu}(4\underline{\mu}-\overline{\mu})] < 0. \tag{A8}$$

The previous analysis confirms that there is a unique $\tau ** \in \left(0, \frac{a-m}{\overline{\mu}}\right)$ that maximises $\overline{\omega}$ and can be found by setting $J(\tau **) = 0$ in (A7). We can calculate $\tau **$ as

$$\tau ** = \frac{(a-m)(2+\gamma\overline{\mu})}{4\underline{\mu}+\gamma\overline{\mu}(4\underline{\mu}-\overline{\mu})}. \tag{A9}$$

To complete the proof, we use (A9) to calculate

$$\frac{\partial \tau **}{\partial \gamma} = \frac{-2\overline{\mu}(a-m)(2\underline{\mu}-\overline{\mu})}{[4\underline{\mu}+\gamma\overline{\mu}(4\underline{\mu}-\overline{\mu})]^2} < 0. \tag{A10}$$

QED.

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