Environmental campaigns and endogenous technology choice under international oligopoly

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Abstract

In an international duopoly context, where two goods are produced by two firms located in two separate countries, F and NF, we study the issue of firms' environmental technology choice. When consumers in country F are environmentally aware, in the sense that they care about emissions in their own country, it is shown that the firm in country F adopts a cleaner technology compared to the firm in country NF. Moreover, leakage appears, as the demand by consumers in country F shifts to the good produced by the firm in country NF. This, in turn, provides a rationale for raising awareness among consumers in country F about the effects of their consumption on pollution in country NF. Thereby, this paper adds to the existing literature by analysing how this increased awareness may affect consumers' demand for the domestic and the foreign good and, therefore, firms' endogenous technology choice. Also, changes in each country's and aggregate pollution are examined in order to assess whether having domestic consumers aware of foreign emissions could be considered as an option for tackling leakage.

1 Introduction

It is widely acknowledged that pollution has no geographical boundaries and that several environmental problems have international dimension since their consequences cannot be restricted to the origin country. In recent years, this is a common phenomenon especially in Asia where pollution (chemical smog and sulphur) from China is causing serious environmental problems in Japan, South Korea and other neighbouring countries. Clearly, environmental degradation in one country can spread to another, demonstrating that the protection of the global environment is the responsibility of all nations.

However, the absence of an international authority to enforce environmental policies, the need for international collaborative action (Benchekroun and Chaudhuri, 2014) and free riding increase the inefficiency of environmental regulations as well as entail market failures. Alongside, emissions which are embodied in international trade hamper the examination of the responsibility for emissions (Wiedmann, 2009). Mainly China and other developing countries export more embedded emissions than they import or they consume domestically (Pan et al., 2008). Thus, unilateral efforts to regulate emissions are likely to create leakage and, often, relocation of the polluting industry.

The asymmetric efforts by nations in order to mitigate pollution are usually in the form of constrained products against unconstrained ones i.e., increased prices for the domestic producers usually due to higher pollution taxes unaccompanied by an increase in import tariffs (Conconi, 2003). In this paper, an additional factor that can cause leakage is proposed; in an international trade context, increased environmental awareness of domestic pollution urges these consumers to substitute the consumption of the domestic good with the consumption of the foreign good in order to reduce emissions in their own country. This, as we will see, increases the demand for the foreign good which is produced employing a 'dirtier' technology since the foreign firm which produces that good has no incentives to adopt a 'cleaner' technology. Thus, having environmentally conscious consumers in one country, in a setting with two regions for simplicity, leads to the increase of the foreign emissions.

Indeed, the problem of emission leakage is ubiquitous and most empirical studies show that the carbon leakage rate can also result from a policy of the size of the Kyoto Protocol is in the range 5% to 25%. However, there are other studies revealing an even greater scope of the problem, especially for the energy-intensive industry which seems to be the most affected one. For instance, according to Babiker's paper (2005), when energy intensive products are modelled as Heckscher-Ohlin goods, the global carbon leakage rate is found to be even higher and range between 50% and 130%, which implies that a policy to limit carbon emissions in the OECD has the adverse effect of increasing global emissions. These significant differences are common in the literature on emission leakage since each empirical paper adopts different assumptions about demand and supply elasticities as well as the actual emission spillovers. Nevertheless, what these studies highlight is the significance of the problem and the need to be addressed in the policy making process.

A recent study by Aichele and Felbermayr (2012) shows that agreements such as

the Kyoto Protocol give rise to the relocation of production inducing leakage and, due to the incomplete coverage, have been ineffective for the global climate. They estimate the effect of the Kyoto Protocol on domestic CO2 emissions, carbon footprints and net carbon imports and they find that committed countries have reduced their emissions relative to the counterfactual of no Kyoto, but they have not reduced their carbon footprints, the carbon dioxide (CO2) emissions that the country's residents cause by consuming or investing a specific vector of goods.

In general, most of the leakage occurs in China, India, and the growing Asian economies; it is found that about 1/4 of China's CO2 emissions are produced during the manufacture of its exports (Yunfeng and Laike, 2010). Therefore, political concerns about the leakage in the fight to mitigate pollution have been addressed in both Europe and the United States.

So far, there has been a lot of debate on how to combat emission leakage and the most prominent policies have been the imposition of import taxes, border adjustments and border rebate for exports among others. Many studies (Elliott et al., 2010; Monjon and Quirion, 2011; Holland, 2012; Altemeyer-Bartscher et al., 2010) have well discussed and evaluated these practises based on their effectiveness, however, they all agree that none is always preferred for mitigating emissions or leakage since their effectiveness is not straightforward but depends on many parameters and conditions such as the policy objective, the relative emissions rates along with their different measures (Ghosh et al., 2012) and data availability.

In addition, on the consumer side, consumers from different countries with various cultures and incentives, have different levels of environmental awareness. Thus, we include in our model the case of having environmental aware consumers for the domestic pollution in one country and consumption oriented consumers in the other country. This separation is common in the existing literature of environmental economics (Zagonari, 1998). It is also supported by other studies such as the one by Schumacher (2013) whose main finding is that for low wealth levels, society is unable to free resources for environmental culture. Also, a recent survey by the European Lifestyles Of Health And Sustainability (LOHAS) shows that Europeans are 50 percent more likely than U.S. residents to buy "green" products indicating such differences on the environmental awareness[1].

Moreover, we model the case where there is environmental awareness in the domestic country for both the domestic and the foreign emissions. This can be thought of as the result of the presence of an interest group such as an environmental group (EG) which runs a campaign, or a course of action initiated by the government or, more generally, any resources devoted to make consumers in that country aware of the environmental problem in the other country due to the leakage that their consumption choice has created and the potential effects of the transboundary pollution [2]. In particular, from an

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[1]http://www.livescience.com/4695-survey-europeans-green-americans.html

[2]An example of an EG's campaign for pollution taking place in another country can be the "Detox campaign" by Greenpeace which took action to cut the hazardous chemicals that leak from clothing manufacturing processes and end up in the rivers in Mexico

interest group's perspective, Zagonari (1998) has already highlighted its important role in such settings when examining the impact of unilateral environmental initiatives by environmental groups in an international framework and Made (2014) shows its effect on pollution and how competition's intensity impinges on how inclined the interest group is to investigate firms. Yet, EG's actions do not always imply less aggregate pollution (Made and Schoonbeek, 2009; Asproudis and Gil-Moltó, 2009). Here, we assume that in case there is a campaign, it is rather persuasive than informative, meaning that it manages to shift consumers' preferences in favour of the product they run the campaign for (Tirole, 1998). In our case, it increases the utility of the consumers in the domestic country when they consume the domestic good while it reduces the utility of those who consume the foreign good. As Heijnen and Schoonbeek (2008) mention, it can be considered as negative persuasive advertising since it is designed to increase the uneasiness felt be the consumer who consumes the damaging good.

In this paper, we analyse how the increased environmental awareness for the domestic pollution and then for both the domestic and the foreign emissions can affect consumers' demand for the domestic and the foreign good as well as firms' endogenous technology choice. This will allow us to examine the changes in the emission rates and outputs as well as the changes in total transboundary pollution in order to comprehend whether informing consumers about pollution in the foreign country could be considered as an option for tackling emissions leakage. Furthermore, we endogenise the technology choice by firms to show how clean each firm is optimally choosing to produce and study how this affects the demand for the two products. As it is shown, when consumers in one country are environmentally aware, in the sense that they care about emissions in their own country, the domestic firm adopts a greener technology compared to the firm in the other country. Besides, as the demand by domestic consumers shifts to the good produced in the other country, we observe leakage.

The remainder of the paper is organised as follows. In section 2, we describe the model and the benchmark case where consumers in both countries are consumption oriented. Then, in section 3, we study the case where consumers in one country are environmentally aware of the domestic emissions and show that this can cause emission leakage. We also solve for the firms' equilibrium technology choices and output produced when consumers in the domestic country care only about the domestic emissions while the next section, we repeat the calculations but for the scenario where consumers in the domestic country care also about the environmental problem in the other country. Lastly, in section 5, we compare the results of the previous cases and analyse the changes in the emissions rates and output for each firm as well as the change in the aggregate pollution. Section 6 concludes.

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and China by informing consumers worldwide which clothing brands follow these practices (http://www.greenpeace.org/international/en/campaigns/toxics/water/detox/).

2   The Model

This section introduces a two-country model which consists of country F and country NF. On the demand side, consider a representative consumer with a utility function of the form[3]:

$$U_j(q_{1j}, q_{2j}) = a(q_{1j} + q_{2j}) - \frac{b}{2}(q_{1j}^2 + 2\theta q_{1j}q_{2j} + q_{2j}^2) + m_j - k_j e_1 q_{1j} - x_j e_2 q_{2j}$$

where $a, b > 0$ and $j = [\text{F, NF}]$. m_j represents all other goods (numeraire good) and has a price normalised to $p_m = 1$. θ is the degree of substitutability of good 1 and good 2 and is assumed to be between $0 < \theta < 1$. This implies that the two goods are neither perfect substitutes ($\theta = 1$) nor independent in demand ($\theta = 0$). k denotes the degree of environmental awareness of pollution generated in country F and x the degree of environmental awareness of pollution generated in country NF. For $k, x > 0$, the consumer suffers a disutility by consuming the two goods based on the degree of their environmental awareness. We assume throughout this paper that $k_{NF}, x_{NF} = 0$ so that consumers in country F are entirely consumption oriented [4]. Inevitably, production of both goods generates pollution $e_i = [0, 1]$ for $i = 1, 2$.

Consumers face the following budget constraint $p_1 q_1 + p_2 q_2 + m = y$. Thus, by maximising the utility function for the representative consumer under the budget constraint, we see that the market is characterised by the following linear inverse demand functions:

$$p_1 = a - b(q_1 + \theta q_2) - ke_1, \qquad\qquad p_2 = a - b(q_2 + \theta q_1) - xe_2. \qquad (1)$$

On the supply side, there are two firms performing under Cournot competition. Firm 1 produces good 1 and is located in country F whereas firm 2 produces good 2 and is located in country NF. We assume free trade between the two countries and the same non-negative marginal cost of production, c, for both firms [5]. Total transboundary pollution can be expressed as the aggregate emissions produced from both countries $E = e_1 Q_1 + e_2 Q_2$, where $Q_1 = nq_{1F} + (1-n)q_{1NF}$ and $Q_2 = nq_{2F} + (1-n)q_{2NF}$ for nq_{1F} (nq_{2F}) as the quantity of good 1 (good 2) consumed in country F and $(1-n)q_{1NF}$ ($(1-n)q_{2NF}$) the quantity of good 1 (good 2) consumed in country NF. We denote by q_{1F} the demand for good 1 in country F and by q_{1NF} the demand for good 1 in country NF. Similarly, for good 2.

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[3]See Bowley (1924) or Martin (2004).

[4]Again, as it is mentioned earlier, we assume that consumers in country F can be environmentally aware whereas those in country F are consumption oriented since not only this is a common assumption in the literature but also, and more importantly, it is interesting to investigate the effects of such a difference in the degree of environmental awareness on the consumption choices, the leakage and the technology choice by the firms as well as on pollution.

[5]We assume that there are fixed costs of quality improvement, while variable costs do not change with quality. This corresponds to one of the two cases analysed in the literature on product differentiation and can be thought of as a situation where the firm engages in R&D and advertising activities to improve quality, see Motta (1993) among others.

The profits for each firm can be defined as the variable profits minus the fixed costs related to the investment required to adopt an available technology:

$$\Pi_i = (p_i - c)nq_i - \phi_i$$

where $\phi_i = \frac{\beta}{2}(1 - e_i)^2$ for $i = 1, 2$.

2.1 The Benchmark Case

We begin by examining the case where consumers in both countries are not environmentally aware and, in other words they are totally consumption oriented, i.e., $k_F, k_{NF} = 0$ and $x_F, x_{NF} = 0$. Hence, for a representative consumer in country F:

$$U_F(q_{1F}, q_{2F}) = a(q_{1F} + q_{2F}) - \frac{b}{2}(q_{1F}^2 + 2\theta q_{1F}q_{2F} + q_{2F}^2) + m_F$$

and for a representative consumer in country NF:

$$U_{NF}(q_{1NF}, q_{2NF}) = a(q_{1NF} + q_{2NF}) - \frac{b}{2}(q_{1NF}^2 + 2\theta q_{1NF}q_{2NF} + q_{2NF}^2) + m_{NF}$$

which implies that using Equation (1):

$$p_{1F} = a - b(q_{1F} + \theta q_{2F}), \qquad p_{1NF} = a - b(q_{1NF} + \theta q_{2NF}).$$

and

$$p_{2F} = a - b(q_{2F} + \theta q_{1F}), \qquad p_{2NF} = a - b(q_{2NF} + \theta q_{1NF}).$$

Solving for the demand functions, we get from $\dfrac{\partial \Pi_1^{(0)}}{\partial q_1} = 0$ and $\dfrac{\partial \Pi_1^{(0)}}{\partial q_2} = 0$ the following:

$$q_1^{(0)} = \frac{(a - c)(2 - \theta)}{b(4 - \theta^2)}, \qquad q_2^{(0)} = \frac{(a - c)(2 - \theta)}{b(4 - \theta^2)}.$$

Then, we can solve for the individual demand functions of each good in each country. Since both $k_F, k_{NF} = 0$ and $x_F, x_{NF} = 0$, we can easily see that

$$q_1^{*(0)} = q_{1F}^{*(0)} = q_{1NF}^{*(0)} = q_2^{*(0)} = q_{2F}^{*(0)} = q_{2NF}^{*(0)} = \frac{(a - c)(2 - \theta)}{b(4 - \theta^2)}. \tag{2}$$

Based on Equation (2), we can write the total demand for good 1 and 2 respectively as

$$Q_1^{*(0)} = nq_{1F} + (1 - n)q_{1NF} = \frac{(a - c)(2 - \theta)}{b(4 - \theta^2)} \tag{3}$$

$$Q_2^{*(0)} = nq_{2F} + (1 - n)q_{2NF} = \frac{(a - c)(2 - \theta)}{b(4 - \theta^2)}. \tag{4}$$

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Also,

$$Q_1^{*(0)} + Q_2^{*(0)} = \frac{2(a-c)(2-\theta)}{b(4-\theta^2)}. \tag{5}$$

It is straightforward that neither individual demand nor the total demand for each good is a function of e_1 and/or e_2 since consumers are not concerned about the pollution generated by the production of these two goods. Solving for the prices of the two goods in each country we get:

$$p_{1F}^{*(0)} = p_{1NF}^{*(0)} = p_{2F}^{*(0)} = p_{2NF}^{*(0)} = \frac{(2-\theta)[(a+c(1+\theta)]}{4-\theta^2}.$$

On the firms' side, the corresponding first order condition of the profit maximisation problem for each of them ($\frac{\partial \Pi_1}{\partial e_1} = 0$ and $\frac{\partial \Pi_2}{\partial e_2} = 0$) yields the equilibrium emission rate for each firm; that is,

$$e_1^{*(0)} = 1, \qquad\qquad e_2^{*(0)} = 1 \tag{6}$$

which implies that both firms find it optimal to produce with the dirtiest technology. This result is intuitive since both firms have no incentives to incur any cost to adopt a cleaner technology as consumers care only about their consumption.

2.2   Consumers aware of domestic emissions

Now let us consider the case where consumers in one of the two countries are environmentally aware. Suppose that this holds for consumers in country F i.e., $k_F > 0$ for them whereas consumers in country NF are still consumption-oriented i.e., for these consumers $k_{NF} = 0$ [6]. In other words, consumers in country F are conscious about pollution generated by the production of the firm that is located in their country whereas consumers in the foreign country care solely about their consumption. Again, we can calculate the optimal outputs and emission rates. Note that, in this case, the utility function of the representative consumer in country F is:

$$U_F(q_{1F}, q_{2F}) = a(q_{1F} + q_{2F}) - \frac{b}{2}(q_{1F}^2 + 2\theta q_{1F}q_{2F} + q_{2F}^2) + m_F - k_F e_1 q_{1F}$$

while for the representative consumer in country NF it is the same as in the benchmark case since he/she is still consumption oriented:

$$U_{NF}(q_{1NF}, q_{2NF}) = a(q_{1NF} + q_{2NF}) - \frac{b}{2}(q_{1NF}^2 + 2\theta q_{1NF}q_{2NF} + q_{2NF}^2) + m_{NF}.$$

So now,

$$p_{1F} = a - b(q_{1F} + \theta q_{2F}) - k_F e_1, \qquad\qquad p_{1NF} = a - b(q_{1NF} + \theta q_{2NF}).$$

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[6]The results are not affected qualitatively in case we assume that consumers in country F are consumption oriented and consumers in country NF are the ones who have become more environmentally aware.

and

$$p_{2F} = a - b(q_{2F} + \theta q_{1F}), \qquad\qquad p_{2NF} = a - b(q_{2NF} + \theta q_{1NF}).$$

From $\dfrac{\partial \Pi_1^{(1)}}{\partial q_{1F}} = 0$ and $\dfrac{\partial \Pi_1^{(1)}}{\partial q_{1NF}} = 0$ we get

$$q_{1F}^{(1)} = \frac{(a-c)(2-\theta) - 2k_F e_1}{b(4 - \theta^2)} \qquad \text{and} \qquad q_{1NF}^{(1)} = \frac{(a-c)(2-\theta)}{b(4 - \theta^2)} \qquad (7)$$

and from $\dfrac{\partial \Pi_2^{(1)}}{\partial q_{2F}} = 0$ and $\dfrac{\partial \Pi_2^{(1)}}{\partial q_{NF}} = 0$,

$$q_{2F}^{(1)} = \frac{(a-c)(2-\theta) + \theta k_F e_1}{b(4 - \theta^2)} \qquad \text{and} \qquad q_{2NF}^{(1)} = \frac{(a-c)(2-\theta)}{b(4 - \theta^2)} \qquad (8)$$

respectively. Recall, that in order to derive q_{1NF} and q_{2NF} we substitute $k_{NF}, x_{NF} = 0$. These demand functions allow us to write the total demand for good 1 as

$$Q_1^{(1)} = nq_{1F} + (1-n)q_{1NF} = \frac{(a-c)(2-\theta) - 2nk_F e_1}{b(4 - \theta^2)}$$

and for good 2 as

$$Q_2^{(1)} = nq_{2F} + (1-n)q_{2NF} = \frac{(a-c)(2-\theta) + \theta n k_F e_1}{b(4 - \theta^2)}.$$

By substituting the demand functions (Equations (7) and (8)) of each good to the inverse demand functions p_1 and p_2, we can solve for the prices of good 1 and good 2 which read [7]:

$$p_{1F}^{(1)} = \frac{(2-\theta)[(a + c(1 + \theta)] - 2k_F e_1}{4 - \theta^2}, \qquad\qquad p_{1NF}^{(1)} = \frac{(2-\theta)[(a + c(1 + \theta)]}{4 - \theta^2}$$

$$p_{2F}^{(1)} = \frac{(2-\theta)[(a + c(1 + \theta)] + \theta k_F e_1}{4 - \theta^2}, \qquad\qquad p_{2F}^{(1)} = \frac{(2-\theta)[(a + c(1 + \theta)]}{4 - \theta^2}.$$

It is apparent that, ceteris paribus, as k_F increases, the price of good 1 will be lowered and the price of good 2 will be increased. This is anticipated since an increase

[7]Note that $p_{1F} \neq p_{1NF}$ and $p_{2F} \neq p_{2F}$ since consumers from different countries have different preferences and thus there is price discrimination by the firms. We assume that consumers cannot buy the same good from elsewhere except for their country and this is not an unrealistic assumption. One example can be goods with short expiry date, textbooks that it is illegal to purchase them from a different country/ continent due to copyright issues or goods that have different specifications in each country or do not include services such as warranty.

in k_F will decrease the demand for $Q_1^{(1)}$ and, thus, this will entail a decrease in the price of that good, whereas it will increase the demand for $Q_2^{(1)}$ which will increase its price. Also we can see that both firms charge a different price for their good in country F and in country NF since in country F, where consumers are more environmentally aware, firm 1 and 2 can extract more consumer surplus.

With regard to the firms, from the first order condition for profit maximisation for each firm ($\dfrac{\partial \Pi_1^{(1)}}{\partial e_1} = 0$ and $\dfrac{\partial \Pi_2^{(1)}}{\partial e_2} = 0$), we obtain the optimal emission rate for each firm; that is,

$$e_1^{*(1)} = \frac{\beta\epsilon - 4k_F\lambda}{\beta\epsilon - 8nk_F^2}, \qquad\qquad e_2^{*(1)} = 1 \qquad\qquad (9)$$

where $\epsilon = b(4 - \theta^2)^2$ and $\lambda = n(a - c)(2 - \theta)$. It is easily shown that $e_1^{*(1)} < 1$ since $\beta\epsilon - 4k_F\lambda < \beta\epsilon - 8nk_F^2 \Leftrightarrow 2nk_F < \lambda$ which holds (see appendix I). Hence, firm 1 chooses to adopt a cleaner technology since consumers in country F where firm 1 is located, have become more environmentally aware. Contrary, firm 2, with no incentives to employ a cleaner technology, continues producing with the dirty technology. The equilibrium emission rates satisfy both the stability and the second order condition for a maximum which guarantee a stable equilibrium (see appendix II).

By taking the derivative of $e_1^{*(1)}$ (Eq. (9)) with respect to n, we obtain:

$$\frac{\partial e_1^{*(1)}}{\partial n} = \frac{4k_F\beta\epsilon(2k_F - (a - c)(2 - \theta)}{(\beta\epsilon - 8nk_F^2)^2}.$$

Rearranging the expression, we can easily see that the numerator is negative since $2nk_F - \lambda < 0$ indicating that the market size in country F is negatively related to the emission rate chosen by firm 1 and that firm 1 in such case has the incentive to produce employing a cleaner technology. Thus, having a larger pool of highly environmentally aware domestic consumers stimulates the domestic firm to reduce its emission rate. Also, the sign in derivative of $e_1^{*(1)}$ with respect to θ is negative since

$$\frac{\partial e_1^{*(1)}}{\partial \theta} = \frac{16k_F\theta\beta b^2(4 - \theta^2)(2nk_F - \lambda)}{(\beta b^2(4 - \theta^2)^2 - 8nk_F^2)^2}$$

where $(16k_F\theta\beta b^2(4 - \theta^2)) > 0$, $(2nk_F - \lambda) < 0$ and $(\beta b^2(4 - \theta^2)^2 - 8nk_F^2)^2) > 0$. Then, the effect of the degree of substitutability between the two goods on the firm's 1 emission rate is negative suggesting that when goods are becoming closer substitutes, firm 1 will choose to adopt a cleaner technology and vice versa.

Regarding $e_2^{*(1)}$, we can see that k_F does not affect firm's 2 technology choice; firm 2 will always choose to produce with the polluting technology in the absence of the environmentalists. This can be explained since there are not any incentives for the firm to adopt a cleaner, but costly, technology as consumers in both countries are

not concerned about the pollution generated by this firm. Additionally, the degree of substitutability between the two goods does not have any impact on firm's 2 technology choice.

Now, we can solve for the profit-maximising outputs of good 1 and good 2 which can be expressed as:

$$Q_1^{*(1)} = \frac{(a-c)(2-\theta) - \frac{2nk_F(\beta\epsilon - 4k_F\lambda)}{\beta\epsilon - 8nk_F^2}}{b(4-\theta^2)} \tag{10}$$

$$Q_2^{*(1)} = \frac{(a-c)(2-\theta) + \frac{\theta nk_F(\beta\epsilon - 4k_F\lambda)}{\beta\epsilon - 8nk_F^2}}{b(4-\theta^2)}. \tag{11}$$

Also,

$$Q_1^{*(1)} + Q_2^{*(1)} = \frac{2(a-c)(2-\theta)}{b(4-\theta^2)} - \frac{nk_F(\beta\epsilon - 4k_F\lambda)}{b(\beta\epsilon - 8nk_F^2)(2+\theta)}. \tag{12}$$

The first derivative of $Q_1^{(1)}$ ($Q_2^{(1)}$) with respect to k_F is negative (positive) indicating that, as environmental awareness of consumers in country F of pollution in their country is increasing, they substitute the good produced in country NF for the domestic good.

Lemma 1. $Q_1^{(1)}$ ($Q_2^{(1)}$) is decreasing (increasing) in k_F.

The intuition is simple. As consumers in country F become more aware of the pollution generated by the good produced domestically (good 1), they reduce the quantity demanded for it. We can also see that from substituting Equation (9) in Equation (7); $q_{1F}^{(1)}$ decreases as k_F increases ($\partial q_{1F}^{(1)}/\partial k_F < 0$). This drives the total demand for good 1 down. Also and more importantly, this encourages them to turn their consumption towards good 2 which is produced in the other country. In particular, for a higher degree of environmental awareness of pollution in country F (that is, k_F), good 2 has increased demand ($Q_2^{(1)}$) since consumers prefer to buy the good whose production emissions do not affect them directly. Again, from Equation (8) along with Equation (9), it is straightforward that $q_{2F}^{(1)}$ increases as k_F increases ($\partial q_{2F}^{(1)}/\partial k_F > 0$).

At this point we can highlight that this asymmetry in the degree of environmental awareness between the two countries which leads to a turn towards good 2 after the increase in k_F, creates a leakage. Specifically, as a result of the increased awareness by the consumers in country F of the pollution in their location, pollution is increased in country NF since demand for good 2 is greater and, as it will be shown later, firm 2 continues to produce employing the dirty technology. Thus, this paper indicates that, in this context, consumers who become more environmentally conscious of pollution in their country can be an additional factor which creates leakage, apart from those already mentioned in the literature, such as domestic taxation, unilateral climate policies and border adjustments.

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2.3 Consumers aware of both the domestic and foreign emissions

Let us now examine the case where consumers in country F are aware of the 'dirty' technology of production chosen by firm 2 ($x_F > 0$). As it is mentioned earlier, this could be a result of a campaign by an EG or the government in country F or of any other resource devoted to discourage consumers in this country (F) from consuming good 2 since it is produced using a more polluting technology than good 1. As it is shown in Lemmas (1) & (2), an emission leakage is created because as consumers in country F become more environmentally aware for pollution generated by good 1 in their country, they consume more of good 2 which is produced employing a dirtier technology. Now, the utility function of the representative consumer in country F is:

$$U_F(q_{1F}, q_{2F}) = a(q_{1F} + q_{2F}) - \frac{b}{2}(q_{1F}^2 + 2\theta q_{1F}q_{2F} + q_{2F}^2) + m_F - k_F e_1 q_{1F} - x_F e_2 q_{2F}$$

while for the representative consumer in country NF it is:

$$U_{NF}(q_{1NF}, q_{2NF}) = a(q_{1NF} + q_{2NF}) - \frac{b}{2}(q_{1NF}^2 + 2\theta q_{1NF}q_{2NF} + q_{2NF}^2) + m_{NF}$$

and

$$p_{1F} = a - b(q_{1F} + \theta q_{2F}) - k_F e_1, \qquad p_{1NF} = a - b(q_{1NF} + \theta q_{2NF}).$$

and

$$p_{2F} = a - b(q_{2F} + \theta q_{1F}) - x_F e_2, \qquad p_{2NF} = a - b(q_{2NF} + \theta q_{1NF}).$$

meaning that here we assume $k_F, x_F > 0$ and $k_{NF}, x_{NF} = 0$. Again, we can solve for the individual and total demands for the two goods,

$$q_{1F}^{(2)} = \frac{(a-c)(2-\theta) - 2k_F e_1 + \theta x_F e_2}{b(4-\theta^2)}, \qquad q_{1NF}^{(2)} = \frac{(a-c)(2-\theta)}{b(4-\theta^2)},$$

$$q_{2F}^{(2)} = \frac{(a-c)(2-\theta) + \theta k_F e_1 - 2x_F e_2}{b(4-\theta^2)} \qquad q_{2NF}^{(2)} = \frac{(a-c)(2-\theta)}{b(4-\theta^2)}$$

and

$$Q_1^{(2)} = nq_{1F} + (1-n)q_{1NF} = \frac{(a-c)(2-\theta) + n[\theta x_F e_2 - 2k_F e_1]}{b(4-\theta^2)},$$

$$Q_2^{(2)} = nq_{2F} + (1-n)q_{2NF} = \frac{(a-c)(2-\theta) + n[\theta k_F e_1 - 2x_F e_2]}{b(4-\theta^2)}.$$

The price of each good now is:

$$p_{1F}^{(2)} = \frac{(2-\theta)[(a+c(1+\theta)] - 2k_F e_1 + \theta x_F e_2}{4-\theta^2}, \qquad p_{1NF}^{(2)} = \frac{(2-\theta)[(a+c(1+\theta)]}{4-\theta^2}$$

$$p_{2F}^{(2)} = \frac{(2-\theta)[(a+c(1+\theta)]-2x_F e_2 + \theta k_F e_1}{4-\theta^2}, \qquad p_{2NF}^{(2)} = \frac{(2-\theta)[(a+c(1+\theta)]}{4-\theta^2}$$

which illustrates again that firms are able to price-discriminate and extract more consumer surplus because of consumers' asymmetry in their environmental awareness between the two countries. We can also calculate the new optimal emission rates for both firm 1 and firm 2, following the same steps as in the previous section but now for $x_F > 0$ to end up with the following reacting functions:

$$e_1^{(2)} = \frac{\beta\epsilon - 4k_F\lambda - 4n\theta k_F x_F e_2}{\beta\epsilon - 8nk_F^2}, \qquad e_2^{(2)} = \frac{\beta\epsilon - 4x_F\lambda - 4n\theta k_F x_F e_1}{\beta\epsilon - 8nx_F^2}. \qquad (13)$$

These reaction functions reveal that the emission rates of each firm are not independent from each other since the degree of environmental awareness of consumers in country F for the domestic pollution (k_F) for the pollution in country NF (x_F) affects the demand for each good and, thus, the technology choice by the firm as well as the output generated. Also, the derivative of $e_1^{(2)}$ with respect to $e_2^{(2)}$ is negative $\frac{\partial e_1^{(2)}}{\partial e_2^{(2)}} = \frac{-4n\theta k_F x_F}{\beta\epsilon - 8nk_F^2} < 0$ and, hence, domestic and foreign emissions are strategic substitutes. By solving this system of equations for $e_1^{(2)}$ and $e_2^{(2)}$, we obtain the following:

$$e_1^{*(2)} = \frac{(\beta\epsilon - 8nx_F^2)(\beta\epsilon - 4k_F\lambda) - 4n\theta k_F x_F(\beta\epsilon - 4x_F\lambda)}{(\beta\epsilon - 8nk_F^2)(\beta\epsilon - 8nx_F^2) - (4n\theta k_F x_F)^2},$$

$$e_2^{*(2)} = \frac{(\beta\epsilon - 8nk_F^2)(\beta\epsilon - 4x_F\lambda) - 4n\theta k_F x_F(\beta\epsilon - 4k_F\lambda)}{(\beta\epsilon - 8nk_F^2)(\beta\epsilon - 8nx_F^2) - (4n\theta k_F x_F)^2}.$$

Again, the stability condition as well as the second order condition for a maximum are fulfilled and imply that the following inequalities hold (see appendix II):

$$\beta\epsilon > 8nk_F^2 \qquad \text{and} \qquad \beta\epsilon > 8nx_F^2.$$

Then, by using Equation (13), we can express the profit-maximising outputs as:

$$Q_1^{*(2)} = \frac{(a-c)(2-\theta) + n\theta x_F e_2^{**} - 2nk_F e_1^{**}}{b(4-\theta^2)} =$$

$$\frac{(a-c)(2-\theta) + \frac{n\theta x_F(\beta\epsilon-8nk_F^2)(\beta\epsilon-4x_F\lambda)-4n\theta k_F x_F(\beta\epsilon-4k_F\lambda)}{(\beta\epsilon-8nk_F^2)(\beta\epsilon-8nx_F^2)-(4n\theta k_F x_F)^2} - \frac{2nk_F(\beta\epsilon-8nx_F^2)(\beta\epsilon-4k_F\lambda)-4nk_F\theta x_F(\beta\epsilon-4x_F\lambda)}{(\beta\epsilon-8nk_F^2)(\beta\epsilon-8nx_F^2)-(4n\theta k_F x_F)^2}}{b(4-\theta^2)}$$

$$(14)$$

$$Q_2^{*(2)} = \frac{(a-c)(2-\theta) - 2nx_F e_2^{**} + nk_F\theta e_1^{**}}{b(4-\theta^2)} =$$

$$\frac{(a-c)(2-\theta) - \frac{2nx_F(\beta\epsilon-8nk_F^2)(\beta\epsilon-4x_F\lambda)-4n\theta k_F x_F(\beta\epsilon-4k_F\lambda)}{(\beta\epsilon-8nk_F^2)(\beta\epsilon-8nx_F^2)-(4n\theta k_F x_F)^2} + \frac{nk_F\theta(\beta\epsilon-8nx_F^2)(\beta\epsilon-4k_F\lambda)-4nk_F\theta x_F(\beta\epsilon-4x_F\lambda)}{(\beta\epsilon-8nk_F^2)(\beta\epsilon-8nx_F^2)-(4n\theta k_F x_F)^2}}{b(4-\theta^2)}$$

$$(15)$$

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and the total demand for both goods as:

$$Q_1^{*(2)} + Q_2^{*(2)} = \frac{2(a-c)(2-\theta)}{b(4-\theta^2)} + \frac{n(k_F - x_F)\beta\epsilon[\beta\epsilon + 4nk_F x_F(2-\theta) - 4(k_F + x_F)\lambda]}{b(2+\theta)[(\beta\epsilon - 8nk_F^2)(\beta\epsilon - 8nx_F^2) - (4n\theta k_F x_F)^2]}.$$

(16)

3 Comparison of the cases

The purpose of this section is to compare the results of the previous cases and examine the changes in outputs, technology choices and both each country's and aggregate (transboundary) pollution.

Let us first begin our analysis with the changes in the emission rates. We start with the benchmark case and compare it with Case I and then we compare that with the last case (Case II).

Proposition 1. *For firm 1, $\Delta e_1' = e_1^{*(1)} - e_1^{*(0)} < 0$ and $\Delta e_1'' = e_1^{*(2)} - e_1^{*(1)} < 0$. For firm 2, $\Delta e_2' = e_2^{*(1)} - e_2^{(0)} = 0$ and $\Delta e_2'' = e_2^{*(2)} - e_2^{*(1)} < 0$.*

Proof. See the Appendix. □

Proposition 1 states that the emission rate for firm 1 is reduced when consumers in country F are becoming environmentally aware of the local emissions and shift their consumption to good 2. Interestingly, it is reduced even more after these consumers care also for the foreign pollution, although it is not directly affected (only indirectly) by x_F. So, although consumers in country F become also aware of pollution in country NF, they still care for pollution in their own country; additionally, firm 1 has to face increased competition from firm 2 as the product differentiation is getting smaller. For firm 2, we can see that it chooses to produce employing the dirty technology when consumers are not conscious about the pollution in country NF since there is no incentive to do otherwise. However, when consumers in country F are informed about the increased pollution in country NF and their demands depend on e_2, firm 2 finds it optimal to adopt a cleaner technology to produce.

Regarding the changes in the outputs, we can show that:

Proposition 2. *For firm 1, $\Delta Q_1' = Q_1^{*(1)} - Q_1^{*(0)} < 0$ and $\Delta Q_1'' = Q_1^{*(2)} - Q_1^{*(1)} > 0$. For firm 2, $\Delta Q_2' = Q_2^{*(1)} - Q_2^{*(0)} > 0$ and $\Delta Q_2'' = Q_2^{*(2)} - Q_2^{*(1)} < 0$.*

Proof. See the Appendix. □

According to Proposition 2, $x_F > 0$ increases the equilibrium output produced by firm 1 and reduces the equilibrium output produced by firm 2. In particular, highlighting the environmental damage caused in country NF, consumers decrease the quantity demanded of the dirtier good and consume more of the cleaner good. Therefore, firm 1 has optimally chosen to produce more but with a cleaner technology whereas firm 2 decreased both the emissions rate, since consumers are now aware of

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the pollution generated in country NF, and the quantity supplied, since consumers are turning their consumption again towards good 1.

Finally, we can observe the differences in each country's and the aggregate transboundary pollution.

Proposition 3. *For $k_F > 0$, pollution in country NF is increased but aggregate pollution is lowered. After $x_F > 0$, pollution in country NF is reduced but the effect on aggregate pollution is ambiguous.*

Proof. See the Appendix. ☐

As it is clear from the previous propositions, for $k_F > 0$, the emission rate chosen optimally by firm 1 is reduced along with a reduction in its output. Since consumers in country F become aware of the domestic pollution which is produced by firm 1, they consume more of the good produced by the foreign firm. Additionally, responding to this change of preferences for consumers in country F, firm 1 chooses to produce employing a cleaner technology compared to the one in the benchmark setting.

Contrary, for $k_F > 0$, firm 2 continues to produce with the dirty technology and increase its output since its demand is higher and hence has no incentive to change the dirty technology it uses. Thus, pollution in country F is reduced because both emission rate and output produced are decreased whereas pollution in country NF is increased (leakage) because output is increased. However, it is really interesting to note that total production $(Q_1 + Q_2)$ in this case is reduced [8] and since the emission rates are lowered (stable by firm 2 but decreased for firm 1), then aggregate pollution is lowered.

So, for $x_F > 0$ consumers in country F are discouraged from consuming the polluting good (good 2) but, based on the aforementioned, this happens when aggregate pollution is already lower. In other words, due to the leakage that takes place, consumers are informed of the environmental problem in country NF in order to reduce pollution in country NF. This is done successfully since both the quantity demanded for good 2 and the emission rate chosen by firm 2 are reduced. Nevertheless, these consumers do not care at all about pollution since they are consumption oriented. Hence, the environmentalists' participation causes a welfare loss for them.

With regard to the effect of $x_F > 0$ on the aggregate pollution, we find that it is ambiguous by comparing case II with case I and and this allows us to find a critical value of x_F that affects the sign of the change in total pollution. If $\hat{x_F} > \frac{\beta\epsilon - 4k_F\lambda}{4\lambda - 4nk_F(2-\theta)}$, then aggregate pollution is lowered since emission rates are also decreased. However, if $\hat{x_F} < \frac{\beta\epsilon - 4k_F\lambda}{4\lambda - 4nk_F(2-\theta)}$, then total output is increased and, thus, the change in aggregate pollution is ambiguous depending on whether the increase in total output is higher than the decrease in the emission rates or not. As it was indicated previously, in a more abstract framework, we could think of x_F as the degree of an EG's efforts (campaign) to make consumers in country F aware of the pollution in country NF. So, based on the

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[8]Equation (3) along with Equation (12), show that the total quantity produced by both firms is lowered in this case by this amount $\frac{nk_F(\beta\epsilon - 4k_F\lambda)}{b(\beta\epsilon - 8nk_F^2)(2+\theta)}$.

intensiveness of the campaign, the effect on total pollution is analogous. This result is quite straightforward. The less aware consumers in country F are of pollution in country NF, the more they will turn their consumption towards good 2 until a point where the increase in consumption of good 2 is greater than the decrease in good 1 and this increase in total production is higher than the reduction in emissions, thus, total pollution is higher and vice versa.

All in all, our results in this section show that in order to mitigate the leakage and the increased pollution in country NF, consumers are discouraged from consuming good 2 while aggregate pollution is already reduced. Additionally, although, after all, pollution is successfully reduced in country NF, this affects negatively the consumers in that country in the sense that they incur a welfare loss since they are consumption oriented. Also, it is not clear whether the aggregate pollution is reduced or not depending on the value of x_F.

4   Conclusion

This paper investigates how increasing the environmental awareness of consumers in the domestic market for their local pollution may affect aggregate pollution and create leakage in a setting with two countries. Additionally, we examine the impact of increased environmental awareness of domestic consumers for the foreign pollution on the demand for the domestic and foreign good and therefore on the endogenous technology choice by the firms.

Our findings suggest that as consumers become more aware of the domestic pollution, they substitute the good that is produced in their country with the good that is produced in the foreign country. As a result, the firm that is located in the domestic market chooses optimally to reduce its emission rate and employ a cleaner technology to respond to the increased awareness by the domestic consumers. Contrary, the firm that is located in the foreign market continues to produce using the dirtiest technology since there is no incentive to do otherwise. Consequently, quantity demanded for the cleaner good is reduced at the expense of a higher quantity demanded for the dirtier good (leakage).

This leakage can be considered as a reason to initiate a government project or an EG campaign to inform domestic consumers of the consequences of their increased demand for the dirty good so that they are discouraged from buying it. Our results show that in terms of quantities demanded, this goal is achieved; quantity of the cleaner good has increased whereas quantity of the other good has become lower. However, it is interesting that when this happens not only the aggregate pollution is lowered compared to the benchmark case but also by reducing pollution in the foreign country, it cases a welfare loss for those consumers who are entirely consumption- oriented.

Overall, in a framework with endogenous technology choice and leakage, our paper highlights the effects of observing different degrees of environmental awareness in such a setting and shows that being aware of the foreign emissions does not always imply less

aggregate pollution. Possible extensions can include modelling explicitly the presence of the EG i.e., its decision to enter the market or not based on the interaction with the firms as well as conducting a welfare analysis in order to propose possible policies.

5 Appendix

Appendix I

The non-negativity constraint on $q_{1F}^{(1)}$ (Eq. (7)) requires:

$$q_{1F}^{(1)} = \frac{(a-c)(2-\theta) - 2k_F e_1}{b(4-\theta^2)} \geq 0 \Rightarrow (a-c)(2-\theta) - 2k_F e_1 \geq 0.$$

Since $\lambda = n(a-c)(2-\theta)$, then $(a-c)(2-\theta) - 2k_F e_1 \geq 0 \Rightarrow \frac{\lambda}{n} - 2k_F e_1 \geq 0 \Rightarrow \lambda - 2nk_F e_1 \geq 0$, so

$$e_1 \leq \frac{\lambda}{2nk_F}.$$

Using Eq.(9) and in order to avoid corner solutions, this condition becomes

$$\frac{\beta\epsilon - 4k_F\lambda}{\beta\epsilon - 8nk_F^2} < \frac{\lambda}{2nk_F} \Rightarrow \beta\epsilon 2nk_F - 8nk_F^2\lambda < \beta\epsilon\lambda - 8nk_F^2\lambda \Rightarrow \lambda > 2nk_F.$$

The above condition guarantees that $e_1^{*(1)} < 1$. Indeed,

$$\frac{\beta\epsilon - 4k_F\lambda}{\beta\epsilon - 8nk_F^2} < 1 \Rightarrow \beta\epsilon - 4k_F\lambda < \beta\epsilon - 8nk_F^2 \Rightarrow \lambda > 2nk_F.$$

Appendix II

Checking whether the optimal solutions for $e_1^{*(1)}$ and $e_2^{*(1)}$ (Eq. (9)) satisfy both the stability condition as well as the second order condition for a maximum which are sufficient for a stable equilibrium we get for e_1:

$$\left|\frac{\partial^2\Pi_1^{(1)}}{\partial e_1^{2(1)}}\right| > \left|\frac{\partial}{\partial e_2^{(1)}}\left(\frac{\partial\Pi_1^{(1)}}{\partial e_2^{(1)}}\right)\right| \Leftrightarrow \left|\frac{8nk_F^2 - \beta\epsilon}{\epsilon}\right| > 0$$

and

$$\frac{8nk_F^2 - \beta\epsilon}{\epsilon} < 0,$$

respectively and for e_2:

$$\left|\frac{\partial^2\Pi_2^{(1)}}{\partial e_2^{2(1)}}\right| > \left|\frac{\partial}{\partial e_1^{(1)}}\left(\frac{\partial\Pi_2^{(1)}}{\partial e_1^{(1)}}\right)\right| \Leftrightarrow |-\beta| > 0$$

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and

$$-\beta < 0$$

respectively, which hold.

For $e_1^{*(2)}$ and $e_2^{*(2)}$, the stability condition as well as the second order condition for a maximum are fulfilled. In particular, the stability condition gives us:

$$\frac{\partial^2\Pi_1^{(2)}}{\partial e_1^{2(2)}}\frac{\partial^2\Pi_2^{(2)}}{\partial e_2^{2(2)}} - \frac{\partial^2\Pi_1^{(2)}}{\partial e_1^{(2)}\partial e_2^{(2)}}\frac{\partial^2\Pi_2^{(2)}}{\partial e_1^{(2)}\partial e_2^{(2)}} > 0 \Leftrightarrow (\beta\epsilon - 8nk_F^2)(\beta\epsilon - 8nx_F^2) > (4n\theta k_F x_F)^2 \quad (17)$$

which implies that $(\beta\epsilon - 8nx_F^2)(\beta\epsilon - 4k_F\lambda) > 4n\theta k_F x_F(\beta\epsilon - 4x_F\lambda)$ since $e_1^{*(2)}$ has to be positive and
$(\beta\epsilon - 8nk_F^2)(\beta\epsilon - 4x_F\lambda) > 4n\theta k_F x_F(\beta\epsilon - 4k_F\lambda)$ since $e_2^{*(2)}$ has also to be positive.

The second order condition implies that:

$$\frac{\partial^2\Pi_1^{(2)}}{\partial e_1^{2(2)}} = \frac{8nk_F^2 - \beta\epsilon}{\epsilon} < 0 \Leftrightarrow \frac{\beta\epsilon - 8nk_F^2}{\epsilon} > 0$$

$$\frac{\partial^2\Pi_2^{(2)}}{\partial e_2^{2(2)}} = \frac{8nx_F^2 - \beta\epsilon}{\epsilon} < 0 \Leftrightarrow \frac{\beta\epsilon - 8nx_F^2}{\epsilon} > 0$$

Thus, it is true that the following inequalities hold:

$$\beta\epsilon > 8nk_F^2 \qquad\qquad \text{and} \qquad\qquad \beta\epsilon > 8nx_F^2.$$

Appendix III

Proof to Proposition 1. By using Equation (6) along with (9), it is easy to see that, for firm 1:

$$\Delta e_1' = e_1^{*(1)} - e_1^{*(0)} = \frac{\beta\epsilon - 4k_F\lambda}{\beta\epsilon - 8nk_F^2} - 1 < 0$$

since $e_1^{*(1)} < 1$ [9] and by using Equations (9) & (13), we get:

$$\Delta e_1'' = e_1^{(2)} - e_1^{*(1)} = \frac{\beta\epsilon - 4k_F\lambda - 4n\theta k_F x_F e_2}{\beta\epsilon - 8nk_F^2} - \frac{\beta\epsilon - 4k_F\lambda}{\beta\epsilon - 8nk_F^2} = -\frac{4n\theta k_F x_F e_2}{\beta\epsilon - 8nk_F^2} < 0$$

since $\beta\epsilon - 8nk_F^2 > 0$. We used the reaction function of $e_1^{(2)}$ since it is more straightforward to show that the difference in firm's 1 emission rate is positive since $e_2 > 0$. Similarly for firm 2,

$$\Delta e_2' = e_2^{*(1)} - e_2^{(0)} = 1 - 1 = 0.$$

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[9] $e_i = [0, 1]$

and

$$\Delta e_2'' = e_2^{*(2)} - e_2^{*(1)} = \frac{(\beta\epsilon - 8nk_F^2)(\beta\epsilon - 4x_F\lambda) - 4n\theta k_F x_F(\beta\epsilon - 4k_F\lambda)}{(\beta\epsilon - 8nk_F^2)(\beta\epsilon - 8nx_F^2) - (4n\theta k_F x_F)^2} - 1 < 0.$$

□

Proof to Proposition 2. Regarding the changes in output of good 1 we have from Equations (3) & (10):

$$\Delta Q_1' = Q_1^{*(1)} - Q_1^{*(0)} =$$

$$= \frac{(a-c)(2-\theta) - \frac{2nk_F(\beta\epsilon - 4k_F\lambda)}{\beta\epsilon - 8nk_F^2}}{b(4-\theta^2)} - \frac{(a-c)(2-\theta)}{b(4-\theta^2)} = -\frac{2nk_F(\beta\epsilon - 4k_F\lambda)}{\beta\epsilon - 8nk_F^2} < 0$$

since $(\beta\epsilon - 4k_F\lambda) > 0$ holds.

By using Equation (10) and (16) we have:

$$\Delta Q_1'' = Q_1^{*(2)} - Q_1^{*(1)} = \frac{nx_F\theta[(\beta\epsilon - 8nk_F^2)(\beta\epsilon - 4x_F\lambda) - 4n\theta k_F x_F(\beta\epsilon - 4k_F\lambda)]}{b(\beta\epsilon - 8k_F^2 n)(4-\theta^2)[(\beta\epsilon - 8nk_F^2)(\beta\epsilon - 8nx_F^2) - (4n\theta k_F x_F)^2]} > 0$$

since it is shown that $nx_F\theta > 0$, $(\beta\epsilon - 8nk_F^2)(\beta\epsilon - 4x_F\lambda) - 4n\theta k_F x_F(\beta\epsilon - 4k_F\lambda) > 0$ and $(\beta\epsilon - 8nk_F^2)(\beta\epsilon - 8nx_F^2) - (4n\theta k_F x_F)^2 > 0$.

For good 2, from Equations (4) and (11):

$$\Delta Q_2' = Q_2^{*(1)} - Q_2^{*(0)} =$$

$$= \frac{(a-c)(2-\theta) + \frac{\theta nk_F(\beta\epsilon - 4k_F\lambda)}{\beta\epsilon - 8nk_F^2}}{b(4-\theta^2)} - \frac{(a-c)(2-\theta)}{b(4-\theta^2)} = \frac{\theta nk_F(\beta\epsilon - 4k_F\lambda)}{\beta\epsilon - 8nk_F^2} > 0$$

and from Equations (11) and (17):

$$\Delta Q_2'' = Q_2^{*(2)} - Q_2^{*(1)} =$$

$$= -\frac{2nx_F(\beta\epsilon - 8nk_F^2 + 2n\theta^2 k_F^2)[(\beta\epsilon - 8nk_F^2)(\beta\epsilon - 4x_F\lambda) - 4n\theta k_F x_F(\beta\epsilon - 4k_F\lambda)]}{b(\beta\epsilon - 8k_F^2 n)(4-\theta^2)[(\beta\epsilon - 8nk_F^2)(\beta\epsilon - 8nx_F^2) - (4n\theta k_F x_F)^2]} < 0$$

since we know that $2nx_F(\beta\epsilon - 8nk_F^2 + 2n\theta^2 k_F^2) > 0$ as it is proven that $\beta\epsilon - 8nk_F^2 > 0$, also $(\beta\epsilon - 8nk_F^2)(\beta\epsilon - 4x_F\lambda) - 4n\theta k_F x_F(\beta\epsilon - 4k_F\lambda) > 0$ and $(\beta\epsilon - 8nk_F^2)(\beta\epsilon - 8nx_F^2) - (4n\theta k_F x_F)^2 > 0$.

□

Proof to Proposition 3. For $k_F > 0$ (case I), according to Proposition 1 we can easily see that, in total, emission rates are lowered ($\Delta e_1' < 0$ & $\Delta e_2' = 0$) and from Equation (5) compared with Equation (12) we get

$$\Delta(Q_1 + Q_2) = (Q_1^{(1)} + Q_2^{(1)}) - (Q_1^{(0)} + Q_2^{(0)}) = -\frac{nk_F(\beta\epsilon - 4k_F\lambda)}{b(\beta\epsilon - 8nk_F^2)(2+\theta)} < 0$$

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which implies that total output is lowered. Hence, aggregate pollution is lower than the benchmark case For $k_F, x_F > 0$ (case II), comparing Equation (12) with Equation (16),

$$\Delta(Q_1 + Q_2) = (Q_1^{(2)} + Q_2^{(2)}) - (Q_1^{(1)} + Q_2^{(1)}) =$$

$$= -\frac{x_F(\beta\epsilon - 4nk_F^2(2-\theta))(\beta\epsilon(-\beta\epsilon + 4k_Fn(2k_F + x_F\theta)) + 4x_F(\beta\epsilon - 4k_F^2n(2+\theta))\lambda)}{(\beta\epsilon - 8k_F^2n)[(\beta\epsilon - 8nk_F^2)(\beta\epsilon - 8nx_F^2) - (4n\theta k_F x_F)^2]}$$

thus, the sign of the expression depends on the numerator and in particular on this part of the expression $(\beta\epsilon(-\beta\epsilon + 4k_Fn(2k + x_F\theta)) + 4x_F(\beta\epsilon - 4k_F^2n(2+\theta))\lambda)$. This allows us to find a critical value of $\hat{x_F} = \frac{\beta\epsilon - 4k_F\lambda}{4\lambda - 4nk_F(2-\theta)}$. $\square$

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