Multilateral and unilateral policy reform of emission taxes and abatement subsidies in a two-country model with oligopolistic interdependence

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Abstract This paper considers a two-country model with oligopolistic interdependence where firms make their output and emission decisions simultaneously, and face an emission tax and abatement subsidy. The impact of multilateral and unilateral policy reform on global emissions and welfare is examined, and the impact of the degree of product differentiation on optimal policy is explored. The analysis indicates that multilateral/unilateral policy reform reduces emissions and raises welfare under alternative assumptions on the cost function and parameter values. Additionally, it is shown that optimal policy is sensitive to the degree of product differentiation.

Keywords Environmental subsidies· Multilateral policy · Horizontal product differentiation

JEL Classification H23·L13·Q58

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This is the accepted version. DOI: https://doi.org/10.1007/s10018-012-0039-1

1 Introduction

This article examines the potential role of a pollution abatement subsidy, emission tax scheme in reducing emissions and increasing welfare in an international context. The impact of multilateral/unilateral policy reform on welfare and emissions is analyzed, and the impact of product differentiation on the characterization of policy is also explored. A two-country model with product differentiation where firms and governments play a two-stage Cournot-Nash game is employed. The government in each country sets policy and firms then make their output and emission decisions simultaneously. Three key results arise from the analysis, viz., several distinct policy reforms may raise global welfare, reduce global emissions and optimal policy is sensitive to the degree of product differentiation.

It is widely agreed upon that if global environmental problems are to be solved participation across countries is crucial, particularly within the context of the development of effective multilateral environmental policies.[1] The literature has studied aspects of multilateral/unilateral environmental policy (e.g., Hoel 1991; Hatzipanayotou et al. 2005; Turunen-Red and Woodland 2004) as well as issues of product differentiation and its impact on policy (e.g., Katsoulacos and Xepapadeas 1995; Poyago-Theotoky and Teerasuwannajak 2002), but the contribution of the present analysis can be narrowed down to the works of Fujiwara (2009) and Lahiri and Semyonidis (2007).[2]

Fujiwara (2009) analyses the sensitivity of policy with respect to the degree of product differentiation in a closed-economy Cournot setting; the only policy considered is an emission tax and abatement efforts by firms is assumed away. One key result from Fujiwara's analysis is that policy is sensitive to the degree of product differentiation. This paper extends Fujiwara's work in two fundamental ways. First, a two-country model is considered, thereby including aspects of cross-border pollution and oligopolistic interdependence. Second, the

[1] For example, multilateral agreements to tackle air pollution include the Kyoto Protocol in 1999, Montreal Protocol in 1987 and the Vienna Convention for the Protection of the Ozone Layer in 1985.

[2] There is a somewhat less related literature where the abatement subsidy is studied although within a different context. Examples of this literature include Conrad and Wang (1993) and Conrad (1993).

paper adds abatement efforts and an abatement subsidy to the model. These two new elements of analysis allow one to examine, inter alia, the impact that policy setting in other countries may have on the relationship between product differentiation and optimal policy.

Lahiri and Symeonidis (2007) consider a two-country model with oligopolistic interdependence with the emission tax as the only policy. The authors explore cases where the tax may increase global emissions as well as the impact of multilateral policy reform, but do not conduct welfare analysis. This paper extends Lahiri and Symeonidis' work by (i) including an additional policy (i.e., abatement subsidy), (ii) examining the welfare implications of multilateral/unilateral policy reform, and (iii) exploring the sensitivity of policy with respect to product differentiation. This extension allows one to explore how a subsidy-tax policy combination may help tackle pollution within the context of multilateral/unilateral policy reform in the presence of country asymmetries.[3] In particular, the framework of analysis allows one to examine the extent to which a subsidy may affect the ability of the emission tax to reduce global emissions and the role of pollution intensity coefficients in this context. In other words, the model allows one to see whether the subsidy either compensates (i.e., helps reduce emissions) or offsets the effect of a tax in terms of reducing global emissions, and in this analysis it will be clear the role of the pollution intensity coefficients across countries and degree of product differentiation.

The framework of analysis can be further motivated by the trade relationship between, as well as the tax and subsidy schemes in, Norway and the EU in mineral fuels, lubricants and related materials, a sector which includes two key components in energy production, namely, oil and natural gas.[4] Arguably, this is an example of imperfect substitutes in the energy sector where emission taxes (CO_2 -based taxes both in Norway and the EU) and subsidies (the NER 300 call for CCS technology for EU member states[5] and Norway's government funding for

[3]See footnote 1 for examples of multilateral efforts; Norway is one example of a country which has implemented environmental policy unilaterally (Hoel 1991, p.56).

[4]For data on trade in the mineral fuels. lubricants and related materials between Norway and the EU see http://trade.ec.europa.eu/doclib/docs/2006/september/tradoc_113429.pdf

[5]For the NER call scheme see http://ec.europa.eu/clima/funding/ner300/00001/summary_en.pdf and http://ec.europa.eu/clima/funding/ner300/docs/projects_perms_en.pdf.

CCS technology[6] to lower production costs) take place.[7] A second example which may help justify the present model set-up is the car industry in the US and Germany. In this case, the car industry (i) exhibits horizontal product differentiation (cars of relatively same quality differ in e.g., color), (ii) faces an emission tax in the US in the form of a gas guzzler tax and in Germany in the form of a CO_2-based tax on cars, and (iii) governments in the US and Germany have provided subsidies in the form of low-cost loans or grants during the recent economic slowdown.[8]

From a policy perspective, the study of the abatement subsidy tax scheme considered here can be motivated also because it intuitively moves the analysis towards a first-best allocation, particularly within the context of imperfect competition. Furthermore, the aspect of product differentiation is relevant because it plays a key role in the characterization of environmental policy as shown, for example, in Katsoulacos and Xepapadeas (1996) and Fujiwara (2009). But this aspect is also important because policy reform, as will be clear from the analysis, may be more or less effective in reducing emissions depending on whether the degree of product of differentiation is small or large.

The rest of the article is structured as follows. The next section presents the model followed by some of the results from the comparative statics exercise. Section four examines the impact of policy on emissions and section five the relationship between policy and the degree of product differentiation. Section six presents the impact of multilateral policy on

[6]For subsidies in Norway directed towards CCS technology see http://www.eeagrants.org/id/2002.0.

[7]The complete data set on environmental taxes in the EU, including pollution taxes, is available at http://epp.eurostat.ec.europa.eu/portal/page/portal/product_details/dataset?p_product_code=ENV_AC_TAXIND . These data show that some of the sectors mentioned, which have applied for NER 300 funding, are also subject to a pollution tax. At the international level there are also examples of CCS technology projects. For examples of power plant and non-power CCS projects go to the MIT CC&ST Program web site http://sequestration.mit.edu/index.html. For more on CCS technology see PEW Center of Global Climate Change, http://www.pewclimate.org/technology/factsheet/ccs. Additionally, although CCS technology has been associated to electricity production from existing and new power plants, there is also a potential role for this technology in other industries and sectors such as refineries, iron and steel manufacturing and cement (Anderson and Newell 2003).

[8]For detailed information on production, taxes and subsidies in each country the reader is referred to http://www.usitc.gov/publications/332/pub3545.pdf, http://www.internationaltransportforum.org/jtrc/RoundTables/feb1018Braathen1.pdf, http://www.oecd.org/officialdocuments/displaydocumentpdf/?cote=env/epoc/wpnep/t(2009)1/final&doc language=en

welfare and the last section concludes.

2 The Model

In a formal sense the model employed here is based on Lahiri and Symeonidis (2007). Consider two countries, labeled h and f with, respectively, n and m firms. Firms within each country produce a homogenous good, but there is product differentiation across countries. Inverse market demand functions come from preferences such that

$$p^h = \alpha^h - \beta^h(q_1^h + q_2^h + \ldots + q_n^h) - \gamma(q_1^f + q_2^f + \ldots + q_m^f) \tag{1}$$

$$p^f = \alpha^f - \beta^f(q_1^f + q_2^f + \ldots + q_m^f) - \gamma(q_1^h + q_2^h + \ldots + q_n^h) \tag{2}$$

where q_l^k denotes output of firm $l = i, j$ ($i = 1, 2, \ldots, n$; $j = 1, 2, \ldots, m$) in country $k = h, f$, and γ the degree of product differentiation satisfying $\beta^k > \gamma > 0$. Each firm in the home (foreign) country is subject to a per-unit emission tax, t^h (t^f), and pollution abatement subsidy, $s^h(s^f)$. Pollution abatement by each firm is given by $a_l^k = d_l^k q_l^k - e_l^k$, where d represents the pollution intensity coefficient, which is assumed to be constant. Therefore, subsidy payments to each firm for the amount of pollution abated are given by $s^k a_l^k$. Notice that the abatement subsidy influences output and emissions by each firm and so let us define the effective tax, $\tau^k = t^k + s^k$, and the effective subsidy, $\varsigma^k = s^k d_l^k$ for $k = h, f$.

Each firm maximizes profit, π_l^k, in a Cournot fashion by simultaneously choosing emissions, e_l^k, and output, q_l^k. In particular,

$$\max_{q_l^k e_l^k} \pi_l^k = p^k q_l^k - c_l^k(q_l^k, e_l^k) - e_l^k \tau^k + \varsigma^k q_l^k \tag{3}$$

where, letting subscripts denote partial derivatives and dropping the subscript l for simplicity, the function $c^k(\cdot,\cdot)$ is assumed to satisfy $c_1^k > 0$, $c_2^k < 0$, $c_{11}^k > 0$, $c_{22}^k > 0$, $c_{12}^k < 0$ and $c_{22}^k c_{11}^k - (c_{12}^k)^2 > 0$. [9] Maximization of (3) yields two first-order conditions for firms in the

[9] The reader is referred to Requate(2006) for a discussion of the properties of the cost function. I follow Lahiri and Symeonidis (2007) in that the pollution intensity coefficient is equal to $-c_{12}/c_{22}$; see footnote 3, page 890.

home country, which under symmetry are given by

$$\alpha^h - c_1^h - \beta^h q^h (n+1) - \gamma m q^f + \varsigma^h = 0 \tag{4}$$

$$-c_2^h - \tau^h = 0 \tag{5}$$

Analogously, firms in the foreign country yield

$$\alpha^f - c_1^f - \beta^f q^f (m+1) - \gamma n q^h + \varsigma^f = 0 \tag{6}$$

$$-c_2^f - \tau^f = 0 \tag{7}$$

These four equations determine the equilibrium level of emissions, e^k, output, q^k, and therefore abatement, a^k, for all $k = h, f$.[10]

3 Comparative Statics

This section examines the comparative static effects of the effective subsidy,ς^k , and tax, τ^k. Total differentiation of (4)-(7) yields the following system

$$\begin{bmatrix} -\beta^h(n+1) - c_{11}^h & -m\gamma & -c_{12}^h & 0 \\ -c_{21}^h & 0 & -c_{22}^h & 0 \\ -n\gamma & -\beta^f(m+1) - c_{11}^f & 0 & -c_{12}^f \\ 0 & -c_{12}^f & 0 & -c_{22}^f \end{bmatrix} \begin{bmatrix} dq^h \\ dq^f \\ de^h \\ de^f \end{bmatrix} = \begin{bmatrix} -d\varsigma^h \\ d\tau^h \\ -d\varsigma^f \\ d\tau^f \end{bmatrix}$$

where the determinant of the coefficient matrix is $\tilde{\Delta} < 0$.

Hence, under the assumption of the $c(\cdot,\cdot)$ function output in the home (foreign) country falls (rises) with the tax in the home country; as explained in Lahiri and Symeonidis (2007) this is because the tax in the home country raises marginal costs to firms in that country thereby providing a competitive advantage to those firms in the other country.

[10] I shall assume an interior solution throughout.

Analogously, an increase in the subsidy in the home country lowers the marginal cost of those firms operating in that country, thus raising (reducing) output in the home (foreign) country. This is because the subsidy provides home-country firms with a cost competitive advantage. It is noteworthy that if products are completely differentiated ($\gamma \simeq 0$) the cross effect of policy is small e.g., an increase in the subsidy in the home country has a negligible effect on output (and therefore emissions) in the foreign country. Formally, for the home country one finds $\partial q^h/\partial \tau^h < 0$, $\partial q^h/\partial \tau^f > 0$, $\partial q^h/\partial \varsigma^h > 0$, $\partial q^h/\partial \varsigma^f < 0$:

$$
\begin{aligned}
\tilde{\Delta} dq^h &= \left[c_{12}^f c_{22}^h m\gamma\right] d\tau^f + \left[c_{22}^f c_{22}^h m\gamma\right] d\varsigma^f \\
&\quad - c_{12}^h \left[c_{11}^f c_{22}^f - (c_{12}^f)^2 + c_{22}^f \beta^f (m+1)\right] d\tau^h \\
&\quad - c_{22}^h \left[c_{11}^f c_{22}^f - (c_{12}^f)^2 + c_{22}^f \beta^f (m+1)\right] d\varsigma^h \qquad (8)
\end{aligned}
$$

$$
\begin{aligned}
\tilde{\Delta} dq^f &= \left[c_{12}^h c_{22}^f n\gamma\right] d\tau^h + \left[c_{22}^f c_{22}^h n\gamma\right] d\varsigma^h \\
&\quad - c_{12}^f \left[c_{11}^h c_{22}^h - (c_{12}^h)^2 + c_{22}^h \beta^h (n+1)\right] d\tau^f \\
&\quad - c_{22}^f \left[c_{11}^h c_{22}^h - (c_{12}^h)^2 + c_{22}^h \beta^h (n+1)\right] d\varsigma^f \qquad (9)
\end{aligned}
$$

The effect of policy on emissions by each firm in each country is given by $\partial e^h/\partial \tau^h < 0$, $\partial e^h/\partial \tau^f > 0$, $\partial e^h/\partial \varsigma^h > 0$, $\partial e^h/\partial \varsigma^f < 0$. The derived expressions for these are provided in the next section.

4 The Impact of Multilateral and Unilateral Policy on Global Emissions

This section examines the impact of policy reform on global emissions and issues of strategic behavior are assumed away for simplicity. Policy reform in the present context is defined as an absolute change in policy.[11] In particular, I shall look at the cases where one country raises the tax and the other the subsidy, and where each country (or just one country) raises the subsidy. The case of policy reform is also examined within the context of an increase in the subsidy and tax in the same country. The impact of policy reform of the tax has been examined in Lahiri and Symeonidis (2007) and so the focus here is on the cases involving the subsidy.[12]

Define global emissions $E = ne^h + me^f$. Then, total differentiation yields

$$\begin{aligned}\tilde{\Delta} nde^h \;=\; & -n\left[c^f_{12}c^h_{21}m\gamma\right]d\tau^f - n\left[c^f_{22}c^h_{21}m\gamma\right]d\varsigma^f + c^h_{21}n\left[c^f_{11}c^f_{22} - (c^f_{12})^2 + c^f_{22}\beta^f(m+1)\right]d\varsigma^h \\ & +n\Big[(c^f_{11}c^f_{22} - (c^f_{12})^2)(c^h_{11} + \beta^h(n+1)) + c^f_{22}\left(\beta^h\beta^f(n+1)(m+1) - nm\gamma^2\right) \\ & +c^h_{11}c^f_{22}\beta^f(m+1)\Big]d\tau^h \qquad (10)\end{aligned}$$

$$\begin{aligned}\tilde{\Delta} mde^f \;=\; & -m\left[c^f_{12}c^h_{21}n\gamma\right]d\tau^h - m\left[c^h_{22}c^f_{21}n\gamma\right]d\varsigma^h + c^f_{21}m\left[c^h_{11}c^h_{22} - (c^h_{12})^2 + c^h_{22}\beta^h(n+1)\right]d\varsigma^f \\ & +m\Big[(c^h_{11}c^h_{22} - (c^h_{12})^2)(c^f_{11} + \beta^f(m+1)) + c^h_{22}\left(\beta^h\beta^f(n+1)(m+1) - nm\gamma^2\right) \\ & +c^f_{11}c^h_{22}\beta^h(n+1)\Big]d\tau^f \qquad (11)\end{aligned}$$

where $\tilde{\Delta} < 0$ and $\beta^h\beta^f - \gamma^2 > 0$. The effect of a *unilateral* increase in the subsidy is now examined. In particular, an increase in ς^h (a policy reform such that $d\varsigma^h > 0$) increases emissions in the home country and lowers emissons in the foreign country via changes in output, and so I look at cases where global emissions may rise/fall with the subsidy. From (10) and (11) and under the assumption of the $c(\cdot,\cdot)$ function the analysis indicates that global emissions rise unambiguously if $\gamma \simeq 0$. This is because when products are completely differentiated the decrease in output in the foreign country (and the associated decrease in

[11] See Lahiri and Symeonidis (2007, p. 892).

[12] The results for the tax obtained here are consistent with Lahiri and Symeonidis (2007).

emissions in that country), arising from the subsidy in the home country, is small because differences in cost competitiveness do not take place (when products are very different the change in output and emissions in the foreign country is small). Global emissions also rise unambiguously with the subsidy in the home country if $c_{22}^h = c_{22}^f$ and $c_{12}^h = c_{12}^f$; i.e., under sufficient symmetry of the cost function across countries. Furthermore, if $\beta^f = \gamma$ then global emissions increase if $d^f \leq d^h$; this is because in this case any increase in emissions in the home country (the pollution-intensive country) offsets the reduction in emissions in the foreign country. In the case where $\beta^f = \gamma$ and the cost function is of the end-of-pipe as previosuly specified global emissions fall if $d^f m > d^h(m+1)$. Intuitively, with a relatively large pollution intensity coefficient in the foreign country reductions in emissions in that country, arising from the subsidy in the home country, are therefore large so that they completely offset increases in emissions in the home country.

Next, the multilateral equal increase in the subsidy is considered (i.e., $d\varsigma^h = d\varsigma^f > 0$). The analysis suggests that the effect of the subsidy on global emissions is unambiguous: a multilateral equal increase in the subsidy raises emissions in the home country and in the foreign country, and global emissions rise as a result. This is because any increase in output, and therefore emissions, in one country arising from the subsidy (the own effect of policy) offsets any reductions in output in the other country (the cross effect). This suggests that this policy reform raises, on the one hand, emissions in the home country and, on the other, emissions in the foreign country. It is noteworthy that in the case of complete product differentiation (i.e., $\gamma \simeq 0$) global emissions are likely to increase by more with the subsidy; this is because in this case the effect of the home subsidy on foreign output (and the effect of the foreign subsidy on home output) and therefore the net effect on emissions is small. For completeness notice that under this policy reform if $\beta^h = \beta^f = \gamma$, then global emissions fall.

The multilateral equal increase in the tax and subsidy is now examined. In particular, I consider the case where the home country raises the tax, τ^h, and the foreign country the subsidy, ς^f i.e., $d\tau^h = d\varsigma^f > 0$. Under this policy it is found that emissions in the home (foreign) country decrease (increase); the effect on global emissions is ambiguous. However, under the assumption of an end-of-pipe cost function similar to the one previously specified i.e., $c^h(q^h, e^h) = \hat{c}q^h + h(d^h q^h - e^h)$, $\hat{c} > 0$, global emissions fall if $(d^h)^2 > d^f$, $m = n$, $\beta^h = \beta^f$ and $\gamma \simeq 0$. The case where $\gamma \simeq 0$ indicates that increases in global emissions arising from the tax in the home country are negligible and the larger intensity coefficient in the home country helps offset any increases in emissions arising from the subsidy in the foreign country. Additionally and still under the end-of-pipe assumption, the policy reform $d\tau^h > 0$ and $d\varsigma^f > 0$ lowers global emissions if $\beta^f = \beta^h = \gamma$ and $d^h n > d^f(n+1)$. That is, where the intensity coefficient of the home country is greater than that of the foreign country, the tax in the home country, on the one hand, lowers global emissions and, on the other, the subsidy in the foreign country lowers global emissions as well. Now, if the assumption of end-of-pipe is relaxed, then under the policy $d\tau^h > 0$ and $d\varsigma^f < 0$, global emissions fall if $\gamma \simeq 0$ or if $\beta^f = \beta^h = \gamma$ and $d^h = d^f$.

Lastly, the effect of a *unilateral* equal increase in the subsidy and tax in the home country on emissions is examined (i.e., $d\tau^h = d\varsigma^h > 0$). The analysis suggests that emissions in the home (foreign) country fall (rise) if $d^h > 1$.[13] This result indicates that in a unilateral context the effect of the tax offsets the effect of the subsidy within each country. In addition, if $\gamma \simeq 0$ and $d^h > 1$ then global emissions fall; this is because under complete product differentiation the effect on emissions in the foreign country is small and with the large pollution intensity coefficient, d^h, the tax increase (and the associated reduction in emissions) offsets the increase in emissions from the subsidy. If $\beta^f = \gamma$, $d^h \geq d^f$ and $d^h > 1$ then global emissions fall as well. This condition suggests that the pollution intensity coefficient in the home country should be sufficiently large that an increase in the tax in the home country lowers global emissions and, at the same time, it offsets any higher level of emissions arising from the subsidy in the home country. This section concludes by stating that if $\beta^f = \gamma$ and

[13] This comes from equations (8) and (9) where $c_{22} + c_{12} = c_{22}(1 + c_{12}/c_{22}) = c_{22}(1 - d^h)$.

$d^h \geq d^f$ then global emissions fall under the policy reform $d\tau^h > 0$ and $d\varsigma^h < 0$.

Proposition 1. *If $\beta^h = \gamma$ and $d^h \geq d^f$ global emissions fall under the policy reform $d\tau^h > 0, d\varsigma^h < 0$. Moreover, under the assumption of an end-of-pipe cost function and $\beta^f = \gamma$ the policy reform $d\varsigma^h > 0$ reduces global emissions for sufficiently large pollution intensity coefficient in the foreign country.*

5 The Role of Product Differentiation

This section analyses the properties of the subsidy and tax when countries do not cooperate. The effect of product differentiation on the characterization of policy is also examined.

The government in the foreign and home countries maximize welfare by choosing the tax and subsidy in a Cournot-Nash fashion. In particular, the government in the home country solves the following maximization problem

$$\max_{\tau^h \varsigma^h} W^h = CS^h(nq^h, mq^f) + ne^h\tau^h - nq^h\varsigma^h + n\pi^h - \varphi^h(E^h + E^f) \tag{12}$$

where $CS^h(\cdot,\cdot)$ denotes consumer surplus and $\varphi^h(\cdot)$ damages from pollution satisfying $\varphi^{h\prime} > 0$, $\varphi^{h\prime\prime} > 0$. Maximization yields (subscripts denote partial derivatives)

$$W^h_{\tau^h} = -mq^f p^f_{\tau^h} + n(\beta^h q^h - \varsigma^h)q^h_{\tau^h} + n(\tau^h - \varphi^{h\prime})e^h_{\tau^h} - \varphi^{h\prime} m e^f_{\tau^h} = 0 \tag{13}$$

$$W^h_{\varsigma^h} = -mq^f p^f_{\varsigma^h} + n(\beta^h q^h - \varsigma^h)q^h_{\varsigma^h} + n(\tau^h - \varphi^{h\prime})e^h_{\varsigma^h} - \varphi^{h\prime} m e^f_{\varsigma^h} = 0 \tag{14}$$

Similarly, in the foreign country first-order conditions are given by $W^f_{\tau^f} = 0$ and$W^f_{\varsigma^f} = 0$. These four equations implicitly determine policy in the foreign and home country, τ^{f^*}, ς^{f^*}, τ^{h^*} and ς^{h^*}. Hence, the following expressions are obtained:

$$\tau^{h^*} = \varphi^{h\prime} \tag{15}$$

$$\varsigma^{h^*} = \frac{-mq^f p^f_{\varsigma^h} + nq^h\beta^h q^h_{\varsigma^h} - \varphi^{h\prime} m e^f_{\varsigma^h}}{nq^h_{\varsigma^h}} > 0 \tag{16}$$

where $e^f_{\varsigma^h} < 0$, $p^f_{\varsigma^h} < 0$. This result is consistent with the literature and analogous to the case of a closed-economy as the one described in Requate (2006). Intuitively, the tax addresses pollution and the positive subsidy the output distortion.

Next, the effect of product differentiation on policy is examined. To make the analysis tractable the following assumptions are made. First, I shall assume an end-of-pipe cost function such that marginal production costs are constant, $d^f = d^h = 1$, $h^{h''} = h^{f''} = 1$; and second, $m = n$, $\varphi^{h''} = \varphi^{f''} = 1$. Specifically, under these assumptions three cases are considered which yield unambiguous signs for *both* $\tau^{h^*}_\gamma$ and $\varsigma^{h^*}_\gamma$ (subscripts denote partial derivatives): when (i) $\gamma = 0$, (ii) $\beta^h = \beta^f = \gamma = 1$, and (iii) $\beta^h\beta^f > 1$, $\beta^k > \gamma$ for $k = h, f$. Differentiation of (15), (16) and analogous expressions for τ^{f^*} and ς^{f^*} yields that in cases (i) and (iii) $\tau^{h^*}_\gamma > 0$, $\varsigma^{h^*}_\gamma > 0$; and $\tau^{h^*}_\gamma < 0$, $\varsigma^{h^*}_\gamma > 0$ in case (ii).

Proposition 2. *Let $c(q, e) = \hat{c}q + a^2/2, \hat{c} > 0$ and assume $m = n$, $\varphi^{h'} = \varphi^{f'} = 1$. If $\gamma = 0$ or $\beta^h\beta^f > 1$, then $\tau^{h^*}_\gamma > 0$, $\varsigma^{h^*}_\gamma > 0$. Furthermore, if $\beta^h = \beta^f = \gamma = 1$ then $\tau^{h^*}_\gamma < 0$, $\varsigma^{h^*}_\gamma > 0$.*

The intuition for these results is as follows. In cases (i) and (iii), as products become less differentiated (increase in γ), output in the home country falls, which prompts the government of that country to raise the subsidy. As a result, emissions in the home country rise, which induces the government of that country to raise the tax. An increase in γ also induces the government of the foreign country to raise the subsidy and as a result emissions in that country rise, which prompts the government in the home country to raise the tax. [14] In contrast, for case (ii) as products become more differentiated (decrease in γ), output and therefore emissions in the home country rise which induces the government in that country to raise the tax, and at the same time, to lower the subsidy as a result of the increase in output.

[14] The effect of γ on q^h, e^h, q^f and e^f can be easily verified differentiating (4)-(7).

6 The Impact of Policy Reform on Welfare

This section presents the analysis of the impact of policy reform on welfare. First, the cooperative equilibrium is characterized; and second, three specific policies are examined in order to ascertain which of these may be welfare enhancing. Starting from the Nash equilibrium a change in (i) the subsidy, (ii) the tax and (iii) the subsidy and tax in one country are considered.

Let us first define global welfare $W^g = W^h + W^f$, where W^h is given by (12) and an analogous expression applies to W^f. The cooperative solution is obtained by solving

$$\max_{\tau^h \tau^f \varsigma^h \varsigma^f} W^g = W^h + W^f \tag{17}$$

which yields four equations which implicitly determine the cooperative equilibrium τ_c^f, τ_c^h, ς_c^h and ς_c^f. Because of the symmetric nature of the model one can simply state that, using the first-order conditions derived from equation (17), the cooperative tax for the home country now takes into account the foreign country's marginal damage from pollution; but for the subsidy, although positive, no clear-cut comparisons between the cooperative and non-cooperative solutions can be made. This result is consistent with the literature.

The main purpose of this section is to examine the effect of policy reform on welfare. I shall first examine the impact of an increase in the subsidy where the home country changes ς^h, starting from the Nash equilibrium (i.e., a policy reform given by $d\varsigma^h > 0$). So, starting from the Nash equilibrium total differentiation gives

$$dW^h|_{Nash} = \left[c_{22}^f \left(m^2 q^f \beta^f - \varphi^{h'} d^f \right) \frac{\mu^f \mu^h - c_{22}^h c_{22}^f n m \gamma^2}{-\tilde{\Delta} \mu^f} \right] d\varsigma^f \tag{18}$$

$$dW^f|_{Nash} = \left[c_{22}^h \left(n^2 q^h \beta^h - \varphi^{f'} d^h \right) \frac{\mu^f \mu^h - c_{22}^h c_{22}^f n m \gamma^2}{-\tilde{\Delta} \mu^h} \right] d\varsigma^h \tag{19}$$

where $\mu^f = c^f_{11}c^f_{22} - (c^f_{12})^2 + c^f_{22}\beta^f(m+1) > 0$, $\mu^h = c^h_{11}c^h_{22} - (c^h_{12})^2 + c^h_{22}\beta^h(n+1) > 0$, $\mu^f\mu^h - c^h_{22}c^f_{22}nm\gamma^2 > 0$, $\tilde{\Delta} < 0$. There are two opposing effects arising from this policy. Consider the case of the home country's welfare given by (18). An increase in the subsidy in the foreign country, on the one hand, increases consumer surplus via lower prices, p^h and p^f, (a positive welfare effect) and, on the other, it raises output and thus pollution in the foreign country thereby increasing transboundary pollution, and it lowers profits in the home country (negative welfare effects). An analogous analysis applies to equation (19), which has been written for completeness. Hence, one can then say that, starting from the Nash equilibrium, welfare in the home country increases if and only if $m^2q^f\beta^f - \varphi^{h'}d^f > 0$ i.e., the effect from transboundary pollution is small. Alternatively, if the pollution intensity coefficient in the foreign country is large such that $m^2q^f\beta^f - \varphi^{h'}d^f < 0$, then a reduction in the subsidy in the pollution-intensive country ($d\varsigma^f < 0$) would increase welfare in the home country.

Next, the combination of an increase in the emission tax holding the subsidy constant is considered. In particular, starting from the Nash equilibrium differentiation yields

$$
\begin{aligned}
-\tilde{\Delta}\mu^f dW^h|_{Nash} &= \Big[c^f_{22}d^f\left(\varphi^{h'}d^f - m^2\beta^f q^f\right)\left(\mu^h\mu^f - nmc^h_{22}c^f_{22}\gamma^2\right) \\
&\quad +\varphi^{h'}(\mu^f/c^f_{22})\left(\mu^h\mu^f - nmc^h_{22}c^f_{22}\gamma^2\right)\Big]d\tau^f \qquad (20) \\
-\tilde{\Delta}\mu^h dW^f|_{Nash} &= \Big[c^h_{22}d^h\left(\varphi^{f'}d^h - n^2\beta^h q^h\right)\left(\mu^h\mu^f - nmc^h_{22}c^f_{22}\gamma^2\right) \\
&\quad +\varphi^{f'}(\mu^h/c^h_{22})\left(\mu^h\mu^f - nmc^h_{22}c^f_{22}\gamma^2\right)\Big]d\tau^h \qquad (21)
\end{aligned}
$$

In this case there are two opposing effects. An increase in the tax in the foreign country, on the one hand, lowers output and thus emissions in that country thereby lowering transboundary pollution, and raises profits in the home country (positive welfare effects); and, on the other, it lowers consumer surplus via higher prices, p^f and p^h (negative welfare effect). The analysis also indicates that in the case of the tax a third positive effect takes place:

the tax in the foreign country induces abatement by firms in that country thereby lowering transboundary pollution further; this effect is captured by the second term in (20).[15] In contrast to the previously explained policy, here the increase in τ^f raises welfare in the home country if $m^2 q^f \beta^f - \varphi^{h\prime} d^f < 0$.[16]

Proposition 3. *Starting from the Nash equilibrium a policy reform such that $d\varsigma^f > 0$ raises welfare in the home country if and only if $m^2 q^f \beta^f - \varphi^{h\prime} d^f > 0$. Additionally, starting from the Nash equilibrium a policy reform such that $d\tau^f > 0$ raises welfare in the home country if $m^2 q^f \beta^f - \varphi^{h\prime} d^f < 0$. Hence, the policy reform $d\tau^f > 0$ and $d\varsigma^f < 0$ raises welfare in the home country if $m^2 q^f \beta^f - \varphi^{h\prime} d^f < 0$.*

This section concludes by briefly looking at the impact of policy reform in the absence of consumer surplus. In this special case it is shown that starting from the Nash equilibrium an increase in the subsidy (tax) in the foreign country decreases (raises) welfare in the home country. Thus, the policy reform characterized by a decrease in the subsidy and increase in the tax in the foreign country raises welfare in the home country.

To see this let us first characterize the cooperative and non-cooperative solutions and then examine the policy reforms. So, in the absence of consumer surplus welfare in the home country is given by $W^h = n\pi^h - \varphi^{h\prime} + ne^h - nq^h\varsigma^h$ and $W^f = m\pi^f - \varphi^{f\prime} + me^f - mq^f\varsigma^f$ where variable definitions are identical from previous sections. In the non-cooperative scenario the government in each country chooses policy in a Cournot-Nash fashion and the solution is characterized by a policy $\tilde{\tau^h}, \tilde{\varsigma^h}, \tilde{\tau^f}$ and $\tilde{\varsigma^f}$ such that $W^h_{\tau^h} = 0$, $W^h_{\varsigma^h} = 0$, $W^f_{\tau^f} = 0$, $W^f_{\varsigma^f} = 0$. On the other hand, the cooperative solution is given by the maximization of total welfare $W^h + W^f$, which yields a policy vector $\hat{\tau^h}, \hat{\varsigma^h}, \hat{\tau^f}$ and $\hat{\varsigma^f}$.

[15] To see this consider $e^f = e^f(q^f, a^f)$. Then, $e^f_{\tau^f} = e^f_{q^f} q^f_{\tau^f} + e^f_{a^f} a^f_{\tau^f} \rightarrow \tilde{\Delta} e^f_{a^f} a^f_{\tau^f} = (\mu^h \mu^f - c^h_{22} c^f_{22} nm\gamma^2)/c^f_{22} > 0$ since $e^f_{a^f} < 0$ and $\tilde{\Delta} < 0$.

[16] It is also found that global welfare rises if $c^f_{12} = 0$ and $c^h_{12} = 0$; this is because in this case the negative welfare effect vanishes. Intuitively, the tax in the foreign country reduces emissions in that country via higher abatement, but output in the foreign country is not affected. Since output in the foreign country is not affected, then output in the home country (and therefore emissions) is not affected either because changes in cost competitiveness do not take place. The result that the tax does not affect output if $c_{12} = 0$ is consistent with Requate (2006, p. 140).

Next, policy reform is considered; specifically, starting from the Nash equilibrium the impact on the home country's welfare from an increase in the subsidy in the foreign country is given by

$$q^h_{\varsigma^h} dW^h|_{Nash} = \left[q^h \gamma n m \left(q^f_{\varsigma^h} q^h_{\varsigma^f} - q^f_{\varsigma^f} q^h_{\varsigma^h} \right) + \varphi^{h'} m \left(e^f_{\varsigma^h} q^h_{\varsigma^f} - e^f_{\varsigma^f} q^h_{\varsigma^h} \right) \right] d\varsigma^f \qquad (22)$$

where each of the terms in parentheses is negative: the first term denotes the decrease in welfare from a reduction in profits and the second from transboundary pollution. This suggests that starting from the Nash equilibrium, a policy reform consisting of a decrease in the subsidy in the foreign country (i.e., $d\varsigma^f < 0$) thus increases welfare in the home country. This is because a decrease in the subsidy in the foreign country increases output and profits in the home country (a positive welfare effect) and reduces transboundary pollution (also a positive welfare effect). In a similar fashion the effect of an increase in the tax in the foreign country, starting from the Nash equilibrium, is given by

$$q^h_{\varsigma^h} dW^h|_{Nash} = \left[q^h \gamma n m \left(q^f_{\varsigma^h} q^h_{\tau^f} - q^f_{\tau^f} q^h_{\varsigma^h} \right) + \varphi^{h'} m \left(e^f_{\varsigma^h} q^h_{\tau^f} - e^f_{\tau^f} q^h_{\varsigma^h} \right) \right] d\tau^f \qquad (23)$$

where each of the terms in parentheses is positive. Starting from the Nash equilibrium an increase in the tax in the foreign country reduces transboundary pollution and at the same time it increases output and profits in the home country. Thus a policy reform consisting of an increase in the tax in the foreign country (i.e.,$d\tau^f > 0$) raises welfare in the home country. Consequently, from (22) and (23) one can say that a policy reform such that $d\tau^f > 0, d\varsigma^f < 0$ is welfare enhancing.

7 Conclusion

This paper examines the role of an emission tax abatement subsidy scheme in raising welfare and reducing global emissions in a two-country model with oligopolistic interdependence.

The impact of product differentiation on optimal policy is also explored. The analysis suggests that policy is sensitive to the degree of product differentiation. It is also shown that under certain conditions about pollution intensity coefficients and other parameter values global emissions fall and welfare rises under several policy reforms. These results are important because they indicate that policy is sensitive to the degree of product differentiation and the potential role of policy reform in reducing global emissions. Moreover, the analysis of multilateral/unilateral policy for the type of tax-subsidy scheme presented here is to the best of my knowledge new in the literature. This will hopefully motivate further research in this area. One extension of the model includes the study of a similar tax-subsidy scheme in the presence of a pollution trading permit system; this would be particularly relevant for the case of the European Union.

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