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ARTICLE

Environmental protection without loss of international competitiveness

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We develop a two-country Cournot oligopoly model with product differentiation across countries and production-generated pollution. The abatement of pollution by the firms in response to emission taxes is endogenous, and the number of firms can be fixed or there may be free entry and exit of firms in both countries. We propose particular unilateral and multilateral piecemeal policy reforms of emission taxes and production subsidies such that domestic industries will not suffer any loss of international competitiveness (defined in terms of either market share or profits), emission levels will be lower, and welfare could be higher in both countries.

1 | INTRODUCTION

Although it is widely acknowledged that serious attempts should be made to reduce environmental degradation, there continues to be much reluctance in many countries to adopt stringent environmental policies. An important reason for this reluctance is the belief that environmental policies in a country may have a negative impact on the competitiveness of domestic industries (see, e.g., Baumol & Oates, 1988, ch. 16; Simpson & Bradford, 1996). This was apparently one of the reasons why the Bush administration was against the ratification of the Kyoto agreement. Even in the Netherlands, where the environmental lobby is powerful, there have been suggestions by the government that exporting sectors should face less stringent environmental policies than other sectors because of the need to be competitive in the international market.[1]

One response to the apparent trade-off between stricter environmental policy and industrial competitiveness has been to argue that it might not exist, once one allows for dynamic effects of environmental policy on innovation (Porter & van der Linde, 1995). However, this proposal remains controversial (see Xepapadeas & de Zeeuw, 1999, for an assessment). Moreover, a potential solution based on industry-specific exemptions from environmental taxes, which have been introduced in several European countries, has been shown not to have the desirable results for either the environment or efficiency (Elkins & Speck, 1999). The issue therefore remains high on the agenda of policymakers and international bodies (see, e.g., OECD, 2003, 2006 & 2010; United Nations Economic Commission for Europe, 2006 & 2007).

A comprehensive review of theory and evidence on the effects of environmental policy (OECD, 2006; see also Cebreiro-Gómez, 2006) describes a number of options for alleviating the impact of environmental taxes on

[1] See, for example, Elbers and Withagen (2003) for a discussion of these issues. A strong case against preferential treatment for the exporting sectors has been made by, among others, Rauscher (1994, 1997). Consistent with these fears, empirical work by Babool and Reed (2010) reports a negative relationship between net exports and environmental regulations in most manufacturing sectors in 10 OECD countries over the period 1987–2003. A survey of recent evidence on the impact of environmental regulations (Dechezlepretre & Sato, 2014) finds, on the whole, small negative effects on productivity and employment.

competitiveness, including the recycling of tax revenue to the industries affected through output subsidies.[2] It is this idea—which has been explored in the literature—that we shall explore further.[3]

Before turning to the specific issue at hand, that is, the effect of environmental policies on competitiveness, it may be helpful to discuss a related literature that examines the use of multiple instruments (including production subsidies) in the presence of environmental externalities. An earlier literature has examined the joint effect of emission taxes and abatement subsidies (e.g., Conrad, 1993; Kohn, 1990). Strand (1998) has analyzed the joint effect of emission taxes and various types of subsidies on employment in a perfectly competitive industry in the presence of unions. More recently, Fullerton and Wolverton (1999) have proposed combining output taxes and environmental subsidies in circumstances where polluting activities are difficult to tax, whereas Fullerton and Mohr (2003) have shown that the joint use of output taxes and input or abatement subsidies can increase welfare more than the use of just one of these instruments. More generally, Bennear and Stavins (2007) have argued that under a fairly broad set of circumstances the use of multiple policy instruments is optimal in a second-best world.

Returning to the main issue at hand, Bovenberg, Goulder, and Gurney (2005) analyze the efficiency cost of a scheme whereby tradable emission permits are given free to firms affected by environmental taxes on the basis of their historical presence in the industry. They use a model with two competitive vertically related pollution-generating industries. Bovenberg, Goulder, and Jacobson (2008) extend this framework to alternative environmental policy instruments other than emission taxes. A number of recent papers analyze the welfare effects of "tax refunding schemes," that is, the partial or total recycling of environmental taxes to the firms affected on the basis of market shares, a policy that has been applied to nitrogen oxide emissions in Sweden (Sterner & Hoglund-Isaksson, 2006). Thus, Gersbach and Requate (2004) analyze conditions under which an optimal degree of refunding can be defined in a Cournot oligopoly. Bernard, Fischer, and Fox (2007) examine the welfare implications of output-based tax refunds in a model with two perfectly competitive sectors, one of which is unregulated. Fischer (2003) analyzes the effect of different forms of output-based tax refunds on the incentive to abate in a Cournot duopoly.

Several of these previous studies examine various aspects of policies that combine environmental taxes with some form of output subsidies in order to "compensate" the firms for their abatement efforts. However, the specific schemes do not target competitiveness of the firms explicitly. Furthermore, only a handful of the papers consider an oligopolistic framework, and even those papers do not address the question of competitiveness in an international context.[4]

In the present paper, we contribute to the existing literature in a number of ways. First, it is to be noted that although politicians use the word competitiveness pervasively, it is not clear what exactly they mean by it. In terms of specifics, the word competitiveness can have a number of different meanings. In this paper, we consider two alternative definitions: competitiveness as reflected on (i) market shares of domestic firms in the international market place, and (ii) the levels of profits of domestic firms. Second, we consider an international context with oligopolistic competition between firms, with all the firms within a country being identical, while heterogeneity exists between domestic and foreign firms. In this context we examine the effect of environmental and other policies on the *relative* competitiveness of the domestic firms *vis-à-vis* the foreign firms. Third, we allow for cross-border pollution so that there are two channels for international externalities of policies: via market shares and via cross-border pollution. Fourth, we derive results both for the case of a unilateral reform, where a policy is implemented by one country only, and for the case of multilateral reform. Fifth, we examine the effect of the proposed reforms on government tax revenue. Sixth, while our basic model assumes free entry and exit of firms in both countries, we check the robustness of our results for the case of a fixed number of firms. It is for this case that we can apply and compare the two alternative definitions of competitiveness described

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[2] A related but different issue is the so-called "double-dividend hypothesis" of environmental taxes (see, e.g., de Mooij, 1999, for a survey of an extensive literature), according to which environmental tax revenues can be recycled to reduce other taxes that create distortions such as income taxes.

[3] Since output subsidy is actionable under current World Trade Organization (WTO) rules, these schemes would require coordination between the WTO and the international agencies responsible for coordinating environmental policies. It is to be noted that discussions have been taking place in WTO for including environmental policies among its remits.

[4] Following the seminal papers by Spencer and Brander (1983) and Brander and Spencer (1985), there is also an extensive literature on the strategic use of subsidies to increase international market shares. However, this literature does not specifically address the links between trade and environmental policy. Lapan and Sikdar (2017) examine the impact of trade on environmental policy but do not discuss the question of competitiveness. On the other hand, Gautier (2017) analyzes environmental policy options for countries aiming to attract foreign investment, which may be seen as a policy aim linked to competitiveness.

above—definition (ii) cannot be applied in the case of free entry and exit of firms because profits are then always equal to zero. Finally, we do not examine optimality of policies; rather, we analyze the environmental and welfare implications of particular schemes for piecemeal unilateral or multilateral reform of environmental taxes and output subsidies that leave the market shares or profits of the two sets of firms unchanged.[5] The choice to focus on piecemeal reform can be justified on empirical grounds: most multilateral policy initiatives such as successive GATT/WTO rounds for trade policy reforms, or the Kyoto and Paris protocols for environmental policy reforms, involved small incremental moves toward an ideal world. Because of this, there is a now a large theoretical literature on piecemeal reforms of policies.[6] We carry out our analysis by developing a general two-country model of an oligopolistic industry serving an integrated market, where the firms make their output and emission decisions simultaneously. We show that the schemes we propose unambiguously reduce the level of pollution, and we also derive conditions under which they increase welfare in both countries.

2 | THE MODEL

There are two countries, a and b, with n^a and n^b firms, respectively. In this section we describe the basic structure of our model taking n^a and n^b as given. In Section 3 we shall consider policy reforms under free entry and exit of firms, so that n^a and n^b are endogenous. Then, in the following section we shall examine the effects of reforms when n^a and n^b are fixed. All firms within a country produce a homogeneous product, but there is product differentiation across countries.[7] Inverse demand functions in the two countries are given, respectively, by

$$p^a = f^a\left(x_1^a + \cdots + x_{n^a}^a, x_1^b + \cdots + x_{n^b}^b\right), \tag{1}$$

$$p^b = f^b\left(x_1^a + \cdots + x_{n^a}^a, x_1^b + \cdots + x_{n^b}^b\right), \tag{2}$$

where x_i^j is the output of firm i in country j. The profit functions are given by

$$\pi_i^j = p^j x_i^j - c_i^j\left(x_i^j, e_i^j\right) - t^j e_i^j + s^j x_i^j - F_i^j,\ j = a, b;\ i = 1, \ldots, n^j, \tag{3}$$

where $c_i^j(x_i^j, e_i^j)$ is the total cost of firm i in country j, e_i^j the level of emissions of firm i in country j, t^j the per unit emission tax in country j, s^j the per unit output subsidy in country j, and F_i^j the fixed cost of production for firm i in country$j$. Total cost is the sum of production and abatement costs.[8]

All firms simultaneously choose a level of output and a level of emissions. In particular, firm i in country a chooses a level of output to maximize its profit treating the output of other firms as given. This yields the following first-order condition:

$$\frac{\partial \pi_i^a}{\partial x_i^a} = f_1^a x_i^a + f^a - c_{i1}^a + s^a = 0, \quad i = 1, \ldots, n^a, \tag{4}$$

while firm i in country b chooses a level of output treating all other outputs as given according to the first-order condition

$$\frac{\partial \pi_i^b}{\partial x_i^b} = f_2^b x_i^b + f^b - c_{i1}^b + s^b = 0, \quad i = 1, \ldots, n^b, \tag{5}$$

[5] Lahiri and Symeonidis (2007) examined the effects of multilateral reforms of environmental taxes without any considerations for competitiveness. For alternative approaches to multilateral reform of environmental taxes, see Michael, Lahiri, and Hatzipanayotou (2015) and d'Autume, Schubert, and Withagen (2016).

[6] See footnote 3 in Michael et al. (2015) for some of the papers in this literature.

[7] The consideration of differentiated products will enable us to consider the case of free entry and exit of firms in both countries in a meaningful way (see also footnote 9).

[8] The absolute value of the partial derivative of this cost function with respect to the second argument is the marginal cost of abatement.

where f_k^j and c_{ik}^j are the partial derivatives of f^j and c_i^j, respectively, with respect to the kth argument, $j = a, b$ and $k = 1, 2$.

In addition, firm i in country j chooses a level of emissions according to

$$\frac{\partial \pi_i^j}{\partial e_i^j} = -c_{i2}^j - t^j = 0,\ j = a, b; \quad i = 1, \ldots, n^j. \tag{6}$$

In deriving the above condition, we assumed away the possibility of corner solutions.

To ensure tractability of our model we will assume symmetry within each country. Assuming that all firms within each country have similar technology is not unrealistic if one thinks of this technology as being determined partly in response to country-specific past policies. Suppressing the firm-specific subscripts, Equations 4–6 can be rewritten as

$$f_1^a(n^a x^a, n^b x^b)x^a + f^a(n^a x^a, n^b x^b) - c_1^a(x^a, e^a) + s^a = 0, \tag{7}$$

$$f_2^b(n^a x^a, n^b x^b)x^b + f^b(n^a x^a, n^b x^b) - c_1^b(x^b, e^b) + s^b = 0, \tag{8}$$

$$-c_2^j(x^j, e^j) - t^j = 0, \quad j = a, b. \tag{9}$$

These four equations implicitly determine the equilibrium values of x^a, x^b, e^a, and e^b. We make the following assumptions:

Assumption 1. *(i)* $c_1^j > 0$, $c_2^j < 0$, *(ii)* $c_{11}^j > 0$, $c_{22}^j > 0$, $c_{11}^j c_{22}^j - \left(c_{12}^j\right)^2 > 0$, *(iii)* $c_{12}^j < 0$ *(*$j = a, b$*)*, *(iv)* $f_i^j < 0$, $(i = 1, 2;\ j = a, b)$, *(v)* $Y^j f_{ik}^j(Y^a, Y^b) + f_l^j(Y^a, Y^b) < 0$ *for any* $j = a, b;\ i, k, l = 1, 2$.

The first part of the assumption states that the cost functions are increasing in output and decreasing in emission levels, the second part that they are convex, and the third that output and emission are complements in the sense that an increase in emission reduces the marginal cost of production. The fourth part says that demand functions are downward-sloping. The fifth part, which is a very common assumption in the theory of Cournot oligopolistic behavior (see, e.g., Dixit, 1986; Farrell & Shapiro, 1990; Shapiro, 1989), has a number of implications. First, it implies strategic substitutability and it is always true whenever $X^j f_{ik}^j(Y^a, Y^b) + f_l^j(Y^a, Y^b) < 0$ for any $0 \le X^j \le Y^j$. It also implies all the properties required by the different propositions of the paper. It is to be noted that Amir (1996, Theorems 2.1 and 2.3) has proven the existence and uniqueness of equilibrium under weaker conditions than ours.

Having described the basic framework of our model, we shall now consider the implications of unilateral or multilateral policy reforms under two scenarios: (i) there is free entry and exit of firms in both countries (Section 3), and (ii) the numbers of firms in both countries are fixed (Section 4).

3 | POLICY REFORM UNDER FREE ENTRY AND EXIT OF FIRMS

In this section we shall assume that there is free entry and exit of firms in both countries so that n^a and n^b are both endogenous.[9] The sequential structure we have in mind is as follows. First, the government(s) set(s) policies. Then the number of firms is determined. Finally, all firms simultaneously make output and emission decisions.

Free entry and exit implies that profits of each firm in both countries are always zero. That is, assuming symmetry within each group of firms, from (3) we write

$$\pi^j = p^j x^j - c^j(x^j, e^j) - t^j e^j + s^j x^j - F^j = 0, \quad j = a, b. \tag{10}$$

[9] We are able to determine both n^a and n^b endogenously because we consider a differentiated oligopoly. If the goods produced by the two countries were perfect substitutes, under free entry and exit one group of firms (the less efficient ones) would disappear.

Note that the zero profit condition implies that the only definition of competitiveness we can use in this section is the one that relates to market shares of firms.

Differentiating (10) and using (7), (8), and (9), we obtain

$$f_1^a x^a dx^a = f_1^a x^a d(n^a x^a) + x^a f_2^a d(n^b x^b) - e^a dt^a + x^a ds^a, \tag{11}$$

$$f_2^b x^b dx^b = f_1^b x^b d(n^a x^a) + x^b f_2^b d(n^b x^b) - e^b dt^b + x^b ds^b. \tag{12}$$

From (11) and (12) we see that, for given levels of demands ($n^a x^a$ and $n^b x^b$), an increase in emission tax t^i, or a decrease in production subsidy s^i, surprisingly increases the output level x^i $(i = a, b)$. This happens because of free entry and exit of firms. An increase in t^i, or a decrease in s^i, reduces the profit of each firm inducing exit of firms and thus increasing the output of each of the firms that remain. This process goes on until a new zero profit equilibrium is achieved.

Totally differentiating (9), we get

$$c_{22}^a de^a = -dt^a - c_{21}^a dx^a, \tag{13}$$

$$c_{22}^b de^b = -dt^b - c_{21}^b dx^b. \tag{14}$$

An increase in tax in a country reduces emissions by firms in that country, for a given level of output, and an increase in output increases emissions.

Totally differentiating (7) and (8) and then substituting (7), (8), (9), (11), and (12) into the expressions derived, we obtain

$$\left[2f_1^a + x^a f_{11}^a - \frac{\Delta^a}{c_{22}^a}\right] d(n^a x^a) + \left[f_2^a + x^a f_{12}^a - \frac{\Delta^a f_2^a}{c_{22}^a f_1^a}\right] d(n^b x^b) = \left[-2 + \frac{\Delta^a}{f_1^a c_{22}^a}\right] ds^a + \left[-\frac{c_{12}^a}{c_{22}^a} - \frac{\Delta^a e^a}{c_{22}^a x^a f_1^a} + \frac{e^a}{x^a}\right] dt^a, \tag{15}$$

$$\left[f_1^b + x^b f_{21}^b - \frac{\Delta^b f_1^b}{c_{22}^b f_2^b}\right] d(n^a x^a) + \left[2f_2^b + x^b f_{22}^b - \frac{\Delta^b}{c_{22}^b}\right] d(n^b x^b) = \left[-2 + \frac{\Delta^b}{f_2^b c_{22}^b}\right] ds^b + \left[-\frac{c_{12}^b}{c_{22}^b} - \frac{\Delta^b e^b}{c_{22}^b x^b f_2^b} + \frac{e^b}{x^b}\right] dt^b, \tag{16}$$

where $\Delta^a = c_{11}^a c_{22}^a - \left(c_{12}^a\right)^2 > 0$ and $\Delta^b = c_{11}^b c_{22}^b - \left(c_{12}^b\right)^2 > 0$.

Having derived the basic equations, we shall now consider a unilateral or multilateral reform and examine its effect on the level of pollution, tax revenue, and welfare. We propose a reform involving changes in tax rates dt^j and in subsidies ds^j $(j = a, b)$ such that

$$\left[-2 + \frac{\Delta^a}{f_1^a c_{22}^a}\right] ds^a = -\left[-\frac{c_{12}^a}{c_{22}^a} - \frac{\Delta^a e^a}{c_{22}^a x^a f_1^a} + \frac{e^a}{x^a}\right] dt^a, \tag{17}$$

$$\left[-2 + \frac{\Delta^b}{f_2^b c_{22}^b}\right] ds^b = -\left[-\frac{c_{12}^b}{c_{22}^b} - \frac{\Delta^b e^b}{c_{22}^b x^b f_2^b} + \frac{e^b}{x^b}\right] dt^b. \tag{18}$$

This includes the case where one of the countries, say country a, sets $dt^a = ds^a = 0$. Given Assumption 1, it should be clear that in the above reform an increase in t^j should be accompanied by an increase in s^j $(j = a, b)$. Note that we are considering a small change in the tax and subsidy rates, starting from the initial equilibrium, and the informational requirements for the implementation of the reforms (17) and (18) are that each country knows the values of outputs, emissions and so on at the initial equilibrium, and also that the countries know the functional forms of the demand and cost functions in their own countries.

From (15) to (18) it follows that this reform will leave the equilibrium values of $n^j x^j$ ($j = a, b$) unchanged. That is, the reform will leave the market shares of the two countries, and the prices of the two goods, unaffected. Using this, from (11) and (12) we obtain

$$f_1^a x^a dx^a = -e^a dt^a + x^a ds^a, \; f_2^b x^b dx^b = -e^b dt^b + x^b ds^b. \tag{19}$$

Substituting (17) and (18) in (19), we get

$$f_1^a x^a \left[2 - \frac{\Delta^a}{f_1^a c_{22}^a}\right] dx^a = -\frac{c_{22}^a e^a + c_{21}^a x^a}{c_{22}^a} \cdot dt^a, \tag{20}$$

$$f_2^b x^b \left[2 - \frac{\Delta^b}{f_2^b c_{22}^b}\right] dx^b = -\frac{c_{22}^b e^b + c_{21}^b x^b}{c_{22}^b} dt^b. \tag{21}$$

Because $d(n^j x^j) = 0$, the effect on the number of firms will be just the opposite sign of that on the output levels.

Although our proposed reform (17) and (18) leaves total outputs in each country unchanged, it does affect the output level of each firm and the number of firms in each country. Our reform has two components: an increase in emission tax and a corresponding increase in production subsidy. The former reduces the output of each firm, but the latter raises it. The effect of the reform on the output of each firm is therefore in general ambiguous, as can be seen from (20) and (21). However, if the cost functions are homogeneous of degree $k > 1$, then using Euler's theorem and (6), we can write $c_{22}^i e^i + c_{21}^i x^i = (k-1)c_2^i = -(k-1)t^i < 0$ ($i = a, b$). Therefore, an increase in emission tax (with a corresponding increase in output subsidy as per the reform) in a country will reduce the output of each firm, and increase the number of firms, in that country. Importantly, with our reform there will be no fiscal externality across the countries, that is, emission tax and production subsidy increases in one country will not affect output, emissions, or the number of firms in the other country. This follows from (13), (14), (20), and (21). The absence of international fiscal externality is a result of a key property of our reform, namely, that the reform in one country does not affect aggregate outputs in the two countries and therefore the inverse demand facing each firm in the other country is not affected either.

Since the effect of the reform on the output of each firm is in general ambiguous, it follows from (13) and (14) that the effect on emissions by each firm will also be ambiguous. However, if the cost functions are homogeneous of degree greater than unity, then the reform will unambiguously reduce emissions by each firm because output is also reduced, as shown above. These results are formally stated in the following lemma.

Lemma 1. *Under free entry and exit of firms, a piecemeal reform of policies such that $dt^j > 0$ and $ds^j > 0$ ($j = a, b$) satisfying* (17) *and* (18), *has the following effects:*

- *The policy reform in one country does not affect each firm's level of output and emission, and the number of firms, in the other country.*
- *The effect of the reform in one country on each firm's level of output and emission, and the number of firms, in the same country is in general ambiguous. However, if the cost functions are homogeneous of degree greater than unity, each firm's output and emission in the same country unambiguously decrease, and the number of firms increases.*

We now turn our attention to the effect of the reform on aggregate emission levels. Because $d(n^j x^j) = 0$, we have

$$d(n^j e^j) = n^j de^j + e^j dn^j = n^j de^j - \frac{n^j e^j}{x^j} \cdot dx^j.$$

Substituting (13), (14), (11), (12), (17), and (18) in the above equation, we get

$$\frac{2 - \Delta^a / \left(f_1^a c_{22}^a\right)}{n^a} \cdot \frac{d(n^a e^a)}{dt^a} = -\frac{2 - \Delta^a / \left(f_1^a c_{22}^a\right)}{c_{22}^a} + \frac{1}{f_1^a} \cdot \left(\frac{c_{21}^a}{c_{22}^a} + \frac{e^a}{x^a}\right)^2 < 0, \tag{22}$$

$$\frac{2-\Delta^b/\left(f_2^b c_{22}^b\right)}{n^b}\cdot\frac{d(n^b e^b)}{dt^b}=-\frac{2-\Delta^b/\left(f_2^b c_{22}^b\right)}{c_{22}^a}+\frac{1}{f_2^b}\cdot\left(\frac{c_{21}^b}{c_{22}^b}+\frac{e^b}{x^b}\right)^2<0, \tag{23}$$

and tax in one country will have no effect on total emissions by firms in the other country.

That is, a unilateral reform in country a, say, satisfying $dt^a>0,\ ds^a>0$ and (17) unambiguously reduces total emissions by firms in country a, and has no effect on total emissions by firms in country b. A multilateral reform satisfying $dt^a>0, ds^a>0, dt^b>0, ds^b>0$, and (17) and (18) will unambiguously reduce aggregate emissions in both countries. Intuitively, emission taxes reduce pollution, while output subsidies increase it, and the net effect is negative for our specific reform rule, which is designed to keep the market shares of the two countries unaffected. These results are formally stated in the following proposition.

Proposition 1. *Under free entry and exit of firms, the effect of our proposed reform on emissions will be as follows:*

- *A unilateral piecemeal reform in one of the countries, say country a , satisfying $dt^a>0, ds^a>0$ and (17) will unambiguously reduce total emissions by firms in that country, and will have no effect on total emissions by firms in the other country.*
- *A multilateral piecemeal reform satisfying $dt^a>0, ds^a>0, dt^b>0, ds^b>0$, and (17) and (18) will unambiguously reduce aggregate emissions in both countries.*

Turning to welfare, because profits are zero and prices do not change, it has two components: tax revenue and disutility from pollution. That is, $W^j=t^jn^je^j-s^jn^jx^j-\phi^j(n^je^j+\rho^jn^ke^k)$, where ϕ^j denotes the disutility from pollution and ρ^j is the spillover parameter describing the extent of cross-border pollution into country j from country k ($j=a,b;\ k\neq j=a,b$). We assume $\phi^{j\prime}>0$, that is, the disutility from pollution is increasing in the level of pollution. Totally differentiating this expression for welfare, and using (17), (18), and the fact that $d(n^jx^j)=0$, we find

$$dW^j=t^jd(n^je^j)+(n^je^j)dt^j-(n^jx^j)ds^j-\phi^{j\prime}d(n^je^j)-\rho^j\phi^{j\prime}d(n^ke^k),$$

and thus

$$dW^a=t^a\cdot\frac{\partial(n^ae^a)}{\partial t^a}dt^a+\frac{n^a}{2-\Delta^a/\left(c_{22}^af_1^a\right)}\cdot\left(e^a+\frac{x^ac_{12}^a}{c_{22}^a}\right)dt^a-\phi^{a\prime}\cdot\frac{\partial(n^ae^a)}{\partial t^a}dt^a-\rho^a\phi^{a\prime}\cdot\frac{\partial(n^be^b)}{\partial t^b}dt^b, \tag{24}$$

$$dW^b=t^b\cdot\frac{\partial(n^be^b)}{\partial t^b}dt^b+\frac{n^b}{2-\Delta^b/\left(c_{22}^bf_2^b\right)}\cdot\left(e^b+\frac{x^bc_{12}^b}{c_{22}^b}\right)dt^b-\phi^{b\prime}\cdot\frac{\partial(n^be^b)}{\partial t^b}dt^b-\rho^b\phi^{b\prime}\cdot\frac{\partial(n^ae^a)}{\partial t^a}dt^a. \tag{25}$$

The first two terms on the right-hand sides of (24) and (25) are the changes in tax revenue and the last two terms are the changes in the disutility from pollution in the two countries. Because pollution levels go down with our reform, the last two terms are positive (or one of them is zero, in the case of unilateral reform), and the first terms negative. The middle terms are in general ambiguous, but if the cost functions are homogeneous of degree $k>1$, from the discussion after (21) we know that these terms are negative, so tariff revenue unambiguously falls. Another situation where tariff revenue unambiguously falls is when the cost functions take the form $c^j(x^j,e^j)=\tilde{c}^j(x^j)+(\theta^jx^j-e^j)^2/2$, which represents the case of end-of-the-pipe type of abatement. It is then easy to verify that $e^j+x^ac_{12}^j/c_{22}^j=-(\theta^jx^j-e^j)<0,\ j=a,b$, that is, tariff revenue decreases. In other words, the reform will increase welfare if the marginal disutilities from pollution are sufficiently high.

When the reform is unilateral and only takes place in country a, we get from (24) and (25)

$$dW^a=t^a\cdot\frac{\partial(n^ae^a)}{\partial t^a}dt^a+\frac{n^a}{2-\Delta^a/\left(c_{22}^af_1^a\right)}\cdot\left(e^a+\frac{x^ac_{12}^a}{c_{22}^a}\right)dt^a-\phi^{a\prime}\cdot\frac{\partial(n^ae^a)}{\partial t^a}dt^a,\qquad dW^b=-\rho^b\phi^{b\prime}\cdot\frac{\partial(n^ae^a)}{\partial t^a}dt^a.$$

In this case, country b unambiguously benefits from the reform, but country a benefits if the marginal disutility from pollution in that country is sufficiently high. Therefore, we have the following proposition:

Proposition 2. *Under free entry and exit of firms, a multilateral piecemeal reform of emission taxes and output subsidies designed to leave the market shares of countries unchanged according to* (17) *and* (18) *will increase welfare in both countries provided the marginal disutilities from pollution are sufficiently high. A unilateral policy reform according to* (17) *will increase welfare in the country implementing the policy if the marginal disutility from pollution is sufficiently high in that country, and will always increase welfare in the other country.*

We also show in the appendix that in the special case of linear demand and end-of-the-pipe type of abatement, the change in tax revenue is negligible when $t^j \simeq 0$. It follows that, if the initial tax rate is $t^j \simeq 0$, the welfare of the country or countries implementing the reform will *always* rise.

4 | THE CASE OF FIXED NUMBER OF FIRMS

In this section we shall assume that both n^a and n^b are exogenously given and therefore Equations 10 do not apply. Totally differentiating (7) and (8) and using (13) and (14) we obtain

$$\pi^a_{11} dx^a + \pi^a_{12} dx^b = \gamma^a dt^a - ds^a, \tag{26}$$

$$\pi^b_{21} dx^a + \pi^b_{22} dx^b = \gamma^b dt^b - ds^b, \tag{27}$$

where
$$\pi^a_{11} = n^a x^a f^a_{11} + (n^a+1) f^a_1 - \Delta^a / c^a_{22} < 0, \qquad \pi^b_{22} = n^b x^b f^b_{22} + (n^b+1) f^b_2 - \Delta^b / c^b_{22} < 0,$$
$$\pi^a_{12} = n^b \left(x^a f^a_{12} + f^a_2 \right) < 0, \qquad \pi^b_{21} = n^a \left(x^b f^b_{21} + f^b_1 \right) < 0, \qquad \gamma^a = -c^a_{12} / c^a_{22} > 0,$$
$$\gamma^b = -c^b_{12} / c^b_{22} > 0, \qquad \Delta^a = c^a_{11} c^a_{22} - \left(c^a_{12} \right)^2 > 0, \qquad \Delta^b = c^b_{11} c^b_{22} - \left(c^b_{12} \right)^2 > 0,$$

because of Assumption 1.

The parameters γ^a and γ^b can be called the pollution intensity of technology in countries a and b, respectively. Note that γ^j gives the marginal emission of production for a given level of marginal cost of abatement.[10]

Solving (26) and (27) simultaneously for dx^a and dx^b, we obtain

$$\Delta\, dx^a = \pi^b_{22} (\gamma^a\, dt^a - ds^a) - \pi^a_{12} (\gamma^b\, dt^b - ds^b), \tag{28}$$

$$\Delta\, dx^b = \pi^a_{11} (\gamma^b\, dt^b - ds^b) - \pi^b_{21} (\gamma^a\, dt^a - ds^a), \tag{29}$$

where $\Delta = \pi^a_{11} \pi^b_{22} - \pi^a_{12} \pi^b_{21} > 0$.

As one would expect, an increase in emission tax (production subsidy) in a country reduces (increases) the output of the firms in that country and increases (reduces) those in the other country.

This completes the preliminary analysis of our model for the case of fixed numbers of firms, and we shall now consider two alternative definitions of competitiveness and examine the implications of unilateral and multilateral environmental policy reforms. These are taken up in turn in the following two subsections.

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[10] $dc^j_2 = c^j_{21} dx^j + c^j_{22} de^j$. Thus, $\gamma^j = (de^j / dx^j)|_{dc^j_2 = 0}$. For the special case of end-of-the-pipe type of abatement, the cost function can be written as $c^j = \tilde{c}^j(x^j) + \xi(\theta^j x^j - e^j)$, where the first part is the production cost function and the second part is the abatement cost function, θ^j being the gross pollution rate. It can be verified that for this cost function $\gamma^j = \theta^j$.

4.1 | Competitiveness as market share

In this subsection we shall consider a unilateral or multilateral reform which will reduce emissions and increase welfare but keep the international market shares of all firms unchanged. If ds^j is chosen such that

$$ds^j = \gamma^j \, dt^j, \tag{30}$$

it follows from (28) and (29) that $dx^a = dx^b = 0$. That is, under the rule (30), the output levels will not change—a result that holds in the case of reform by one country only (so that $ds = dt = 0$ in the other country) or by both countries. However, the important difference under the reform is that the level of emissions in country j will be lower if $dt^j > 0$. To be specific, the change in emissions is obtained from (13) and (14) after setting $dx^a = dx^b = 0$. Since $c^j_{22} > 0$, emissions in country j will decrease if $dt^j > 0$.

We shall now examine under what conditions a higher welfare level can be achieved by an increase in emission tax and a simultaneous introduction (or increase) of output subsidy such that (30) holds. First, note that since output levels will not change, prices and the consumers' surplus in each country will not be affected by the policy. As for profits, using (7)–(9), it is easy to check that the change in the profit of each firm is given by

$$d\pi^j = -e^j dt^j + x^j ds^j, \qquad j = a, b, \tag{31}$$

which, using (30), becomes

$$d\pi^j = e^j \left[-1 + \frac{x^j \gamma^j}{e^j} \right] dt^j.$$

Because $\gamma^j = (de^j/dx^j)|_{dc^j_2=0}$ (see footnote 10), the above expression can be rewritten as

$$d\pi^j = e^j \left[-1 + \epsilon^j \right] dt^j, \tag{32}$$

where $\epsilon^j = (x^j/e_j)(de^j/dx^j)|_{dc^j_2=0}$ is the emission elasticity of production along the iso-marginal abatement cost curve. Clearly, our reform scheme (with $dt^j > 0$) given in (30) will increase profits if and only if $\epsilon^j > 1$.

The net tax revenue of the government, T^j, can be obtained as

$$T^j = t^j n^j e^j - s^j n^j x^j. \tag{33}$$

Defining the level of welfare in a country as the sum of profits, consumers' surplus and net tax revenue, minus the disutility from the pollution generated in that country or transmitted across the border from the other country, we can describe the welfare levels W^j as

$$W^j = n^j \pi^j + CS^j + T^j - \phi^j (n^j e^j + \rho n^k e^k), \qquad j = a, b; \; k \neq j. \tag{34}$$

As in the previous section, the function ϕ^j denotes the disutility of total pollution experienced by country j, and ρ is the spillover parameter describing the extent of cross-border pollution. We assume again $\phi^{j\prime} > 0$.

Totally differentiating (34), using (6), (13), (14), (30), (31), and (33), and setting $dCS^j = 0$, we obtain

$$dW^j = -n^j t^j dt^j / c^j_{22} + \phi^{j\prime} n^j dt^j / c^j_{22} + \phi^{j\prime} \rho n^k dt^k / c^k_{22}. \tag{35}$$

Equation 35 can be explained intuitively as follows. Because the policy reform of $dt^j > 0$ and $ds^j > 0$ satisfying (30) does not affect output levels, it has no effect on consumers' surplus. The sum of total profits and tax revenue is equal to the total revenue of the firms net of production and abatement costs. As the output levels do not change, the total revenue of the firms will not change either. But total costs will increase because of an increase in abatement levels needed to reduce emissions. This negative effect on welfare is given by the first term in (35). On the other hand, since the reform reduces emission levels, it reduces disutility from pollution and thus increases welfare. The second term reflects the positive effect on welfare via a decrease in domestic pollution, and the third term gives the positive effect on welfare via a reduction in cross-border pollution for the case where the reform is implemented by both countries.

From (35), it should be clear that if the initial levels of emission tax are low and/or the marginal utility of pollution reduction is high, it is possible to increase the tax rates in such a way that not only emissions are reduced, but also welfare increases in both countries. For instance, if, say, $dt^a = dt^b = dt > 0$, we find

$$dW^j > 0 \Longleftrightarrow t^j < \phi^{j\prime}\left[1 + \rho(n^k/n^j)\left(c^j_{22}/c^k_{22}\right)\right]. \tag{36}$$

That is, if condition (36) is satisfied, each country will be better off by an agreement to increase emission taxes by a common amount and at the same time provide output subsidies according to the formula (30). Since $t^j = -c^j_2$ (see (9)), a sufficient condition for the multilateral reform to increase welfare is that $-c^j_2 \leq \phi'$, that is, that the marginal private cost of abatement is smaller than the marginal social benefit of abatement. If the initial tax rates in the two countries are at the Pigouvian optimal levels, that is, $-c^j_2 = \phi'$, the reform scheme given in (30) will unambiguously increase welfare in both countries.

Alternatively, for the case of a unilateral policy, that is $dt^a > 0$ and $dt^b = 0$, we have

$$dW^a = -n^a t^a dt^a/c^a_{22} + \phi^{a\prime} n^a dt^a/c^a_{22}, \tag{37}$$

$$dW^b = \phi^{b\prime}\rho n^a dt^a/c^a_{22}. \tag{38}$$

In this case the country that is increasing the environmental tax and the output subsidy will have higher welfare if $t^j < \phi^{j\prime}$, while the other country will always be better off. Thus, if the initial tax rate of the country implementing the policy is lower than the marginal social benefit of abatement, a unilateral policy will increase welfare in the country implementing it.

We can summarize the above results as follows:

Proposition 3. *When the number of firms is fixed in the two countries, a unilateral or multilateral piecemeal reform of emission taxes and output subsidies designed to leave the market shares of countries unchanged under the rule* (30) *will have the following effects:*

- *It will unambiguously reduce pollution.*
- *It will increase welfare under certain conditions. In particular, under a multilateral policy welfare will increase if the initial levels of emission tax are low and/or the marginal utility of pollution reduction is high. With a unilateral policy, welfare will increase in the country implementing the policy if the initial tax rate is lower than the marginal social benefit of abatement and will always increase welfare in the other country.*

Finally, we examine the effect of the proposed policy reform on government tax revenue. This is difficult to examine for a general cost function, so we focus on the special case of end-of-the-pipe type of abatement, where the cost function can be written as $c^j = \tilde{c}^j(x^j) + \xi(\theta^j x^j - e^j)$, with θ^j being the gross pollution rate. It can be verified that for this cost function $\gamma^j = \theta^j$. We also assume the abatement cost to be quadratic, so that Equation 6 becomes $\theta^j x^j - e^j = t^j$, $j = a, b$. For simplicity, we shall only consider a unilateral reform in country a, that is, $dt^a > 0$, $ds^a > 0$, and $dt^b = ds^b = 0$. The change in net revenue is then given by

$$dT^a = n^a(t^a de^a + e^a dt^a) - n^a(s^a dx^a + x^a ds^a).$$

Setting $dx^a = 0$ and using (6), (30), and $\gamma^a = \theta^a$, we obtain $dT^a = -2n^a t^a dt^a$. Therefore, if the initial tax rate $t^a \simeq 0$, the policy reform will have negligible effect on tax revenue. However, if $t^a >> 0$, then the reform will reduce tax revenue.

4.2 | Competitiveness as profits

The scheme proposed in the previous subsection ensures that the firms' market shares remain unchanged, while emissions unambiguously decrease and welfare increases under certain (plausible) conditions, in both countries. A possible objection to this scheme is that it may cause firms' profits to either rise or fall (see (32)). A fall in profits may be seen as a loss of competitiveness under an alternative definition of the term unless firms receive lump-sum transfers from the government.[11] In this section, we consider unilateral and multilateral reforms of environmental policy that will leave firms' profits (rather than their market shares) constant.[12]

To keep the analysis short, we examine a special case of the model. In particular, the demand functions are assumed to be linear, while the cost functions are quadratic and take a specific form where abatement is of the end-of-the-pipe type and thus total costs can be separated into production and abatement costs. However, the intuition for our results can be applied to the general case, as we discuss below.

Once again there are two countries, a and b, with n^a and n^b firms, respectively. All firms within a country produce a homogeneous product, but there is product differentiation across countries. The inverse demand functions are given by

$$p^a = 1 - n^a x^a - \lambda n^b x^b \tag{39}$$

$$p^b = 1 - n^b x^b - \lambda n^a x^a, \qquad \lambda \in (0, 1], \tag{40}$$

where p^i and x^i are, respectively, the price and output of each firm of the good produced in country i, and λ is an inverse measure of the degree of product differentiation.

We now introduce policy interventions. Denoting emission tax and production subsidy imposed by country i by t^i and s^i, respectively, the profit of the firm in country i is given by

$$\pi^i = (p^i - c^i)x^i - \frac{(\theta^i x^i - e^i)^2}{2} - t^i e^i + s^i x^i, \qquad i = a, b, \tag{41}$$

where θ^i is the gross emission of pollution per unit of output before any abatement is carried out, and e^i is the net emission level. In the above formulation, it is assumed that the total abatement cost of the firm is $(\theta^i x^i - e^i)^2/2$. It should be noted that by assuming separability between production and abatement costs, we are effectively assuming abatement is of the end-of-the-pipe type.[13]

When the firms make their output and emission decisions simultaneously, the first-order profit-maximizing conditions for output and emission level for firm i are given, respectively, by

$$\frac{\partial \pi^i}{\partial x^i} = p^i - c^i - x^i - \theta^i(\theta^i x^i - e^i) + s^i = 0, \qquad i = a, b, \tag{42}$$

$$\frac{\partial \pi^i}{\partial e^i} = \theta^i x^i - e^i - t^i = 0, \qquad i = a, b. \tag{43}$$

Solving (42) and (43), substituting x^i and e^i into the profit function and simplifying, we obtain

$$\pi^i = (x^i)^2 + \frac{(t^i)^2}{2}, \tag{44}$$

[11] If the reform increases welfare levels, then it is potentially strictly Pareto-improving if lump-sum transfers are possible. However, in reality lump-sum transfers are difficult to implement.

[12] This particular reform is not meaningful under free entry and exit of firms because profits there do not exist.

[13] Important examples of end-of-pipe abatement include catalytic converters in cars, scrubbers on smokestacks, and various technologies for the treatment of industrial waste water and municipal solid waste. According to an OECD report (OECD, 1989), in 1987 around 80% of total investment in pollution control was being used for end-of-pipe technologies, although there is some evidence that this percentage has declined somewhat in several OECD countries during the 1990s.

and therefore

$$d\pi^i = 0 \quad \Rightarrow \quad 2x^i dx^i = -t^i dt^i, \qquad i = a, b. \tag{45}$$

Using (43) and (45) we get

$$de^i = \theta^i dx^i - dt^i = -\left[1 + \frac{\theta^i t^i}{2x^i}\right] dt^i.$$

It follows that

$$dt^i > 0 \quad \Longleftrightarrow \quad de^i < 0,$$

irrespective of whether the reform is unilateral or multilateral.

Next we analyze the effect of the proposed policy reform on government tax revenue for the current special case. For simplicity, we shall only consider a unilateral reform in country a, that is, $dt^a > 0$, $ds^a > 0$ and $dt^b = ds^b = 0$. Using (39), (40), (42), and (43), the closed-form solution for x^a is solved as

$$[(n^a + 1)(n^b + 1) - \lambda^2 n^a n^b)]x^a = (n^b + 1)(1 - c^a - \theta^a t^a \lambda + s^a) - \lambda n^b(1 - c^b - \theta^b t^b + s^b),$$

which gives

$$[(n^a + 1)(n^b + 1) - \lambda^2 n^a n^b)]dx^a = -(n^b + 1)(\theta^a dt^a - ds^a). \tag{46}$$

Taking the derivative of (33) in the present case and using (43), (45), and (46), we get

$$\frac{dT^a}{dt^a} = \frac{d(n^a(t^a e^a - s^a x^a))}{dt^a} = -\frac{t^a n^a[3 - n^a + 3n^b - (1 - \lambda^2)n^a n^b]}{2(n^b + 1)} + \frac{t^a n^a(s^a - \theta^a t^a)}{2x^a}.$$

From the above, it follows that if the initial tax rate $t^a \simeq 0$, the reform will have negligible effect on tax revenue. However, if $t^a >> 0$, then the reform can increase or reduce tax revenue.

The overall effect of environmental policy on welfare when profits are kept constant consists of three separate effects: on consumer surplus, net tax revenue, and emissions. Using (42), (43), (45), and (46), it can be shown that

$$(n^b + 1)dp^a = -n^a\{(n^b + 1) - \lambda^2 n^b\}dx^a.$$

Thus, using (45), it is seen that the reform will reduce p^a. It can also be shown that p^b will not change, and hence consumer surplus will unambiguously increase. The effect on net tax revenue, as shown above, is potentially ambiguous. However, because an increase in emission tax reduces emissions when profits are kept constant, welfare will increase provided δ^i is sufficiently large, that is, if consumers care sufficiently about reductions in emission levels.[14] Note that this result holds also for the general model used in the previous subsection. Note also that a high value of δ^i is a sufficient but not necessary condition for an increase in welfare; for instance, the higher the value of n^b relative to n^a and of s^a relative to $\theta^a t^a$, the greater the likelihood of a positive effect of the reform on net tax revenue and therefore on overall welfare.

We now collect the main results of this subsection in the following proposition.

Proposition 4. *When the number of firms is fixed in the two countries, and for a special case of the model featuring linear demand functions and quadratic cost functions where abatement is of the end-of-the-pipe type, a unilateral or multilateral piecemeal reform of emission taxes and output subsidies designed to keep the firms' profits in the two countries unchanged according to the rule* (45) *will have the following effects:*

[14] Note that Dechezlepretre and Sato (2014) found that the benefits of an environmental policy are likely to far outweigh the costs even in the absence of a compensating production subsidy.

- *It will unambiguously reduce pollution.*
- *It will increase welfare if consumers care sufficiently about reductions in pollution.*

5 | CONCLUSION

The perceived negative impact of environmental policies on domestic industrial competitiveness is often the reason why countries are reluctant to implement stringent environmental regulations. In this paper we have shown that if environmental regulations are accompanied by production subsidies in a particular way, then domestic industries will not be harmed in terms of their relative international competitiveness and at the same time pollution will be reduced and welfare could increase, in all countries.

More specifically, we have examined three different scenarios. We began with the case of free entry and exit of firms, using a fairly general model with general demand and cost functions. We established that in this case a unilateral or multilateral piecemeal policy reform designed to leave the market shares of countries unchanged will unambiguously reduce pollution. Furthermore, a multilateral policy will increase welfare in both countries provided the marginal disutilities from pollution are sufficiently high. A unilateral policy will increase welfare in the country implementing the policy if the marginal disutility from pollution is sufficiently high in that country, and will always increase welfare in the other country.

We then considered the case of an exogenously given fixed number of firms in each country. Again we showed that a unilateral or multilateral policy designed to leave the market shares of countries unchanged will unambiguously reduce pollution, and will increase welfare under certain conditions. Under a multilateral policy, welfare will increase if the initial levels of emission tax are low and/or the marginal utility of pollution reduction is high. With a unilateral policy, welfare will increase in the country implementing the policy if the initial tax rate is lower than the marginal social benefit of abatement, and will always increase in the other country.

Finally, while maintaining our assumption of a fixed number of firms in each country, we explored an alternative reform, designed to keep the profits (rather than the market shares) of the two countries unchanged. For a special case of our model we showed that such a unilateral or multilateral policy of emission taxes and output subsidies will unambiguously reduce pollution, and once again will increase welfare if consumers care sufficiently about reductions in pollution. The intuition for these results can be applied to the general model as well. All in all, we have described a number of environmental policy reforms such that their implementations are simple and do not involve any trade-off between environmental protection and industrial competitiveness.

APPENDIX

To provide additional results and intuition for the case of free entry and exit of firms, we consider here a special case of the model. In particular, we shall make all the simplifying assumptions on preferences and technologies made in Section 4.2. That is, Equations 39 and 40 will hold, and profits are given by

$$\pi^i = (p^i - c^i)x^i - \frac{(\theta^i x^i - e^i)^2}{2} - t^i e^i + s^i x^i - F^i, \quad i = a, b. \tag{A1}$$

The existence of fixed costs will not affect the first-order profit maximizing conditions so that Equations 42 and 43 will hold. Substituting these in (A1), we can write the free entry conditions as

$$\pi^i = \left(x^i\right)^2 + \frac{\left(t^i\right)^2}{2} - F^i = 0, \quad i = a, b, \tag{A2}$$

whence for $i = a, b$, we get

$$x^i = \sqrt{F^i - \frac{\left(t^i\right)^2}{2}}, \tag{A3}$$

$$e^i = \theta^i x^i - t^i = \theta^i \sqrt{F^i - \frac{(t^i)^2}{2}} - t^i, \tag{A4}$$

$$dx^i = -\frac{t^i}{2x^i} \cdot dt^i, \tag{A5}$$

$$de^i = \theta^i dx^i - dt^i = -\left[1 + \frac{\theta^i t^i}{2x^i}\right] dt^i. \tag{A6}$$

Substituting (39), (40), and (43) in (42) and then differentiating it and using (43) and (A5), we obtain

$$d(n^a x^a) + \lambda d(n^b x^b) = -\bar{\gamma}^a dt^a + ds^a, \tag{A7}$$

$$\lambda d(n^a x^a) + d(n^b x^b) = -\bar{\gamma}^b dt^b + ds^b, \tag{A8}$$

where

$$\bar{\gamma}^i = \frac{1}{2}\left(\frac{e^i}{x^i} + \theta^i\right), \quad i = a, b.$$

If we now consider a unilateral or multilateral policy reform ($dt^a > 0,\ dt^b \geq 0$) such that $\bar{\gamma}^i dt^i = ds^i$, it is clear from (A7) and (A8) that we shall have $d(n^i x^i) = 0$ for $i = a, b$. Thus, the reform will leave the market share of the two countries unchanged.

Turning to the effect of the reform on the level of pollution, because $n^i dx^i = -x^i dn^i$, using (43), (A5), and (A6), we find that

$$\frac{d(n^i e^i)}{dt^i} = -n^i - \frac{n^i (t^i)^2}{2 (x^i)^2} < 0, \quad i = a, b. \tag{A9}$$

That is, the reform will reduce pollution unambiguously.

Finally, because the reform does not change total outputs by the two sets of firms, the prices will not change and so the consumers' surplus will remain unchanged. Tax revenue T^i is given by $T^i = n^i t^i e^i - n^i s^i x^i$. Differentiating this expression for tax revenue and using the reform rule, (43), and (A9), we find

$$\frac{1}{n^i} \cdot \frac{dT^i}{dt^i} = -\frac{t^i}{2}\left[3 + \left(\frac{t^i}{x^i}\right)^2\right],$$

which is negative for $t^i > 0$, but is negligible when $t^i \simeq 0$.

Thus, we find that one component of welfare (tax revenue) goes down with the reform, another component goes up (since the disutility from pollution decreases), and the other components (consumers' and producers' surplus) remain unchanged. Clearly, the net effect will depend on the society's willingness to pay for lower pollution. If the initial tax rate $t^a \simeq 0$, the welfare of the country or countries implementing the reform will rise.

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