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The Role of Multiple Pollutants and Pollution Intensities in the Policy Reform of Taxes and Standards

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Abstract:
Countries with varying degrees of pollution intensities, facing increasing global competition and addressing emissions from multiple pollutants may undertake policy reforms inconsistent with cooperative outcomes, where global welfare is higher. Among others, this is because of the incentives to set laxer policy to be more cost competitive. A number of welfare-enhancing and emissions-reducing policy reforms consistent with the cooperative equilibrium, but also consistent with addressing concerns about global competitiveness are derived. The analysis indicates that the nature of multiple pollutants and asymmetries in pollution intensities are key in the design of policy reform and characterization of optimal policy. With complementarity and asymmetry in pollution intensities, laxer taxation and stricter standards are consistent with welfare gains. Laxer taxation arises with large asymmetry in pollution intensities regardless of whether pollutants are complements/substitutes. The policy reform of standards requires both complementarity and asymmetry in pollution intensities. Results are reversed if pollutants are substitutes.

Keywords: policy reform, multiple pollutants, emission tax, environmental standards, pollution intensity, heterogeneous abatement costs

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1 Introduction

Countries with varying degrees of pollution intensities, facing increasing global competition and addressing emissions from multiple pollutants may undertake policy reforms inconsistent with cooperative outcomes, where global welfare is likely higher. Among others, this is because of the incentives to set laxer policy to be more cost competitive. This paper derives policy reforms not only consistent with the cooperative equilibrium, but also aimed at addressing concerns about global competitiveness and damages from pollution. The analysis underlines the previously unexplored roles of multiple pollutants and asymmetry in pollution intensities.

The analysis of policy reform is timely and relevant.[1] For example, as part of the Paris COP21 agreement an important number of countries submitted independent nationally determined contributions (INDCs) along with policies, including market-based mechanisms and stricter environmental standards. The process by which the INDCs are implemented entails policy reforms within each country. Given that there is evidence to suggest that the Paris agreement is unlikely to yield the required reduction in greenhouse gases (e. g. Kahn 2016), the analysis of policy reform is relevant because countries will likely change policies as new agreements take place or as current ones evolve. Policy reforms are defined formally in Sections 4 and 5.

Concerns about losing competitiveness to foreign competition has been used as a justification to set laxer environmental policies.[2] The idea is that countries may set laxer standards and/or emission taxes to reduce costs and raise profits. In the presence of multiple pollutants, for example, a laxer policy may be set on one pollutant while a stricter policy is set on a second pollutant.[3] Thus, in setting different policies across pollutants countries engage in policy reforms to tackle issues with local and international repercussions.

The presence of multiple pollutants has implications for the design of environmental policy, the potential spillover effects on abatement across pollutants, and the creation of local, regional and international externalities (Endres 1986; Repetto 1987; von Ungern-sternberg 1987; Caplan and Silva 2005; Moslener and Requate 2007, 2009; Kuosmanen and Lankkanen 2011; Ambec and Coria 2013, 2015; Fullerton and Karney 2014). For instance, multiple pollutants may induce a reduction in one pollutant which in turn may result in an increase (not a

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decrease) in the abatement cost of a second pollutant, potentially increasing overall pollution. Specifically, the use of biomass to produce energy may reduce greenhouse gases but at the same time it may raise emissions of nitrogen oxides, and the use of scrubbers to capture sulfur dioxide may generate more carbon dioxide as a result of more energy use (Ambec and Coria 2013).[4]

Surprisingly, the literature of environmental policy under oligopoly has not explored, in a unified framework of analysis, the role of asymmetries in pollution intensities, multiple pollutants and strategic behavior in the design of policy reforms. This paper, therefore, develops a two-country, multipollutant model where firms behave à la Cournot to examine the effects of policy reform on global emissions and welfare. Each country sets two policies: an emission tax controls one pollutant, whereas an environmental standard, which is assumed to be binding, controls the second pollutant.[5] Firms across countries exhibit different pollution intensities. The analysis indicates *inter alia* that complementarity of pollutants (meaning that the reduction in one pollutant results in lower marginal abatement cost and thus lower pollution of the second pollutant) and large asymmetries in pollution intensities across countries play a crucial role in the design of policy reform consistent with lower global pollution and higher welfare.

The contribution of the present paper is at the intersection of three important lines of research in the literature. One line characterizes optimal environmental policies in the presence of interactions of multiple pollutants (e. g. Endres 1985, 1986; Caplan and Silva 2005; Moslener and Requate 2007, 2009; Ambec and Coria 2013, 2015; Fullerton and Karney 2014), but does not analyze multilateral/unilateral policy reforms, a key aspect in current environmental policy setting. In particular, Ambec and Coria (2013, 2015, and 2018) characterize optimal policy in a multi-country, multipollutant setting and show that there is an additional inefficiency in the presence of complementarity/substitutability between pollutants. Even though this inefficiency is in line with the analysis presented here, the chief contribution to Ambec and Coria's work is that I analyze, in an international context, multilateral/unilateral policy reforms consistent with optimal policy under cooperation and, at the same time, consistent with scenarios where countries address concerns about competitiveness and damages from pollution. In doing so I underline the role of complementarity/substitutability of pollutants and asymmetry in pollution intensities.

Fullerton and Karney (2014, 2018) present a general equilibrium model with many pollutants and characterize different policy schemes e. g. tax on one pollutant and permits on the other pollutant, or a tax on each pollutant. Their model does not capture profit-shifting effects which may arise in an international context, and issues of transboundary pollution are assumed away; these aspects are analyzed in the present paper. Even though they consider the case of a binding permit system (closest to the present model with a binding standard), the analysis of policy reform is not examined in their model. Moreover, although the analysis in Fullerton and Karney (2018) is complementary to the one here, the present model looks at aspects related to oligopolistic interdependence in policy setting (policy reform), which are key when comparing the non-cooperative and cooperative equilibrium. None of these works focus on aspects of policy reform in the presence of the interaction of multiple pollutants.[6]

A second line of research examines the impact of unilateral/multilateral policy reforms on emissions and welfare (e. g. Hoel 1991; Hatzipanayotou, Lahiri, and Michael 2005; Turunen-Red and Woodland 2004; Kayalica and Lahiri 2005; Lahiri and Symeonidis 2007, 2017; Gautier 2013, 2014, and 2017), but assumes away the possibility of interaction of multiple pollutants, a key aspect to consider to achieve a reduction in global emissions. For example, Kayalica and Lahiri (2005) consider the policy reform of standards in a two-country model, but assume away emission taxes and the possibility of complementarity/substitutability of pollutants. Lahiri and Symeonidis (2007) consider emission taxes and allow for asymmetries in abatement costs, but does not look at the welfare effects of policy reform, include standards or allow for the interaction of multiple pollutants. None of these papers allow for the interaction of multiple pollutants, where policy reform may need to be more aggressive to achieve cooperative outcomes if damages are sufficiently large and pollutants are complements. Additionally, the present paper develops a model which incorporates many of the features of this literature in a unified framework of analysis, which allows to derive some of the results in a more general setting.

A third important line of research is that of strategic environmental policy, which examines aspects of strategic behavior in the presence of multiple pollutants (e. g. Silva and Zhu 2009; Bhattacharya and Pal 2010; Ambec and Coria 2015) or a single pollutant (e. g. Ulph and Ulph 1996, 2007).[7] The contribution to this line of research is the study of the role of large asymmetries in pollution intensities, where lower taxation can control emissions but also achieve an outcome consistent with the cooperative equilibrium.

The overarching contribution of the analysis is that it points to the previously unexplored roles of multiple pollutants and asymmetry in pollution intensities by showing a number of policy reforms under which global emissions fall (Section 4) and welfare rises (Section 5) even as governments seek to reduce emission taxes by acting strategically. The analysis first characterizes optimal policy in the non-cooperative scenario vis-à-vis cooperation. It is shown that the non-cooperative standard exceeds that under cooperation if pollutants are complements and asymmetry in pollution intensities is present. This is because with complementarity in pollutants a stricter standard addresses aspects of damages from pollution and profit shifting. Additionally, the non-cooperative tax, regardless of whether pollutants are complements/substitutes, exceeds that under cooperation in the presence of large asymmetries in pollution intensities. The reason is that large asymmetries allow to control global emissions via lower taxation via the strategic behavior of firms. But it is also shown (Section 6.1) that the extent of the policy reform depends on whether pollutants are complements/substitutes. For instance, laxer taxation should be aggressive enough if pollutants are complements. This is because the presence of large asymmetries in pollution intensities and the resulting reduction in damages from transboundary pollution imply a larger non-cooperative tax and, therefore, a larger reduction in taxation to achieve the cooperative outcome.

These results are then combined to argue for policy reforms consisting of laxer/stricter policies consistent with the cooperative equilibrium, but also with addressing concerns about global competitiveness. For instance, if pollutants are complements, then laxer taxes and stricter standards can be welfare-enhancing. The reason is that reductions in damages arising from stricter standards are sufficiently large thus opening the possibility for lower taxation. Even when only a laxer tax is set welfare can increase; the driver here is the presence of large asymmetries in pollution intensities which allow to control global emissions via lower taxation. The implications for policy reform when pollutants are substitutes are discussed in Section 7, where I argue that results are reversed (the case for laxer standards and stricter taxes is made) if pollutants are substitutes. Results are relevant, particularly in the case where high/low polluting countries may have incentives to retract from environmental agreements/commitments.

The paper is structured as follows. Section 2 presents the model. Section 3 presents the comparative statics analysis, followed by Sections 4 and 5, which look at policy reform and the implications for global emissions and welfare. Section 6 delves into the role of complementarity/substitutability in the characterization of policy. Section 7 concludes.

2 The Model

Consider a home and foreign country. There is only one firm operating in each country; by assuming one firm in each country I can focus on the role of cross-country asymmetries in pollution intensities and interaction of multiple pollutants. Firms compete for the production of an imperfect substitute, which is exported to a third market.[8]

Demand faced by each firm is given by $P^k = P^k(q^h, q^f)$, where q^k denotes output in country $k = h, f$; and where (subscripts denote partial derivatives) $P^k_{q^k} < 0$, $2P^k_{q^k} + q^k P^k_{q^k q^k} < 0$, for $k = h, f$. Following Dixit (1986, p.110) and Lahiri and Symeonidis (2007) I shall assume $2P^h_{q^h} + q^h P^h_{q^h q^h} < P^h_{q^f} + q^h P^h_{q^h q^f} < 0$ and $2P^f_{q^f} + q^f P^f_{q^f q^f} < P^f_{q^h} + q^f P^f_{q^f q^h} < 0$ which help ensure stability in the output market.

I follow Requate (2006) and Ambec and Coria (2013) in the structure of the cost function for each firm operating in country $k = h, f$, where the cost function incorporates two pollutants $C^k = C(q^k, e^k_1, e^k_2)$, and where the subscript 1 in e^k_1 denotes the first pollutant and in e^k_2 the second pollutant. The function $C^k(\cdot)$ satisfies (subscripts e and q denote partial derivatives) $C^k_{q^k e^k_1} = C^k_{e^k_1 q^k} < 0$, $C^k_{q^k e^k_2} = C^k_{e^k_2 q^k} < 0$, $C^k_{q^k q^k} > 0$, $C^k_{e^k_l e^k_l} > 0$, $C^k_{e^k_l e^k_l} C^k_{q^k q^k} - C^k_{q^k e^k_l} C^k_{e^k_l q^k} > 0$, for pollutant $l = 1, 2$. Furthermore, following Ambec and Coria (2013) the degree of substitutability across pollutants is captured via marginal abatement costs and thus given by $-C^k_{e^k_1 e^k_2}$, where pollutants are complements (substitutes) if $-C^k_{e^k_1 e^k_2} > (<) 0$. That is, pollutants are complements (substitutes) if the reduction in one pollutant decreases (increases) marginal abatement costs of the other pollutant. It is noteworthy that there are two abatement technologies (one for each pollutant in each country) through which each firm's output level and emissions are affected. For instance, the home (foreign) country firm's output, $q^h (q^f)$, can be affected via changes in abatement costs in the second pollutant, $e^h_2 (e^f_2)$, and first pollutant, $e^h_1 (e^f_1)$. The intuition for this is provided in Section 3.

Definition 2.1.
Pollutants are complements (substitutes) if $-C^k_{e^k_1 e^k_2} > (<) 0$ *for* $k = h, f$.

Each firm faces two environmental policies, and each of these policies will target specifically one of the two pollutants. I shall assume that the tax targets the first pollutant and a standard the second pollutant. Specifically, the home-country firm faces a per unit emission tax, t^h, for the level of pollution, e^h_1, and analogously the foreign-country firm faces a tax, t^f, which targets e^f_1. Moreover, firms face an environmental standard as in Requate

(2006, p. 147): in the home (foreign) country the second pollutant is controlled via an environmental standard, $\bar{e}_2^h$ ($\bar{e}_2^f$), which is assumed to be binding. Firms do not have a say over the standard.

Assumption 2.2.

(i) In each country the tax targets the first pollutant and a binding standard the second pollutant. (ii) Pollution intensities are identical within countries.

The implications of Assumption 2.2 will be apparent in Section 3, but here I make three remarks. First, changes in output do not have an impact on the emissions coming from the second pollutant. This is because the second pollutant is determined by the standard, which is binding and set by the government, not the firm. Changes in output, however, have an impact on marginal abatement costs of the second pollutant ($C^k_{\bar{e}_2^k q^k} < 0$).[9] In contrast, changes in emissions of the second pollutant, and thus marginal abatement costs of the second pollutant, have an impact on emissions coming from the first pollutant via changes in marginal abatement costs of the first pollutant, ($C^k_{e_1^k q^k} < 0$), and therefore output ($C^k_{q^k \bar{e}_2^k} < 0$). That is, via the substitutability/complementarity of pollutants. Second, Assumption 2.2 implies that changes in the tax are only going to affect the first pollutant since the standard is binding and not chosen by firms.[10] In contrast, changes in the standard affect emissions both via changes in emissions coming from the second pollutant (e. g. laxer/stricter standard) and the first pollutant through changes in the marginal abatement cost function of the first pollutant. Third, Assumption 2.2(ii) implies the home country exhibits only one pollution intensity coefficient, while keeping intact the assumption that each pollutant exhibits different pollution abatement technologies.[11] Thus, Assumption 2.2(ii) allows to focus the analysis on the role of asymmetries in pollution intensities exclusively *across* countries, while allowing for the interaction of multiple pollutants. Pollution intensities as defined in Lahiri and Symeonidis (2007, p. 890) are given by $-C^h_{e_1^h q^h}/C^h_{e_1^h e_1^h} > 0$ for the home country and $-C^f_{e_1^f q^f}/C^f_{e_1^f e_1^f} > 0$ for the foreign country.[12] To illustrate some of the features of the model, the appendix works the case of an end-of-pipe cost function.

Events unfold as follows. Each country chooses the tax and standard simultaneously taking the other country's tax and standard as given. Firms then take policy as given and maximize profits by choosing the level of emissions and output simultaneously in a Cournot–Nash fashion. The assumption of simultaneous decision on output and emissions assumes away issues of the strategic choice of abatement; these have been analyzed elsewhere (e. g. Montero 2002a, 2002b; Carlsson 2000). I assume interior solutions throughout the analysis. Similar to Ambec and Coria (2013) interior solutions are assumed in order to account for the role of the interaction of the second and first pollutants, and aspects of economies (diseconomies) of scope associated with the multiple pollutants. The model is solved by backwards induction.

The home country's firm simultaneously chooses the level of output, q^h, and emissions, e_1^h, taking policy, the foreign firm's output, q^f, and emissions, e_1^f, as given. In particular, the home country's firm solves the following profit-maximization problem

$$\max_{q^h e_1^h} \pi^h = P^h q^h - C^h(q^h, e_1^h, \bar{e}_2^h) - e_1^h t^h \tag{1}$$

where $\bar{e}_2^h$ denotes the environmental standard which controls the second pollutant in the home country, and the tax, t^h, which controls the first pollutant, e_1^h. Maximization of eq. (1) yields the following first-order conditions (subscripts denote partial derivatives)

$$P^h + q^h P^h_{q^h} - C^h_{q^h} = 0 \tag{2}$$

$$-C^h_{e_1^h} - t^h = 0 \tag{3}$$

Analogously, the foreign country's firm profits are given by

$$\max_{q^f e_1^f} \pi^f = P^f q^f - C^f(q^f, e_1^f, \bar{e}_2^f) - e_1^f t^f \tag{4}$$

where $\bar{e}_2^f$ denotes the environmental standard which controls the second pollutant in the foreign country, and the tax, t^f, which controls the first pollutant, e_1^f. From eq. (4) first-order conditions are given by

$$P^f + q^f P^f_{q^f} - C^f_{q^f} = 0 \tag{5}$$

$$-C^f_{e_1^f} - t^f = 0 \tag{6}$$

Equations (2), (3), (5) and (6) implicitly determine the equilibrium level of output and emissions, q^h, q^f, e_1^h, e_1^f. For the stability of the global equilibrium I assume that the following conditions are satisfied (i) $\pi^h_{q^h q^h}\pi^f_{q^f q^f} - \pi^h_{q^h q^f}\pi^f_{q^f q^h} > 0$; and (ii) within each country $\pi^k_{q^k q^k}\pi^k_{e_1^k e_1^k} - \pi^k_{q^k e_1^k}\pi^k_{e_1^k q^k} > 0$.

3 Comparative Statics

Total differentiation of eqs. (2), (3), (5), (6) yields the comparative statics effects of the tax and standards (see Appendix for a derivation). The "bar" is dropped from $\bar{e}_2^h$ and $\bar{e}_2^f$ for notational simplicity.

3.1 Taxes

Since the effects of a tax are established in the literature (e. g. Lahiri and Symeonidis 2007) here I just provide an overview. An increase in the emission tax in one country renders the firm in that country relatively less cost competitive and, as a result, output in that country falls, but the firm in the other country reacts strategically by raising output. Global output, $q^h + q^f$, falls from a tax increase since by assumption the own effect dominates the cross effect. Moreover, an increase in the tax in the home country reduces output and thus emissions in that country, but raises output and emissions in the foreign country since the tax renders the home firm relatively less cost competitive. As a result, emissions, $e_1^h + e_1^f$, rise (fall) with a tax reduction in the foreign country if the foreign country exhibits a sufficiently large (small) pollution intensity. The notion and relevance of a relative (and sufficient) pollution-intensive country is defined formally later on. Taxes have an impact exclusively on the first pollutant which they aim to controlling (i. e. t^k controls e_1^k for $k = h, f$). This is due to Assumption 2.2, where taxes affect the first pollutants, e_1^h and e_1^f, but also because the second pollutant is subject to a binding standard and firms do not choose the level of pollution arising from the second pollutant.

3.2 Standards

The effect of the emission standard (which is binding) depends, among others, on whether the pollutants are complements or substitutes (Definition 2.1). I look at the case of the standard in the home country, e_2^h. Results are analogous to changes in the standard of the foreign country, e_2^f.

Using eqs. (21) and (22) gives

$$\frac{\mu}{C^h_{e_1^h e_1^h}C^f_{e_1^f e_1^f}}de_1^h = -\frac{C^h_{q^h e_1^h}}{C^h_{e_1^h e_1^h}}C^h_{e_1^h e_2^h}\left[\left(\frac{C^h_{q^h e_2^h}}{C^h_{e_1^h e_2^h}} - \frac{C^h_{q^h e_1^h}}{C^h_{e_1^h e_1^h}}\right)\left(-\pi^f_{q^f q^f}\right) + \mu/C^h_{q^h e_1^h}\right]de_2^h$$
$$-\frac{C^h_{q^h e_1^h}}{C^h_{e_1^h e_1^h}}C^f_{e_1^f e_2^f}\left(\frac{-C^f_{q^f e_2^f}}{C^f_{e_1^f e_2^f}} + \frac{C^f_{q^f e_1^f}}{C^f_{e_1^f e_1^f}}\right)\left(-\pi^f_{q^f q^h}\right)de_2^f \tag{7}$$

$$\frac{\mu}{C^h_{e_1^h e_1^h}C^f_{e_1^f e_1^f}}de_1^f = -\frac{C^f_{q^f e_1^f}}{C^f_{e_1^f e_1^f}}C^f_{e_1^f e_2^f}\left[\left(\frac{C^f_{q^f e_2^f}}{C^f_{e_1^f e_2^f}} - \frac{C^f_{q^f e_1^f}}{C^f_{e_1^f e_1^f}}\right)\left(-\pi^h_{q^h q^h}\right) + \mu/C^f_{q^f e_1^f}\right]de_2^f$$
$$-\frac{C^f_{q^f e_1^f}}{C^f_{e_1^f e_1^f}}C^h_{e_1^h e_2^h}\left(\frac{-C^h_{q^h e_2^h}}{C^h_{e_1^h e_2^h}} + \frac{C^h_{q^h e_1^h}}{C^h_{e_1^h e_1^h}}\right)\left(-\pi^h_{q^h q^f}\right)de_2^h \tag{8}$$

where $\mu < 0$, $-C^k_{e_1^k q^k}/C^k_{e_1^k e_1^k} > 0$, $C^k_{q^k e_l^k} < 0$, and $\pi^h_{q^h q^h} < 0$, $\pi^h_{q^h q^f} < 0$ denote second-order derivatives from the profit function in the home country (analogous results apply to the profit function in the foreign country).[13] The key term is $C^k_{e_1^k e_2^k}$, since it captures the degree of substitutability or complementarity of pollutants. In line with the literature (e. g. Kayalica and Lahiri 2005) if the degree of substitutability/complementarity is very small (e. g. $C^h_{e_1^h e_2^h} \simeq 0$) the effects of the standard on output and emissions across pollutants become negligible and, therefore, only the standard can achieve reductions in the second pollutant.

Now suppose pollutants are complements (i. e. $C^h_{e^h_1 e^h_2} < 0$). A stricter standard in the home country (i. e. reduction in e^h_2) reduces emissions e^h_2, but it also raises marginal abatement costs of that pollutant, thereby lowering output, q^h, and thus emissions of the first pollutant, e^h_1; this is captured by the first term in parenthesis, $C^h_{q^h e^h_2} < 0$, in the first line of eq. (7). Now, since pollutants are complements, a stricter standard for the second pollutant, e^h_2, results in a reduction in the marginal abatement cost of the first pollutant (the marginal abatement cost curve of the first pollutant, e^h_1, shifts down) resulting in a reduction in output and emissions, e^h_1; this is captured by the second term in parenthesis, $-C^h_{e^h_1 e^h_2} C^h_{q^h e^h_1} / C^h_{e^h_1 e^h_1} < 0$, in the first line of eq. (7). Because e^h_1 is controlled via an emission tax, a decrease in marginal abatement costs (while the tax remains unchanged) of the first pollutant results in a reduction in output (and thus emissions, e^h_1) up to the point where the tax equals marginal abatement costs. The decrease in marginal abatement costs of the first pollutant raises abatement for that pollutant, thereby reducing emissions, e^h_1; this is captured by the term $\mu / C^h_{q^h e^h_1}$ in the second line of eq. (7). Therefore, in the case where pollutants are complements output, q^h, and emissions from the first and second pollutant, e^h_1 and e^h_2, respectively, fall as a result of a stricter standard imposed specifically on the second pollutant. Since the standard, e^h_2, reduces output by the home-country firm, the foreign-country firm reacts strategically by raising output, q^f, and thus emissions, e^f_1, rise. These results are consistent with the literature (e. g. Bhattacharya and Pal 2010).

However, if pollutants are substitutes (i. e. $C^h_{e^h_1 e^h_2} > 0$), there are two opposing effects. On one hand, a stricter standard on e^h_2 still raises marginal costs for that pollutant and thus output, q^h, falls. On the other, however, a stricter standard raises marginal abatement costs of the first pollutant, e^h_1, thereby raising output, q^h, and emissions, e^h_1: because the first pollutant faces an emission tax, t^h, output rises in order to emit at the level where the tax is equal to marginal costs of the first pollutant. As marginal abatement costs of the first pollutant rise, abatement for that pollutant falls which results in an increase in emissions, e^h_1. If the degree of substitutability across pollutants is large (i. e. first terms in parenthesis in the first line of eq. (7), $C^h_{e^h_1 e^h_2} C^h_{q^h e^h_1} / C^h_{e^h_1 e^h_1} > -C^h_{q^h e^h_2}$), then emissions, e^h_1, rise as a result of a stricter standard, e^h_2. As the home-country firm raises output the foreign-country firm reacts by lowering output and thus emissions in the foreign country fall. Alternatively, if the degree of substitutability is small then output, q^h, and emissions, e^h_1, fall with a stricter standard imposed specifically on the second pollutant. In this case, the foreign firm reacts strategically by raising output, q^f, and therefore emissions in the foreign country, e^f_1, i. e. second line in eq. (8).

The implications of the aforementioned results are analyzed in subsequent sections.

4 Global Emissions and Policy Reform

Policy reforms impact global emissions via two channels: (i) asymmetry in pollution intensities across countries, and (ii) differences in the degree of substitutability/complementarity in pollutants. A policy reform refers to stricter and/or laxer taxes/standards set by either country or both countries. The analysis of policy reform shows the extent to which laxer/stricter taxes/standards yield reductions/increases in global emissions. The welfare effects of these policies are analyzed in Section 5. In Sections 4.1 and 4.2 I look at policy reforms of taxes and standards, respectively. In Section 4.3 the combined reform of standards and taxes is examined. I focus on cases where the second pollutant is tackled via stricter standard (e. g. international commitment) while the first pollutant sees a laxer tax e. g. due to concerns about cost competitiveness. The analysis rests on the expression in eq. (9) below, which captures changes in global emissions resulting from changes in standards, along with the expression in eq. (10) below, which gives the change in total emissions with respect to the tax.

Define global emissions, E, as the sum of emissions coming from the home country, $E^h = e^h_2 + e^h_1$, and the foreign country, $E^f = e^f_2 + e^f_1$.[14,15] Thus, using eqs. (7) and (8) the change in global emissions, $dE = de^h_1 + de^h_2 +$

$de_1^f + de_2^f$, arising from changes in the standards e_2^h and e_2^f, is given by

$$
\begin{aligned}
\frac{\mu}{C^h_{e_1^h e_1^h} C^f_{e_1^f e_1^f}} dE = & \Bigg[C^h_{e_1^h e_2^h} \left(\frac{C^h_{q^h e_2^h}}{C^h_{e_1^h e_2^h}} - \frac{C^h_{q^h e_1^h}}{C^h_{e_1^h e_1^h}} \right) \left[\frac{-C^h_{q^h e_1^h}}{C^h_{e_1^h e_1^h}} \left(-\pi^f_{q^f q^f} \right) - \frac{C^f_{q^f e_1^f}}{C^f_{e_1^f e_1^f}} \left(\pi^f_{q^f q^h} \right) \right] \\
& - \frac{C^h_{q^h e_1^h}}{C^h_{e_1^h e_1^h}} C^h_{e_1^h e_2^h} \frac{\mu}{C^h_{q^h e_1^h}} + \frac{\mu}{C^h_{e_1^h e_1^h} C^f_{e_1^f e_1^f}} \Bigg] de_2^h \\
& + \Bigg[C^f_{e_1^f e_2^f} \left(\frac{C^f_{q^f e_2^f}}{C^f_{e_1^f e_2^f}} - \frac{C^f_{q^f e_1^f}}{C^f_{e_1^f e_1^f}} \right) \left[\frac{-C^f_{q^f e_1^f}}{C^f_{e_1^f e_1^f}} \left(-\pi^h_{q^h q^h} \right) - \frac{C^h_{q^h e_1^h}}{C^h_{e_1^h e_1^h}} \left(\pi^h_{q^h q^f} \right) \right] \\
& - \frac{C^f_{q^f e_1^f}}{C^f_{e_1^f e_1^f}} C^f_{e_1^f e_2^f} \frac{\mu}{C^f_{q^f e_1^f}} + \frac{\mu}{C^h_{e_1^h e_1^h} C^f_{e_1^f e_1^f}} \Bigg] de_2^f
\end{aligned}
\tag{9}
$$

where variable definitions are as before. The first two lines in eq. (9) capture the change in global emissions resulting from a change in the standard in the home country. The first term in squared brackets captures changes in global emissions arising from changes in home and foreign output; the second term, $-\mu C^h_{q^h e_1^h} C^h_{e_1^h e_2^h} / C^h_{e_1^h e_1^h} C^h_{q^h e_1^h}$, captures changes in abatement resulting from an increase/decrease in the marginal abatement cost curve of the pollutant, e_1^h and the last term, $\mu / C^h_{e_1^h e_1^h} C^f_{e_1^f e_1^f}$, captures the direct reduction in global emissions via reductions in e_2^h as a result of a stricter standard. Analogous terms show in the last two lines of eq. (9) as a result of a change in the standard in the foreign country.

Furthermore, using eqs. (24) and (25), and keeping in mind Assumption 2.2 the effect of the tax on global emissions is given by

$$
\begin{aligned}
\frac{\mu}{C^h_{e_1^h e_1^h} C^f_{e_1^f e_1^f}} dE = & \frac{-C^h_{q^h e_1^h}}{C^h_{e_1^h e_1^h}} \left[\frac{-C^h_{q^h e_1^h}}{C^h_{e_1^h e_1^h}} \left(-\pi^f_{q^f q^f} \right) - \frac{C^f_{q^f e_1^f}}{C^f_{e_1^f e_1^f}} \left(\pi^f_{q^f q^h} \right) + \mu / C^h_{q^h e_1^h} \right] dt^h \\
& \frac{-C^f_{q^f e_1^f}}{C^f_{e_1^f e_1^f}} \left[\frac{-C^f_{q^f e_1^f}}{C^f_{e_1^f e_1^f}} \left(-\pi^h_{q^h q^h} \right) - \frac{C^h_{q^h e_1^h}}{C^h_{e_1^h e_1^h}} \left(\pi^h_{q^h q^f} \right) + \mu / C^f_{q^f e_1^f} \right] dt^f
\end{aligned}
\tag{10}
$$

where the term $\mu / C^k_{q^k e^k} > 0$ denotes the abatement induced by the tax in country $k = h, f$, and the rest of the terms capture changes in emissions via changes in output.

4.1 Taxes

As a first case if pollution intensities are equal then global emissions in eq. (10) fall with an increase in the tax in either country (or both countries) regardless of whether pollutants are complements or substitutes. This is because of Assumption 2.2 where taxes do not have an impact on the second pollutant because the second pollutant is set by a binding standard and it is not chosen by firms.

Next, suppose countries differ in their pollution intensities (i. e. $-C^h_{e_1^h q^h} / C^h_{e_1^h e_1^h} \neq -C^f_{e_1^f q^f} / C^f_{e_1^f e_1^f}$). One application here is to industry/countries which differ greatly in terms of their pollution intensities. The following remark will prove useful in subsequent analyses.

Remark 4.1.

Consider a decrease in the emission tax in the home country. Then, global emissions fall if the foreign country exhibits a sufficiently large pollution intensity coefficient i. e. $C^h_{e_1^h q^h} / C^h_{e_1^h e_1^h} \pi^h_{q^h q^h} + \mu / C^h_{q^h e_1^h} < C^f_{e_1^f q^f} / C^f_{e_1^f e_1^f} \pi^f_{q^f q^h}$.

A key implication of Remark 4.1 is that it points to the role of pollution intensities. The driver for this result is the presence of asymmetries in pollution intensities (not the presence of multiple pollutants), where global emissions fall with laxer taxation through the strategic interaction of firms. This result is in line with Gautier (2017) where linear demand is assumed.

4.2 Standards

As a benchmark consider the case where there is no interaction of pollutants (i. e. $C^k_{e^k_1 e^k_2} \simeq 0, k = h, f$) and pollution intensities are symmetric across countries (i. e. $-C^h_{e^h_1 q^h}/C^h_{e^h_1 e^h_1} = -C^f_{e^f_1 q^f}/C^f_{e^f_1 e^f_1}$). This case can be thought of as one where countries are not too different in their pollution intensities (e. g. a subset of EU countries). Then, eq. (9) indicates that global emissions fall (rise) exclusively through a stricter (laxer) standard in either country. However, with symmetry in pollution intensities, but $C^k_{e^k_1 e^k_2} \neq 0$, eq. (9) suggests that stricter (laxer) standards lower global emissions if pollutants are complements (substitutes). This is because with identical pollution intensities the reduction in emissions via the standard offsets any increase in output (and thus emissions) via the strategic behavior of firms in the output market. This points to the role of multiple pollutants, but also suggests that policy setting can be flexible (in the case of similar pollution intensities across countries) depending upon the nature of the interaction of pollutants.

Consider the policy reform of standards when pollution intensities differ across countries. As an initial case consider a stricter standard in the foreign country i. e. $de^f_2 < 0$. Using eq. (9) yields that global emissions fall (rise) if (i) the foreign country is more pollution intensive (i. e. $-C^h_{e^h_1 q^h}/C^h_{e^h_1 e^h_1} < -C^f_{e^f_1 q^f}/C^f_{e^f_1 e^f_1}$), and (ii) pollutants are complements (highly substitutes). Highly substitute pollutants refers to pollutants with a high degree of substitutability in the sense that the emissions-increasing effect that takes place via the interaction of pollutants within a country is sufficiently large so that global emissions rise. This is because complementarity (high degree of substitutability) ensures a reduction (increase) in emissions in the pollution intensive foreign country to offset higher (lower) pollution in the home country i. e. $\partial E/\partial e^f_2 > (<) 0$.

Remark 4.2.
Consider a stricter standard in the foreign country. Then, global emissions fall (rise) if (i) the foreign country is relatively more pollution intensive and (ii) pollutants are complements (highly substitutes).

4.3 Taxes and Standards

Suppose the foreign country is more pollution intensive (i. e. $-C^h_{e^h_1 q^h}/C^h_{e^h_1 e^h_1} < -C^f_{e^f_1 q^f}/C^f_{e^f_1 e^f_1}$), but consider a policy reform consisting of a stricter standard in the foreign country, $de^f_2 < 0$, and at the same time a lower tax in that country, $dt^f < 0$. This policy reform intends to capture the case where a country acts strategically by setting a lower tax on the first pollutant even as it tackles a second pollutant via a stringent standard. On the one hand, global emissions rise via the tax reduction because the foreign country is pollution intensive and output in that country rises as a result of the lower tax, t^f, but on the other a stricter standard, e^f_2, lowers global emissions if pollutants are complements or the degree of substitutability is small. If the policy reform is proportional[16] in the sense that $de^f_2/e^f_2 = dt^f/t^f$, then eqs. (9) and (10) suggest that global emissions fall if complementarity in the foreign country is sufficiently large (i. e. $1 + C^f_{e^f_1 e^f_2} < 0$). In this case, the reduction in global emissions takes place because the reduction in emissions from a stricter standard is sufficiently large. But this result also points to the possibility of increased emissions by the foreign country resulting from strategic environmental policy (i. e. tax reduction), particularly if the degree of substitutability between pollutants in the foreign country is large. Thus, policy prescriptions should account for the nature of pollutants, particularly in the presence of strategic behavior.

In particular, eqs. (9) and (10) under policy reform $\alpha = de^f_2 = dt^f$ simplify to[17]

$$\frac{\mu}{C^h_{e^h_1 e^h_1} C^f_{e^f_1 e^f_1}} dE = \Bigg[\left(-\frac{C^f_{q^f e^f_1}}{C^f_{e^f_1 e^f_1}} - C^f_{e^f_1 e^f_2} \frac{C^f_{q^f e^f_1}}{C^f_{e^f_1 e^f_1}} + C^f_{q^f e^f_2} \right) \left(\frac{-C^f_{q^f e^f_1}}{C^f_{e^f_1 e^f_1}} \left(-\pi^h_{q^h q^h} \right) - \frac{C^h_{q^h e^h_1}}{C^h_{e^h_1 e^h_1}} \left(\pi^h_{q^h q^f} \right) \right) + \mu \left(-1/C^f_{e^f_1 e^f_1} - C^f_{e^f_1 e^f_2}/C^f_{e^f_1 e^f_1} + 1/C^f_{e^f_1 e^f_1} C^h_{e^h_1 e^h_1} \right) \Bigg] \alpha \tag{11}$$

where $dE > 0$, if $-C^h_{e^h_1 q^h}/C^h_{e^h_1 e^h_1} < -C^f_{e^f_1 q^f}/C^f_{e^f_1 e^f_1}$ and $1 + C^f_{e^f_1 e^f_2} < 0$.

Proposition 4.3.
Let the foreign country be the pollution intensive country (i. e. $-C^h_{e^h_1 q^h}/C^h_{e^h_1 e^h_1} < -C^f_{e^f_1 q^f}/C^f_{e^f_1 e^f_1}$). If the foreign country sets a stricter standard (i. e. $de^f_2 < 0$) and a lower emission tax (i. e. $dt^f < 0$) non-proportionally (proportionally), then

global emissions fall if pollutants in the foreign country are complements (respectively, sufficiently complements i. e. $C^f_{e^f_1 e^f_2} + 1 < 0$).

5 Welfare and Policy Reform

I follow Ulph and Ulph (2007) in the set-up of the welfare function where consumer surplus effects are assumed away to facilitate comparisons with the literature and focus on issues of strategic environmental policy, as it pertains to profit-shifting effects, and transboundary pollution. The strategy here is to compare the non-cooperative and cooperative policy vector (Sections 5.1 and 5.2) and by doing so substantiate the analysis of policy reform in previous sections. I derive conditions under which the non-cooperative tax exceeds the cooperative tax in, say, the home country and, as a result, the case for policy reforms consistent with lower taxation. That is, policy reforms consistent with addressing concerns about competitiveness and at the same time the cooperative equilibrium. A similar analysis for the standard is presented.

Define welfare in the home country as follows:

$$W^h = \pi^h + e^h_1 t^h - \varphi^h(E) \tag{12}$$

where φ^h denotes damages from pollution in the home country, which is assumed to be increasing and strictly convex. Since the function $\varphi^h(\cdot)$ depends on global emissions, damage from pollution in the home country captures effects via local and transboundary pollution. An analogous expression applies to W^f, the welfare function of the foreign country. The reason for assuming $\varphi^h(\cdot)$ as a function of E is to capture damages to the home country coming from pollutants originating in the foreign country as well as the home country. The implication here is that marginal damages to the home country do not differ too much across pollutants regardless of the country of origin. This simplifying assumption is made to focus the analysis specifically on the role of complementarity/substitutability of pollutants and not on potential differences coming from marginal damages.

Assumption 5.1.
Marginal damages to each country are identical throughout pollutants regardless of the country of origin.

5.1 Non-Cooperative Equilibrium

The home and foreign country simultaneously choose the emission tax and standard taking the other country's policies as given. This yields a non-cooperative policy vector $t^{h*}, t^{f*}, e^{h*}_2, e^{f*}_2$. I shall assume interior solutions in order to account for the role of the interaction of pollutants.[18] In particular, first-order conditions for the home country are given by

$$\frac{\partial W^h}{\partial t^h} = \frac{\partial \pi^h}{\partial t^h} + e^h_1 + t^h \frac{\partial e^h_1}{\partial t^h} - \varphi^{h\prime} \frac{\partial E}{\partial t^h} = 0 \tag{13}$$

$$\frac{\partial W^h}{\partial e^h_2} = \frac{\partial \pi^h}{\partial e^h_2} + t^h \frac{\partial e^h_1}{\partial e^h_2} - \varphi^{h\prime} \frac{\partial E}{\partial e^h_2} = 0 \tag{14}$$

where an analogous set of equations applies to the foreign country. The role of substitutability/complementarity of pollutants in the characterization of policy is examined in Section 6.

5.2 Cooperative Equilibrium

In this section I derive conditions under which the non-cooperative tax (standard) exceeds the cooperative tax (standard). The conditions for a relatively large non-cooperative tax in the home country rely on one key factor: large asymmetry in pollution intensities. This result, because of Assumption 2.2(i), does not depend on the nature of pollutants. A similar analysis for the standard indicates that the presence of complementarity/substitutability plus asymmetry in pollution intensities are key.

To see these results, define global welfare as $W = W^h + W^f$. Differentiation with respect to home-country policies yields (analogous expressions apply to foreign-country policy variables):

$$\frac{\partial W}{\partial t^h} = \left[\frac{\partial \pi^h}{\partial t^h} + e_1^h + t^h\frac{\partial e_1^h}{\partial t^h} - \varphi^{h\prime}\frac{\partial E}{\partial t^h}\right] + \left[\frac{\partial \pi^f}{\partial t^h} + t^f\frac{\partial e_1^f}{\partial t^h} - \varphi^{f\prime}\frac{\partial E}{\partial t^h}\right] \tag{15}$$

$$\frac{\partial W}{\partial e_2^h} = \left[\frac{\partial \pi^h}{\partial e_2^h} + t^h\frac{\partial e_1^h}{\partial e_2^h} - \varphi^{h\prime}\frac{\partial E}{\partial e_2^h}\right] + \left[q^f P^f_{q^h}\frac{\partial q^h}{\partial e_2^h} + t^f\frac{\partial e_1^f}{\partial e_2^h} - \varphi^{f\prime}\frac{\partial E}{\partial e_2^h}\right] \tag{16}$$

where $\partial\pi^f/\partial t^h > 0$, $\partial e_1^f/\partial t^h > 0$, $P^f_{q^h} < 0$ and where complementarity (substitutability) ensures $\partial q^h/\partial e_2^h > (<)0$, $\partial e_1^h/\partial e_2^h > (<)0$, $\partial e_1^f/\partial e_2^h < (>)0$. At the Nash equilibrium, the first terms in square brackets in eqs. (15) and (16) vanish.

Using eq. (15) and assuming strict concavity in the $W(\cdot)$ function, the non-cooperative tax in the home country exceeds the cooperative tax if the foreign country exhibits a sufficiently large pollution intensity (as defined in Remark 4.1) and damages from global emissions are large.[19] This is because with large foreign pollution intensity $\partial E/\partial t^h > 0$, thus indicating the need for lower taxation in order to control for damages from pollution. This result is relevant particularly with increasing damages from, say, climate change in the presence of country asymmetries in pollution intensities.

Proposition 5.2.

Regardless of whether pollutants are complements or substitutes the non-cooperative tax in the home country exceeds the cooperative tax in that country, if (i) the foreign country is sufficiently pollution intensive and (ii) damages from global emissions are large.

Analogously, applying Remark 4.2 in eq. (16) the non-cooperative standard in the home country exceeds (falls short of) the cooperative standard in that country if (i) pollutants are complements (highly substitutes) and (ii) the home country is relatively more pollution intensive, $-C^h_{q^h e_1^h}/C^h_{e_1^h e_1^h} > -C^f_{q^f e_1^f}/C^f_{e_1^f e_1^f}$. Under (i) and (ii) $\partial E/\partial e_2^h > (<)0$. This is because with complementarity (substitutability) a stricter (laxer) standard in the home country lowers damages and eliminates profit-shifting effects.

Proposition 5.3.

The non-cooperative standard in the home country exceeds the cooperative standard in that country, if (i) pollutants in that country are complements, (ii) the home country is relatively pollution intensive, and (iii) damages from global emissions are large.

5.3 Policy Reform

In this section I examine the effects of policy reform on welfare. The analysis can be thought of as efforts by countries to try and coordinate multilateral policy. As presented in the literature (e. g. Kayalica and Lahiri 2005; Hatzipanayotou, Lahiri, and Michael 2005; Gautier 2014) this type of analysis captures the inefficiencies of the non-cooperative equilibrium. The analysis therefore analyzes policy changes starting at the Nash equilibrium under conditions derived in the previous section.

The analysis indicates that the change in the standard in, say, the home country affects welfare in the foreign country via changes in output and emissions in the foreign country, but the extent of these effects depends on whether pollutants are complements or substitutes. This section points to welfare-enhancing policies consistent with (i) the cooperative equilibrium and (ii) cases where countries seek to become more cost competitive.

Differentiation of eq. (12) yields at the Nash equilibrium

$$\begin{aligned} dW^f|_{Nash} &= \left[q^f P^f_{q^h}\frac{\partial q^h}{\partial e_2^h} - C^f_{e_1^f}\frac{\partial e_1^f}{\partial e_2^h} - \varphi^{f\prime}\frac{\partial E}{\partial e_2^h}\right]de_2^h \\ &+ \left[q^f P^f_{q^h}\frac{\partial q^h}{\partial t^h} - C^f_{e_1^f}\frac{\partial e_1^f}{\partial t^h} - \varphi^{f\prime}\frac{\partial E}{\partial t^h}\right]dt^h \end{aligned} \tag{17}$$

where at the Nash equilibrium $\partial W^f/\partial t^f = 0$, $\partial W^f/\partial e_2^f = 0$, and

$$\varphi^f = \varphi^f(E) \Rightarrow d\varphi^f = \varphi^{f\prime}dE = \varphi^{f\prime}\left[\frac{\partial e_1^f}{\partial t^h} + \frac{\partial e_1^h}{\partial t^h}\right]dt^h + \varphi^{f\prime}\left[\frac{\partial e_1^f}{\partial e_2^h} + \frac{\partial e_1^h}{\partial e_2^h} + 1\right]de_2^h \tag{18}$$

In eq. (17) the terms $\varphi^{f\prime}\partial E/\partial e_2^h$ and $\varphi^{f\prime}\partial E/\partial t^h$ capture the cross effect of policy on changes in home emissions but also transboundary pollution. The terms $q^f P_{q^h}\partial q^h/\partial e_2^h$ and $q^f P^f_{q^h}\partial q^h/\partial t^h$ denote the effects on foreign's welfare arising from the strategic (profit-shifting) behavior of the government in the home country, and the terms $-C^f_{e_1^f}\partial e_1^f/\partial e_2^h$ and $-C^f_{e_1^f}\partial e_1^f/\partial t^h$ the effect from changes in marginal abatement costs of the first pollutant at foreign.

A decrease in the tax in the home country, $dt^h < 0$, *ceteris paribus*, raises output in the home country as the home country becomes more cost competitive, which in turn lowers welfare in the foreign country both via the profit-shifting effect (i. e. $q^f P^f_{q^h}\partial q^h/\partial t^h > 0$) and damages from transboundary pollution. Additionally, a lower tax, t^h, reduces emissions in the foreign country via the strategic interaction of firms in the output market, thereby raising welfare at foreign through a reduction in marginal damages from pollution, but at the same time raises abatement costs thus lowering welfare at foreign (i. e. $-C^f_{e_1^f}\partial e_1^f/\partial t^h > 0$). The welfare-enhancing conditions are summarized in the following proposition.

Proposition 5.4.

Starting at the Nash equilibrium a reduction in the tax in the home country raises welfare in the foreign country, if (i) the foreign country is sufficiently pollution intensive and (ii) the reduction in damages from pollution are sufficiently large.

Proposition 5.4 says that one country may benefit as a result of laxer environmental taxation on the first pollutant in the other country. This result arises crucially from the presence of large asymmetries in pollution intensities, which ensures that lower taxation controls global emissions via the strategic interaction of firms. This result is particularly relevant as damages from climate change become increasingly important.

Next, consider the policy reform of a stricter standard in the home country. If pollutants are complements in both countries (i. e. $C^k_{e_1^k e_2^k} < 0$), a stricter standard e_2^h has three effects on the foreign country's welfare. First, a stricter standard lowers output in the home country which results in higher output in the foreign country as a result of the strategic behavior of firms, thereby raising welfare in the foreign country (i. e. $q^f P^f_{q^h}\partial q^h/\partial e_2^h < 0$). Second, as output increases in the foreign country emissions in that country rise, thereby lowering abatement costs for the first pollutant for the foreign-country firm (i. e. $-C^f_{e_1^f}\partial e_1^f/\partial e_2^h < 0$), which raises welfare at foreign. Third, if a stricter standard is set by the home country and the home country is relatively more pollution intensive (i. e. $-C^h_{e_1^h q^h}/C^h_{e_1^h e_1^h} \geq -C^f_{e_1^f q^f}/C^f_{e_1^f e_1^f}$), then global emissions fall thereby raising welfare in the foreign country. This result points to the potential role of stricter standards to both tackle global emissions and raise welfare, as well as the role of complementarity of pollutants.

Proposition 5.5.

Starting at the Nash equilibrium a stricter standard in the home country raises welfare in the foreign country, if (i) pollutants are complements and (ii) the home country is relatively pollution intensive.

The impact on the foreign country's welfare from a policy reform of laxer taxation *and* stricter standards in the home country is summarized in Proposition 5.6.[20] This result points to the important case where welfare can increase even as a country sets a proportional laxer policy on the first pollutant and stricter policy on the second pollutant. It also points to the key role of complementarity in pollutants. The reason for this result is that the standard reduces damages sufficiently thereby allowing for a laxer tax. Proportionality can be thought of as a policy reform where a country seeks to address competitiveness and environmental issues via an increase in the stringency of the standard and, at the same time, a proportional reduction in the tax to compensate for the stricter standard.

Proposition 5.6.

Let the home country be relatively pollution intensive (i. e. $-C^h_{e_1^h q^h}/C^h_{e_1^h e_1^h} \geq -C^f_{e_1^f q^f}/C^f_{e_1^f e_1^f}$) and the degree of complementarity in pollutants in the home country is sufficiently large (i. e. $C^h_{e_1^h e_2^h} + 1 < 0$). Then, a reduction in taxes and a proportional stricter standard in the home country (i. e. $\alpha = dt^h = de_2^h$) raises welfare in the foreign country.

In contrast to the case where the tax is the only policy which is relaxed (Proposition 5.4), in Proposition 5.6 the home country is pollution intensive and therefore lower taxation does not control global emissions; hence the need for a large degree of complementarity in pollutants to ensure a large reduction in damages via the standard.

6 The Role of Substitutability/Complementarity on the Characterization of Policy

6.1 Taxation

Next, I look at the role of substitutability/complementarity in the characterization of the non-cooperative tax. To do this I use eqs. (13) and (14), and follow Ambec and Coria (2013) in the use of an end-of-pipe cost function.

Definition 6.1.
An end-of-pipe cost function is given by $C^k(q^k, e_1^k, e_2^k) = \tilde{c}^k q^k + (\delta^k q^k - e_1^k)^2/2 + (\delta^k q^k - e_2^k)^2/2 + \omega(\delta^k q^k - e_1^k)(\delta^k q^k - e_2^k)$.

where δ^k denotes a constant pollution intensity, ω captures substitutability and complementarity in pollutants, where $\omega \in (-1, 1)$ to satisfy the convexity of the cost function (see Appendix). Pollutants are complements (substitutes) if $\omega < (>) 0$. The cost function keeps intact the assumption of one pollution intensity per country. Properties of the cost function and expressions for the comparative statics under an end-of-pipe cost function as defined in Definition 6.1 and linear demand are given in the Appendix. Differentiation of eqs. (13) and (14) under Definition 6.1 and linearity of demand yields

$$
\begin{aligned}
-W^h_{t^h t^h}\left.\frac{dt^h}{d\omega}\right|_{\omega=0} &= -\beta\left(q^h\frac{\partial^2 q^f}{\partial t^h \partial\omega} + \frac{\partial q^f}{\partial t^h}\frac{\partial q^h}{\partial\omega}\right) + (t^h - \varphi^{h'})\frac{\partial^2 e_1^h}{\partial t^h \partial\omega} - \varphi^{h'}\frac{\partial^2 e_1^f}{\partial t^h \partial\omega} - \varphi^{h''}\frac{\partial E}{\partial t^h}\frac{\partial E}{\partial\omega} \\
&= \frac{\beta\delta^h}{\kappa}\left(q^h + \frac{\partial q^h}{\partial\omega}\right) + (t^h - \varphi^{h'})\frac{\left(2\beta + \delta^{f2}\right)2\delta^{h2}}{\kappa} + \varphi^{h'}\frac{2\delta^h\delta^f\beta}{\kappa} - \varphi^{h''}\frac{\partial E}{\partial t^h}\frac{\partial E}{\partial\omega} \\
&= L_{t^h} - \varphi^{h'}\frac{\left(2\beta + \delta^{f2}\right)2\delta^{h2} - 2\delta^h\delta^f\beta}{\kappa} - \varphi^{h''}\frac{\partial E}{\partial t^h}\frac{\partial E}{\partial\omega}
\end{aligned} \tag{19}
$$

where $W^h_{t^h t^h} < 0$ from the concavity of the welfare function, $W^h_{t^h e_2^h} = 0$ and $\kappa < 0$ is the determinant of the system in eqs. (26)–(29) in the Appendix. Equation (19) gives the adjustment in taxation arising from substitutability (i. e. $\omega > 0$) or complementarity (i. e. $\omega < 0$); it helps characterize taxation in the presence of substitutability/-complementarity vis-à-vis no interaction of pollutants. For example, starting at $\omega = 0$, where pollutants are independent from each other, a reduction in ω denotes the case where the tax adjusts given pollutants are complements. The terms in eq. (19) include L_{t^h}, where it captures profit-shifting effects and adjustment in the tax arising from changes in abatement costs of the second pollutant. The second and third terms capture aspects of damages and the role of asymmetry in pollution intensities.

A reduction in ω implies lower abatement costs and, as a result, home emissions fall. But lower costs also imply an increase in home output. Overall home emissions fall. By the same token foreign emissions and output fall and rise, respectively, which prompts home to react by lowering output via the oligopolistic interdependence. To avoid proliferation of cases I shall assume oligopolistic interdependence effects are small and, therefore, emissions and output in each country fall and rise, respectively, with a reduction in ω i. e. $\partial E/\partial\omega > 0$, $\partial q^k/\partial\omega < 0$.

With these in mind, starting at $\omega = 0$ a reduction in ω puts a downward pressure on the home tax since damages from home emissions fall. But because damages from transboundary pollution also fall, the need to tackle damages from transboundary pollution via lower taxation is less. If asymmetries in pollution intensities are large in the sense that the reduced damages from transboundary pollution are large (i. e. from second term, $2\delta^f\delta^h\beta > (2\beta + \delta^{f2})2\delta^2$), then the need to lower the tax is less. Also, by Remark 4.1$\partial E/\partial t^h > 0$ and so the third term in eq. (19) negative.[21] Moreover, from L_{t^h} with complements foreign output rises so home lowers the tax to offset profit shifting, and also complements imply lower costs of abatement. Overall, home taxation is larger in the presence of complementarity if foreign is sufficiently pollution intensive and the reduced damage from transboundary pollution is large. Results are reversed in the case where pollutants are substitutes i. e. starting at $\omega = 0$, ω increases.

Proposition 6.2.
In the presence of complementarity in pollutants the home non-cooperative tax is higher, if (i) the reduction in damages from transboundary pollution is sufficiently large, and (ii) the foreign country is sufficiently pollution intensive.

Connecting Proposition 6.2 and Proposition 5.4 implies that starting at an equilibrium where pollutants are complements would require a more aggressive policy reform with laxer taxation to achieve the cooperative outcome. This is because in this case (i) the gap between the cooperative and non-cooperative tax is larger, and (ii) lower taxation controls emissions due to the presence of large asymmetry in pollution intensities.

6.2 Standards

This subsection conducts a similar analysis for the standard. In particular,

$$\begin{aligned} -W^h_{e_2^h e_2^h} \frac{de_2^h}{d\omega}\bigg|_{\omega=0} &= \left(\beta \frac{\partial q^f}{\partial e_2^h}\frac{\partial q^h}{\partial e_2^h} + t^h \frac{\partial^2 e_1^h}{\partial e_2^h \partial\omega} - \frac{\partial C^h_{e_2^h}}{\partial \omega}\right) - \varphi^{h\prime} \frac{\partial^2 E}{\partial e_2^h \partial \omega} - \varphi^{h\prime\prime} \frac{\partial E}{\partial e_2^h}\frac{\partial E}{\partial \omega} \\ &= L_{e_2^h} - \varphi^{h\prime} \frac{\beta\delta^f\left(2\delta^f - \delta^h\right) + 3\beta^2}{\kappa} - \varphi^{h\prime\prime}\frac{\partial E}{\partial e_2^h}\frac{\partial E}{\partial \omega} \end{aligned} \tag{20}$$

where $W^h_{e_2^h e_2^h} < 0$, and $L_{e_2^h} < 0$ denotes the first three terms in parenthesis in the first line in eq. (20). As before, the case of complements (substitutes) is captured in eq. (20) via a reduction (increase) in ω, starting at $\omega = 0$, meaning that abatement costs fall (rise). And with complements (substitutes) emissions in each country fall (rise), and output in each country rises (falls).

The first term (negative), $L_{e_2^h}$, captures profit-shifting effects, where with complements foreign output rises and so a laxer standard offsets profit shifting; in the case of substitutes the need for laxer standard is less since foreign output falls. And the second and third terms capture adjustments in the standard from changes in abatement costs of the second pollutant. Overall, these effects are negative indicating a laxer (stricter) standard when complements (substitutes). The reason is that a stricter standard is set with lower abatement costs and a laxer standard with higher abatement costs, since in the former emissions are controlled at a lower cost and in the latter a laxer policy offsets the increased costs.

The last two terms in eq. (20) capture adjustments via changes in damages from pollution. If complements (i. e. decrease in ω) a laxer standard is obtained (i. e. $de_2^h/d\omega < 0$) if home is relatively pollution intensive i. e. $\delta^h > (\beta 2\delta^2 + 3\beta^2)/\beta\delta^f$. This is because with lower damages from home pollution resulting from the fact that pollutants are complements affords a laxer policy. Similarly, with substitutes (i. e. increase in ω) a laxer standard is obtained (i. e. $de_2^h/d\omega > 0$) if foreign is relatively pollution intensive (i. e. $\delta^f > \delta^h$) and damages from pollution are sufficiently large. This is because damages from transboundary pollution are large and so a laxer standard controls foreign emissions. The mechanism here is that a laxer standard at home lowers costs which encourages home output, but this results in lower foreign output and emissions from the first pollutant via the oligopolistic interdependence.

As before the implication is that, along with Proposition 5.5, under complementarity policy reform of a standard needs to be aggressive (i. e. requires very strict standard) if the cooperative outcome is to be achieved.

Proposition 6.3.
In the presence of complementarity in pollutants the home standard is laxer if (i) damages from home pollution are relatively large, and (ii) the home country is sufficiently pollution intensive.

7 Conclusion

The extent to which policy reform lowers emissions and raises welfare depends crucially upon the interaction of pollutants and differences between pollution intensities across countries. Outcomes consistent with the cooperative equilibrium can take place via policy reform, even as countries have incentives to deviate from pre-established policies i. e. environmental agreements. Although the analysis emphasizes the case of laxer taxation and stricter standards with complement pollutants, the case for stricter taxation and laxer standards can be made if pollutants are substitutes and the country undertaking policy reform is the pollution intensive country. In such a case non-cooperative policies fall short of their cooperative counterpart and, as a result, higher taxation and laxer standards are welfare enhancing and consistent with the cooperative outcomes. Although this policy reform contrasts with that of laxer taxation and stricter standards, the intuition is analogous: if the home country is the pollution intensive country and pollutants are substitutes, then laxer standards and stricter taxes lower global emissions thereby raising welfare as long as damages from global emissions are relevant. More broadly, such policy reform points to the possibility of achieving cooperative outcomes and at the same time addressing concerns about competitiveness via a laxer standard.

The general set-up of the model allows to generalize some of the results in the literature, where under oligopoly the interaction of pollutants has been assumed away. In the present model if $C_{e_1 e_2} = 0$, then results from this literature can be obtained. For closed-economy models under oligopoly, the present model would yield results from this literature assuming negligible cross-country interactions e. g. $\pi^h_{q^h q^f} = 0$. Moreover, results in the literature which depend on specific cost functions (e. g. end-of-pipe or linear demand as in Gautier (2013, 2014), and Lahiri and Symeonidis (2007)) can be regarded as special cases, particularly the analysis of policy reform of taxes. More specifically, Proposition 5.2 derives conditions under which the role of substitutability/complementarity does not play a role in the characterization of the non-cooperative tax vis-à-vis cooperation. The literature has certainly characterized the non-cooperative tax vis-à-vis cooperation, but has not given conditions under which substitutability/complementarity is relatively unimportant due to the presence of asymmetry in pollution intensities. This asymmetry captures the idea of "very polluting" vis-à-vis "clean" countries. Thus, results in the literature can be replicated by either assuming identical pollution intensities across countries or/and no complementarity/substitutability. This also applies to Proposition 5.5 which underscores the role of complements/substitutes plus pollution intensities in policy reforms potentially explored elsewhere in the literature e. g. stricter standards.

There are several extensions to the model. First, the model assumes that the interaction of pollutants via policy changes works in one direction: a change in the standard affects the second and first pollutant, but the same is not true via a change in the tax. This is because the standard is binding and the level of emissions controlled by the standard is not a choice variable for the firm, but rather it is determined by the government. Relaxing these assumptions would render the analysis richer: the analysis would include the choice of two pollutants by firms within each country and, in addition, the possibility that a change in the tax could affect the level of emissions associated to the standard. Alternatively, changing the order in which policy is set could yield interesting results and render the model more flexible as in Fullerton and Karney (2018). For example, suppose the tax is set first and then the standard. A change in the tax not only has an impact on emissions on pollutant one, but also the second pollutant (the pollutant covered by the standard), where as a result substitutability/-complementarity would play a role even via the tax and not just the standard as in the current set-up. Another extension is to study the case where a policy in one country (e. g. tax) covers one pollutant, but the same type of policy in the other country covers the second pollutant. As long as there is only one pollution intensity in each country and the standard is binding the mechanisms through which results are derived are not likely to change, though the effects in each pollutant may. This extension can usher in the consideration of additional policy reforms which could be directly applicable to real-world settings.

Second, it is assumed that there is only one producer in each country so extending the analysis to the n firm case would allow to capture issues of free entry and exit, which is a relevant aspect in the analysis of FDI and environmental policy. The model could also be expanded to a two-sector model, where different pollutants and pollution intensities could exist within each country and issues of competitiveness could be examined in that context. Third, the current set-up assumes only two pollutants within each of the two countries and so extending the analysis to the case of more than two pollutants, plus multiple policies, would capture policy combinations currently used e. g. not only carbon pricing and standards, but also subsidies for R&D. This type of analysis would add an important dimension in the context of developing and developed economies.

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Appendix

Total differentiation of eqs. (2), (3), (5), (6) yields the following system (the "bar" is dropped from $\bar{e}_2^h$ and $\bar{e}_2^f$ for notational simplicity):

$$\begin{bmatrix} 2P^h_{q^h} + q^h P^h_{q^h q^h} - C^h_{q^h q^h} & P^h_{q^f} + q^h P^h_{q^h q^f} & -C^h_{q^h e_1^h} & 0 \\ -C_{e_1^h q^h} & 0 & -C^h_{e_1^h e_1^h} & 0 \\ P^f_{q^h} + q^f P^f_{q^f q^h} & 2P^f_{q^f} + q^f P^f_{q^f q^f} - C^f_{q^f q^f} & 0 & -C^f_{q^f e_1^f} \\ 0 & -C^f_{e_1^f q^f} & 0 & -C^f_{e_1^f e_1^f} \end{bmatrix} \begin{bmatrix} dq^h \\ dq^f \\ de_1^h \\ de_1^f \end{bmatrix} = \begin{bmatrix} C^h_{q^h e_2^h} de_2^h \\ C^h_{e_1^h e_2^h} de_2^h + dt^h \\ C^f_{q^f e_2^f} de_2^f \\ C^f_{e_1^f e_2^f} de_2^f + dt^f \end{bmatrix}$$

where the determinant of the coefficient matrix is $\mu < 0$.In what follows the comparative statics effects on output and emissions for each country are derived. In particular, the change in output for the home and foreign countries are given by

$$
\begin{aligned}
\frac{\mu}{C^h_{e_1^h e_1^h} C^f_{e_1^f e_1^f}} dq^h &= \frac{-C^h_{q^h e_1^h}}{C^h_{e_1^h e_1^h}} \left[-\left(2P^f_{q^f} + q^f P^f_{q^f q^f}\right) + \frac{C^f_{e_1^f e_1^f} C^f_{q^f q^f} - C^{f2}_{e_1^f q^f}}{C^f_{e_1^f e_1^f}} \right] dt^h - \frac{C^f_{q^f e_1^f}}{C^f_{e_1^f e_1^f}} \left[P^h_{q^f} + q^h P^h_{q^h q^f} \right] dt^f \\
&+ C^h_{e_1^h e_2^h} \left(\frac{C^h_{q^h e_2^h}}{C^h_{e_1^h e_2^h}} - \frac{C^h_{q^h e_1^h}}{C^h_{e_1^h e_1^h}} \right) \left[-\left(2P^f_{q^f} + q^f P^f_{q^f q^f}\right) + \frac{C^f_{e_1^f e_1^f} C^f_{q^f q^f} - C^{f2}_{e_1^f q^f}}{C^f_{e_1^f e_1^f}} \right] de_2^h \\
&+ C^f_{e_1^f e_2^f} \left(-\frac{C^f_{q^f e_2^f}}{C^f_{e_1^f e_2^f}} + \frac{C^f_{q^f e_1^f}}{C^f_{e_1^f e_1^f}} \right) \left[-\left(P^h_{q^f} + q^h P^h_{q^h q^f}\right) \right] de_2^f
\end{aligned} \tag{21}
$$

$$
\begin{aligned}
\frac{\mu}{C^h_{e_1^h e_1^h} C^f_{e_1^f e_1^f}} dq^f &= \frac{-C^f_{q^f e_1^f}}{C^f_{e_1^f e_1^f}} \left[-\left(2P^h_{q^h} + q^h P^h_{q^h q^h}\right) + \frac{C^h_{e_1^h e_1^h} C^h_{q^h q^h} - C^{h2}_{e_1^h q^h}}{C^h_{e_1^h e_1^h}} \right] dt^f - \frac{C^h_{q^h e_1^h}}{C^h_{e_1^h e_1^h}} \left[P^f_{q^h} + q^f P^f_{q^f q^h} \right] dt^h \\
&+ C^f_{e_1^f e_2^f} \left(\frac{C^f_{q^f e_2^f}}{C^f_{e_1^f e_2^f}} - \frac{C^f_{q^f e_1^f}}{C^f_{e_1^f e_1^f}} \right) \left[-\left(2P^h_{q^h} + q^h P^h_{q^h q^h}\right) + \frac{C^h_{e_1^h e_1^h} C^h_{q^h q^h} - C^{h2}_{e_1^h q^h}}{C^h_{e_1^h e_1^h}} \right] de_2^f \\
&+ C^h_{e_1^h e_2^h} \left(-\frac{C^h_{q^h e_2^h}}{C^h_{e_1^h e_2^h}} + \frac{C^h_{q^h e_1^h}}{C^h_{e_1^h e_1^h}} \right) \left[-\left(P^f_{q^h} + q^f P^f_{q^f q^h}\right) \right] de_2^h
\end{aligned} \tag{22}
$$

where $\mu < 0$:

$$
\begin{aligned}
\mu &= -C^h_{e_1^h e_1^h} C^f_{e_1^f e_1^f} \Big((2P^h_{q^h} + q^h P_{q^h q^h})(2P^f_{q^f} + q^f P_{q^f q^f}) - (P^f_{q^h} + q^f P_{q^f q^h})(P^h_{q^f} + q^h P_{q^h q^f}) \Big) \\
&\quad - (C^h_{e_1^h e_1^h} C^h_{q^h q^h} - C^{h2}_{e_1^h q^h})(C^f_{e_1^f e_1^f} C^f_{q^f q^f} - C^{f2}_{e_1^f q^f}) + C^h_{e_1^h e_1^h} (2P_{q^h} + q^h P_{q^h q^h})(C^f_{e_1^f e_1^f} C^f_{q^f q^f} - C^{f2}_{e_1^f q^f}) \\
&\quad + C^f_{e_1^f e_1^f} (2P_{q^f} + q^f P_{q^f q^f})(C^h_{e_1^h e_1^h} C^h_{q^h q^h} - C^{h2}_{e_1^h q^h}) < 0
\end{aligned} \tag{23}
$$

where $C^k_{e^k e^k} C^k_{q^k q^k} - C^{k2}_{q^k e^k} > 0$, for $k = h, f$ by the concavity assumption of the cost function.Next, the effect of taxes on foreign and home emissions is given by

$$
\begin{aligned}
\frac{\mu}{C^h_{e_1^h e_1^h} C^f_{e_1^f e_1^f}} de_1^h &= \frac{-C^h_{q^h e_1^h}}{C^h_{e_1^h e_1^h}} \left[\frac{-C^h_{q^h e_1^h}}{C^h_{e_1^h e_1^h}} \left(-\left(2P^f_{q^f} + q^f P^f_{q^f q^f}\right) + \frac{C^f_{e_1^f e_1^f} C^f_{q^f q^f} - C^{f2}_{e_1^f q^f}}{C^f_{e_1^f e_1^f}} \right) + \mu / C^h_{q^h e_1^h} \right] dt^h \\
&+ \frac{C^h_{q^h e_1^h}}{C^h_{e_1^h e_1^h}} \frac{C^f_{q^f e_1^f}}{C^f_{e_1^f e_1^f}} \left(P^h_{q^f} + q^h P^h_{q^h q^f} \right) dt^f
\end{aligned} \tag{24}
$$

$$
\begin{aligned}
\frac{\mu}{C^h_{e_1^h e_1^h} C^f_{e_1^f e_1^f}} de_1^f &= \frac{-C^f_{q^f e_1^f}}{C^f_{e_1^f e_1^f}} \left[\frac{-C^f_{q^f e_1^f}}{C^f_{e_1^f e_1^f}} \left(-\left(2P^h_{q^h} + q^h P^h_{q^h q^h}\right) + \frac{C^h_{e_1^h e_1^h} C^h_{q^h q^h} - C^{h2}_{e_1^h q^h}}{C^h_{e_1^h e_1^h}} \right) + \mu / C^f_{q^f e_1^f} \right] dt^f \\
&+ \frac{C^f_{q^f e_1^f}}{C^f_{e_1^f e_1^f}} \frac{C^h_{q^h e_1^h}}{C^h_{e_1^h e_1^h}} \left(P^f_{q^h} + q^f P^f_{q^f q^h} \right) dt^h
\end{aligned} \tag{25}
$$

Next, the expressions in eqs. (13) and (14) are expanded; these are used to derive eq. (32): $\partial \pi^h / \partial t^h + e_1^h = q^h P^h_{q^f} q^f_{t^h} - C^h_{e_2^h} (\partial e_2^h / \partial t^h)$, $\partial \pi^h / \partial e_2^h = q^h P^h_{q^f} q^f_{e_2^h} - C^h_{e_2^h}$, $\partial E / \partial t^h = \partial e_1^h / \partial t^h + \partial e_2^h / \partial t^h + \partial e_1^f / \partial t^h + \partial e_2^f / \partial t^h$, $\partial E / \partial e_2^h = \partial e_1^h / \partial e_2^h + 1 + \partial e_1^f / \partial e_2^h + \partial e_2^f / \partial e_2^h$, and $\partial e_2^f / \partial t^h = 0$, $\partial e_2^f / \partial e_2^h = 0$ since the home country takes the foreign country's standard as given.

A End-of-pipe type cost function

Next, the case of end-of-pipe type cost function as in Definition 6.1 is examined, where for the home country:

$$
\begin{aligned}
C^h_{q^h} &= \tilde{c}^h + (1+\omega)\delta^h\left(\delta^h q^h - e^h_1 + \delta^h q^h - e^h_2\right)\\
C^h_{q^h e^h_1} &= -(1+\omega)\delta^h\\
C^h_{q^h e^h_2} &= -(1+\omega)\delta^h\\
C^h_{e^h_1} &= -(\delta^h q^h - e^h_1) - \omega(\delta^h q^h - e^h_2)\\
C^h_{e^h_2} &= -(\delta^h q^h - e^h_2) - \omega(\delta^h q^h - e^h_1)\\
C^h_{e^h_1 e^h_1} &= 1, C^h_{e^h_2 e^h_2} = 1\\
C^h_{e^h_1 e^h_2} &= \omega\\
C^h_{e^h_1 e^h_1} C^h_{q^h q^h} - C^h_{e^h_1 q^h} C^h_{q^h e^h_1} &= \delta^{h2}(1+\omega)(1-\omega)
\end{aligned}
$$

where $\omega \in (-1, 1)$. Assume also a linear demand function $P^k = \alpha - \beta(q^h + q^f)$, where $P^h_{q^h} = P^h_{q^f} = P^f_{q^f} = P^f_{q^h} = -\beta$. Using first-order conditions eqs. (2), (3), (5) and (6) gives the following system, which implicitly determines the equilibrium q^h, q^f, e^h_1, e^f_1:

$$q^h\left(2+\beta+2\delta^{f2}(1+\omega)\right) + q^f\beta - e^h_1(1+\omega)\delta^h = \alpha - \tilde{c}^h + (1+\omega)\delta^h e^h_2 \tag{26}$$

$$q^h(1+\omega)\delta^h - e^h_1 = t^h + \omega e^h_2 \tag{27}$$

$$q^h\beta + q^f\left(2+\beta+2\delta^{h2}(1+\omega)\right) - e^f_1(1+\omega)\delta^h = \alpha - \tilde{c}^f + (1+\omega)\delta^f e^f_2 \tag{28}$$

$$q^f(1+\omega)\delta^f - e^f_1 = t^f + \omega e^f_2 \tag{29}$$

whence,

$$
\begin{aligned}
\kappa q^h &= -\left(2\beta + \delta^{f2}(1+\omega)(1-\omega)\right)\left(\alpha - \tilde{c}^h - (1+\omega)\delta^h t^h + (1+\omega)(1-\omega)\delta^h e^h_2\right)\\
&\quad +\beta\left(\alpha - \tilde{c}^f - (1+\omega)\delta^f t^f + (1+\omega)(1-\omega)\delta^f e^f_2\right)
\end{aligned} \tag{30}
$$

$$
\begin{aligned}
\kappa e^h_1 &= -(1+\omega)\delta^h\Big[\left(2\beta + \delta^{f2}(1+\omega)(1-\omega)\right)\left(\alpha - \tilde{c}^h - \delta^h t^h + \delta^h e^h_2\right)\\
&\quad -\beta\left(\alpha - \tilde{c}^f - (1+\omega)\delta^f t^f + (1+\omega)(1-\omega)\delta^f e^f_2\right)\Big]\\
&\quad +\Big[\left(2\beta + \delta^{f2}(1+\omega)(1-\omega)\right)\left(2\beta + \delta^{h2}(1+\omega)\right) - \beta^2\Big](t^h + \omega e^h_2)
\end{aligned} \tag{31}
$$

where $\kappa = -\Big[\left(2\beta + \delta^{f2}(1+\omega)(1-\omega)\right)\left(2\beta + \delta^{h2}(1+\omega)(1-\omega)\right) - \beta^2\Big] < 0$ is the determinant of the coefficient matrix, which is equal to μ in eq. (23) under end-of-pipe as defined in Definition 6.1. Analogous expressions apply to q^f, e^f_1 because of the symmetric nature of the model. From eqs. (30) and (31) the following are obtained:

$$
\begin{aligned}
-\kappa\frac{\partial q^h}{\partial t^h} &= -\left(2\beta + \delta^{f2}(1+\omega)(1-\omega)\right)(1+\omega)\delta^h < 0\\
-\kappa\frac{\partial q^h}{\partial t^f} &= (1+\omega)\delta^h > 0\\
-\kappa\frac{\partial e^h_1}{\partial t^h} &= -\left(2\beta + \delta^{f2}(1+\omega)(1-\omega)\right)\left(2\beta + 2\delta^{h2}(1+\omega)\right) - \beta^2 < 0\\
&= -\left(2\beta + \delta^{f2}(1+\omega)(1-\omega)\right)\left(2\beta + 2\delta^{h2}(1+\omega) - \delta^{h2}(1+\omega)^2 + \delta^{h2}(1+\omega)^2\right) - \beta^2\\
&= -\left(\left(2\beta + \delta^{f2}(1+\omega)(1-\omega)\right)\left(2\beta + \delta^{h2}(1+\omega)(1-\omega)\right) - \beta^2\right)\\
&\quad -\left(2\beta + \delta^{f2}(1+\omega)(1-\omega)\right)\delta^{h2}(1+\omega)^2\\
-\kappa\frac{\partial e^h_1}{\partial t^f} &= (1+\omega)^2\delta^h\delta^f\beta > 0
\end{aligned}
$$

And

$$\begin{aligned}
-\kappa\frac{\partial q^h}{\partial e_2^h} &= \left(2\beta+\delta^{f2}(1+\omega)(1-\omega)\right)(1+\omega)(1-\omega)\delta^h>0\\
-\kappa\frac{\partial q^h}{\partial e_2^f} &= -(1+\omega)(1-\omega)\delta^f\beta<0\\
-\kappa\frac{\partial e_1^h}{\partial e_2^h} &= \left(2\beta+\delta^{f2}(1+\omega)(1-\omega)\right)(1+\omega)^2\delta^{h2}\\
&-\omega\left[\left(2\beta+\delta^{f2}(1+\omega)(1-\omega)\right)\left(2\beta+2\delta^{h2}(1+\omega)\right)-\beta^2\right]\\
&=\left(2\beta+\delta^{f2}(1+\omega)(1-\omega)\right)(1+\omega)^2\delta^{h2}\\
&-\omega\left[\left(2\beta+\delta^{f2}(1+\omega)(1-\omega)\right)\left(2\beta+2\delta^{h2}(1+\omega)-\delta^{h2}(1+\omega)^2+\delta^{h2}(1+\omega)^2\right)-\beta^2\right]\\
&=\left(2\beta+\delta^{f2}(1+\omega)(1-\omega)\right)(1+\omega)^2(1-\omega)\delta^{h2}\\
&-\omega\left[\left(2\beta+\delta^{f2}(1+\omega)(1-\omega)\right)\left(2\beta+\delta^{h2}(1+\omega)(1-\omega)\right)-\beta^2\right]\\
-\kappa\frac{\partial e_1^h}{\partial e_2^f} &= -(1+\omega)^2(1-\omega)\delta^h\delta^f\beta<0
\end{aligned}$$

B Derivation of eq. (19)

Next, eq. (19) is derived. Consider the first-order conditions $W^h_{t^h}(t^h,e_2^h,\omega)=0$, $W^h_{e_2^h}(t^h,e_2^h,\omega)=0$. Differentiation gives a system of two unknowns $dt^h/d\omega$, $de_2^h/d\omega$. Equation (19) is obtained by evaluating $dt^h/d\omega$ at $\omega=0$, while keeping in mind $W^h_{t^h e_2^h}=0$ because of the linear demand and end-of-pipe cost function assumption. Also,

$$\begin{aligned}
q^h\big|_{\omega=0} &= -(2\beta+\delta^{f2})(\alpha-\bar{c}^h-\delta^h t^h+\delta^h e_2^h)+\beta(\alpha-\bar{c}^f-\delta^f t^f+\delta^f e_2^f)>0\\
\kappa\frac{\partial q^h}{\partial\omega}\bigg|_{\omega=0} &= (2\beta+\delta^{f2})\delta^h t^h-\delta^f t^f\beta\\
\kappa\frac{\partial e_1^h}{\partial\omega}\bigg|_{\omega=0} &= \delta^h\left[-(2\beta+\delta^{f2})(\alpha-\bar{c}^h+2\delta^h e_2^h-2\delta^h t^h)+\beta(\alpha-\bar{c}^f-2\delta^f t^f+\delta^f e_2^f)\right]\\
&+e_2^h\left((2\beta+\delta^{f2})(2\beta+2\delta^{h2})-\beta^2\right)\\
\kappa\frac{\partial e_1^f}{\partial\omega}\bigg|_{\omega=0} &= \delta^f\left[-(2\beta+\delta^{h2})(\alpha-\bar{c}^f+2\delta^f e_2^f-2\delta^f t^f)+\beta(\alpha-\bar{c}^h-2\delta^h t^h+\delta^h e_2^h)\right]\\
&+e_2^f\left((2\beta+\delta^{h2})(2\beta+2\delta^{f2})-\beta^2\right)
\end{aligned}$$

C Strategic use of standards and taxation

Assume governments still choose standards and taxes, but now standards are chosen first using eq. (14) which gives, in the case of the home country, say, a standard as a function of the tax i. e. $e_2^h(t^h)$. The home government then takes this standard into account and chooses the tax. This case can be thought of as one where a country sets a policy first (e. g. environmental standards to tackle one pollutant), but uses the other policy strategically. That is, I look at the interplay between the tax and standard. The analysis does not rely on Definition 6.1.

Differentiation of the welfare function with respect to the tax and substituting eq. (14) into eq. (13) gives

$$t^{h*}=\varphi^{h\prime}+\left[-q^h P^h_{q^f}q^f_{t^h}+q^h P^h_{q^f}q^f_{e_2^h}\frac{\partial e_2^h}{\partial t^h}+\varphi^{h\prime}\left(\frac{\partial e_1^f}{\partial t^h}-\frac{\partial e_2^h}{\partial t^h}\frac{\partial e_1^f}{\partial e_2^h}\right)\right]\left(\frac{1}{\frac{\partial e_1^h}{\partial t^h}(1-\eta)}\right)\tag{32}$$

where $\eta=(\partial e_2^h/\partial t^h)(\partial e_1^h/\partial e_2^h)/(\partial e_1^h/\partial t^h)$, $\partial e_1^h/\partial t^h<0$, $\partial e_1^f/\partial t^h>0$, and $P^h_{q^f}<0$, $q^f_{t^h}>0$ (subscripts denote partial derivatives). The first term denotes the upward adjustment in the tax to tackle damages from home pollution. The second and third terms denote profit-shifting effects, and the fourth and fifth terms adjustments in the tax to address damages from transboundary pollution. The term $1-\eta$ captures tax adjustments due to how emissions change, which has an upward pressure. But also the interplay between the tax and standard, which sign depends upon complementarity/substitutability.

The term $\partial e_1^h/\partial e_2^h$ captures the degree of complementarity/substitutability of pollutants in the home country: if pollutants in the home country are complements (substitutes), then $\partial e_1^h/\partial e_2^h > (<)0$, meaning that a reduction in the second pollutant results in a reduction (increase) in the first pollutant, which is consistent with $C^h_{e_1^h e_2^h} < (>)0$. And the term $\partial e_2^h/\partial t^h$ denotes the interplay between the tax and standard in the home country: if $\partial e_2^h/\partial t^h > (<)0$, then laxer taxation in the home country results in the home government setting a stricter (laxer) standard.

To illustrate the role of complementarity/substitutability of pollutants, as a benchmark case suppose these are independent (i. e. $\partial e_1^h/\partial e_2^h \simeq 0$) and that adjustments in the home tax have a negligible effect on the standard i. e. $\partial e_2^h/\partial t^h \simeq 0$. Then, the expression in eq. (32) reduces to

$$\frac{\partial e_1^h}{\partial t^h} t_1^{h*} = \varphi^{h'} \frac{\partial e_1^h}{\partial t^h} - q^h P^h_{q^f} q^f_{t^h} + \varphi^{h'} \frac{\partial e_1^f}{\partial t^h} \tag{33}$$

where the first, second and third terms denote, respectively, damages from local pollution, profit-shifting effects and adjustments from transboundary pollution.

Now suppose home pollutants are complements (i. e. $\partial e_1^h/\partial e_2^h > 0$) and to analyze the interplay between the home tax and standard assume, also, that the home country sets a stricter standard as a result of a laxer tax i. e. $\partial e_2^h/\partial t^h > 0$. As a result of complementarity, in eq. (32) (i) $q^f_{e_2^h} < 0$ and $\partial e_1^f/\partial e_2^h < 0$: with complement pollutants a stricter standard raises foreign output and emissions of the first pollutant in that country via the strategic interaction of firms in the output market (the second pollutant in the foreign country is set by the binding agreement and so does not change). And (ii) $1 - \eta > 0$, $(\partial e_1^f/\partial t^h) - (\partial e_2^h/\partial t^h)(\partial e_1^f/\partial e_2^h) > 0$. Under (i) and (ii), then, the optimal tax is set below marginal damages due to two factors. First, profit shifting incentives via lower taxation, but also because the presence of the standard (third term in 32) renders home firms less cost competitive and so the tax is lowered to offset this. Second, a lower tax at home reduces damages coming from transboundary pollution, but also the presence of the standard raises foreign output (since home pollutants are assumed to be complements) and thus damages from transboundary pollution are addressed via lower taxation (fifth term in 32). Similar results are obtained if pollutants are substitutes and $\partial e_2^h/\partial t^h < 0$. But interestingly, if pollutants are complements and, also, $\partial e_2^h/\partial t^h < 0$ and large (i. e. $1 - \eta < 0$ in the last parenthesis in eq. (32) and $(\partial e_1^f/\partial t^h) - (\partial e_2^h/\partial t^h)(\partial e_1^f/\partial e_2^h) < 0$), then the tax exceeds marginal damages from home pollution if damages from transboundary pollution are small. This is because with a sufficiently large adjustment in the standard (i. e. very lax standard) damages from home pollution rise and so addressed via higher taxation; there is no need to control transboundary pollution via lower taxation. These cases point to the important role of complementarity/substitutability of pollutants in the interplay between taxes and standards.

Result A.1.

Suppose home chooses the standard first, followed by the choice of the tax. The non-cooperative tax in the home country is less than marginal damages from home pollution if (i) home pollutants are complements (substitutes) and (ii) a reduction in the tax is met by a stricter (laxer) standard in the home country i. e.$\partial e_2^h/\partial t^h > (<)0$.

Result A.2.

Suppose home chooses the standard first, followed by the choice of the tax. The non-cooperative tax in the home country exceeds marginal damages from home pollution if (i) home pollutants are complements, (ii) there is a sufficiently laxer standard in the home country (i. e.$\partial e_2^h/\partial t^h < 0$ *and large), and (iii) damages from transboundary pollution are small.*

Notes

1 The Convention on Long-range Transboundary Air Pollution (LRTAP) illustrates the relevance of the analysis of policy reform: as part of the LRTAP member countries identify new ways to cut emissions of air pollutants unilaterally and/or multilaterally. And the UNECE Committee on Environmental Policy supports member countries to improve cooperation to address transboundary pollution.

2 The literature has examined issues of strategic and optimal environmental policy (e. g. Ulph 1996; Ulph and Ulph 1996, 2007; Bayındır-Upmann 2003; Turunen-Red and Woodland 2004; Silva and Zhu 2009; Bhattacharya and Pal 2010; Elliott and Zhou 2013; Ambec and Coria 2013; Caplan and Silva 2005) and the pollution heaven hypothesis (e. g. Zarsky 1999; Neumayer 2001; Grether and de Melo 2004).

3 Ambec and Coria (2013, p. 124) mention the US and EU as examples where taxes and emission standards are set to regulate multiple pollutants.

4 Alternatively, the reduction in one pollutant may lower abatement costs of a second pollutant thereby reducing overall emissions. For instance, switching from coal to natural gas may result in reductions both of sulfur dioxide and carbon dioxide (Slechten and Verardi 2014), and jet scrubbers used to remove particles can reduce gaseous pollutants (Caplan and Silva 2005).

5 e. g. the case of Chile and US where each country sets standards on SO_2, and Chile has submitted INDCs, as per the Paris Agreement with taxation on pollutants in the energy sector, while the proposed Clean Power Plant exemplifies a potential mechanism in the US.

6 Caplan and Silva (2005) present a theoretical model (under perfect competition) with multiple pollutants and countries, and analyze the efficiency of permits and taxes, but do not consider differences in pollution intensities across countries and aspects of policy reform. And Moslener and Requate (2007, 2009) show in a dynamic context that complementarity/substitutability play a key role in the optimal path of abatement. The papers by Kuosmanen and Lankkanen (2011) and von Ungern-sternberg (1987) look at non-convexities and its implications for optimal policy in the presence of many pollutants.
7 Silva and Zhu (2009) and Bhattacharya and Pal (2010) look at the strategic behavior of policy setting in an international trade setting, but consider either a standard or trading permit system while here I incorporate emission taxes and standards into the analysis of policy reform.
8 With the assumption of exports to a third market I can focus the analysis on the role of strategic (profit-shifting) effects and transboundary pollution; this assumption is further substantiated in Section 5.
9 A change in output shifts the marginal abatement cost (MAC) function of the second pollutant but leaves emissions from the second pollutant unchanged because of the standard. One would expect output to change as a result of changes in abatement costs of the second pollutant. But output remains unchanged even as MAC change because of the presence of an emission tax, which forces MAC of the first pollutant and therefore output to be consistent with the level of the tax.
10 To see this consider an increase in the tax. Emissions from the first pollutant fall and therefore output up the point where the tax equals marginal abatement cost (MAC) of the first pollutant. Now, because of complementarity/substitutability of pollutants MAC of the second pollutant change (though not the level of emissions of the second pollutant), but this change in costs does not have a further effect on output/emissions because of the presence of the tax which forces MAC of the first pollutant to be consistent with higher taxation.
11 Because there is one pollution intensity in each country whether the tax or standard covers the first or second pollutant does not change results as long as each country covers each pollutant with the same policy. This is because firms do not have a say on the pollutant covered by the standard.
12 For given marginal benefit of emissions, the change in emissions via output is given by $de/dq|_{dC_e=0} = -C_{eq}/C_{ee} > 0$.
13 $\pi^f_{q^f q^f} = -(2P^f_{q^f} + q^f P^f_{q^f q^f}) + (C^f_{q^f q^f} C^f_{e^f_1 e^f_1} - C^{f2}_{q^f e^f_1})/C^f_{e^f_1 e^f_1}$; $\pi^h_{q^h q^h} = -(2P^h_{q^h} + q^h P^h_{q^h q^h}) + (C^h_{q^h q^h} C^h_{e^h_1 e^h_1} - C^{h2}_{q^h e^h_1})/C^h_{e^h_1 e^h_1}$; $\pi^h_{q^h q^f} = P^h_{q^h} + q^h P^h_{q^h q^f}$; $\pi^f_{q^f q^h} = P^f_{q^f} + q^f P^f_{q^f q^f}$.
14 The reason for having all pollutants in the definition of E is that I want to capture the fact that the second and first pollutant influence global emissions coming from each country. In order to track changes in each pollutant but at the same time avoid additivity issues, pollutants can be thought of in terms of carbon dioxide equivalent units or CO_2-equivalent. For example, consider a tax on N_2O and standard on Methane (CH_4). To track changes in each pollutant but also compare these in same carbonequivalent units, the 100-year Global Warming Potential (GWP) of greenhouse gases for each is used to establish CO_2 equivalence. Gohar and Shine (2007, p. 308) state that "The GWP is a useful construct which provides policymakers with a relatively simple method for placing emissions of different gases on a common carbonequivalent scale." As an example, the Kyoto Protocol sets targets of emissions reductions in terms of aggregate carbon dioxide equivalent emissions of greenhouse gases (Reilly et al. 1999). For a discussion on differences between CO_2e and CO_2-equivalent, and drawbacks of the latter see Gohar and Shine (2007). For alternative methods see Allen et al. (2018).
15 The idea of equivalence used here follows that used to build a greenhouse data inventory as exemplified in the *EEA greenhouse gas data viewer* as described in the *Manual for the EEA greenhouse gas data viewer* (available here: https://www.eea.europa.eu/data-and-maps/data/data-viewers/greenhouse-gases-viewer), but also in the *Summary Report for national greenhouse gas inventories, Annex I, working group, 2015* (available here: https://www.stat.fi/static/media/uploads/tup/khkinv/nc7_contributors_annex_working_groups.pdf). The UN Framework Convention on Climate Change also offers an example of estimates of total greenhouse gas inventories in CO_2-equivalent units (available here: http://di.unfccc.int/time_series), described in the Data Interface Help page (https://unfccc.int/process/transparency-and-reporting/greenhouse-gas-data/ghg-data-unfccc/data-interface-help#eq-8).
16 Since standards and emission taxes are in different units, the proportional change is in the form of an equal percentage change.
17 Formally, $\alpha = e^f_2 \alpha_1 = de^f_2$, and $\alpha = t^f \alpha_2 = dt^f$ for $0 < \alpha_i < 1$, $i = 1, 2$.
18 As Ambec and Coria (2013) argue, to avoid corner solutions is to account for the economies (diseconomies) of scope associated with the multiple pollutants.
19 That is, the global welfare function evaluated at the Nash equilibrium is negative in eq. (15), which implies, assuming strict concavity, that the non-cooperative tax exceeds the cooperative tax.
20 The result in Proposition 5.6 is derived by applying to eq. (17) the result in Proposition 4.3 and using eqs. (22) and (24) in the Appendix.
21 The case of large asymmetries is consistent with the analysis of policy reform previously presented, where the condition in Remark 4.1 under an end-of-pipe cost function implies $2\delta^f \delta^h \beta > (2\beta + \delta^{f2})2\delta^2$.

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