Abatement Level in Environmental Agreements when Firms are Heterogeneous in Abatement Costs

Luis Gautier

1. Introduction

There is an important number of regional and international environmental agreements where countries have agreed upon in order tackle environmental degradation (e.g., reduce greenhouse gases). In addition, member countries exhibit varying pollution abatement technologies and degrees of pollution intensities as well as different cost structures. As new agreements take place (e.g., COP21 Paris) and existing ones evolve as climate and economic conditions change, the analysis of policy reform of environmental policy becomes timely and relevant. With these in mind, this paper builds a two-country model where firms compete in a Cournot fashion, face an emission tax and exhibit heterogeneous abatement costs. In this context, the analysis of policy reform is presented, particularly its impact on global emissions. It is shown that asymmetries in abatement and production costs play a crucial role on the extent to which global emissions fall via unilateral and multilateral policy reform.

Over the last several decades a number of multilateral environmental agreements have been established which exemplify efforts of policy reform e.g., see Barrett (2003) and the IEA Database Project[1] for examples of environmental agreements. For instance, the Convention on Long-range Transboundary Air Pollution (LRTAP) illustrates how LRTAP member

[1] Ronald B. Mitchell. 2002-2016. International Environmental Agreements Database Project (Version 2014.3). Available at: http://iea.uoregon.edu/ Date accessed: 25 March 2016.

countries identify ways to reduce emissions of air pollutants via unilateral and multilateral policy reform, and the UNECE Committee on Environmental Policy provides support to member countries to enhance cooperation and reduce transboundary pollution. The Basel Convention[2] also illustrates multilateral efforts to address the disposal of hazardous waste including technology transfer to manage waste, and the Clean Technology Fund exemplifies efforts to provide funds to promote low-carbon technologies across countries[3]. More recently, the COP21 2015 meeting in Paris brought countries together in the sense of putting forward independent, nationally-determined contributions (INDCs) along with policies, including market-based mechanisms and standards. The Paris agreement may not necessarily achieve the desired level of pollution abatement of greenhouse gases (e.g., Barrett et al. 2015; Kahn 2016) and, therefore, countries may need to adjust INDCs and policies accordingly. Even if national emission targets are achieved, economic conditions are likely to change thereby prompting countries to adjust policy.

Concerns about losing competitiveness to foreign competition has been used as an argument by less-developed and developed countries to avoid implementing carbon pricing policies as well as other environmental policies. Indeed, the literature has studied aspects of strategic environmental policy and the characterization of optimal 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). The idea here is that countries may engage in laxer (less stringent) environmental policy (e.g., lower emission taxes or lower costs in the form of laxer environmental regulation) in order to avoid losing to foreign competition and attract profits. The contribution of the present work to this literature is that here I look at elements of strategic environmental policy, but with particular attention to policy reform and its impact on

[2]The Basel Convention on the Control of Transboundary Movements of Hazardous Wastes and their Disposal of 1989. See http://www.basel.int/TheConvention/Overview/tabid/1271/Default.aspx

[3]http://www.climatefundsupdate.org/listing/clean-technology-fund

global emissions in the presence of heterogeneous abatement costs across countries; I do not delve into the characterization of optimal policy since this has been examined in the aforementioned literature. For instance, as countries set laxer environmental policies to become more cost competitive (e.g., set cost-reducing policies) optimal taxation may be adjusted which may, consequently, have an impact on global emissions. I explore changes in both production costs and pollution abatement costs via policy reform and how these may alter optimal emission taxes, with particular attention to the effects on global emissions. Aspects of strategic environmental policy are captured via the combination of policy reforms such as lower taxation and at the same cost-reducing (or alternatively cost-increasing) reforms. The aforementioned literature does not focus on the analysis of policy reforms and does not delve into the role of asymmetries in pollution intensity coefficients, both key contributions of this paper.

The present analysis also contributes to a second important branch of the literature which examines the policy reform of reducing emissions under imperfect competition (e.g., Hoel 1991), particularly the role of environmental standards (e.g., Kayalica and Lahiri 2005; Bhattacharya and Pal 2010) and emission taxes (e.g., Hatzipanayotou et al. 2005; Lahiri and Symeonidis 2007; Gautier 2013, 2014). The contribution to this line of research is on the policy reform of emission taxes. Lahiri and Symeonidis (2007) examine the effects of policy reform of emission taxes on global emissions, but do not look at the implications of welfare which is an aspect I examine in section 4. Furthermore, Gautier (2013, 2014) examine aspects of policy reform of taxes on welfare, but the present analysis adds to these works by incorporating changes in costs (both abatement and production costs) into the policy reform of emission taxes. This is important because as cost structures change governments may adjust optimal taxation, thus having an impact on the extent to which policy reform may reduce global emissions. Additionally, part of the literature has assumed linear demand or specific cost functions to derive some of the results about policy reform. This paper, in contrast, presents a model with asymmetries in pollution abatement and production costs, and demand functions in a general setting thus providing a unified framework of analysis.

The model set-up consists of two countries where firms behave à la Cournot, face an emission tax and exhibit heterogeneity in the cost functions across countries. The heterogeneity in costs is captured through two channels. First, marginal abatement costs may differ across countries. This captures differences in pollution abatement technologies across countries as well as differences in pollution intensities. Different costs structures also capture different levels of production efficiencies in terms of marginal production costs. These two aspects are important in the analysis of policy reform since in the context of environmental agreements countries are likely to exhibit these types of asymmetries. Second, there is heterogeneity in costs through a cost parameter, assumed to be exogenous, which changes the *level* of the cost functions for any level of output and emissions i.e., shifts costs for any level of output and emissions. This is an important channel through which cost heterogeneity is captured because it allows to examine potential policy reform on costs (whether cost-reducing or cost-increasing policies) within each country. For instance, exogenous changes in this parameter not only may be interpreted as cost-reducing policies in both pollution abatement and production costs (e.g., cost-reducing R&D), but also the exogenous nature of the parameter allows to see how cost-reducing (or alternatively cost-increasing) policies may affect the effectiveness of policy reforms of emission taxes on reducing emissions e.g., cost-reducing policy affects optimal taxation and consequently policy reform of taxes.

The analysis indicates that differences in pollution intensities across countries as well as asymmetries in production and abatement costs affect the effectiveness of policy reform to lower global emissions. Additionally, policy reforms consisting of cost-reducing policies (to increase firms' cost competitiveness in one country, say) may reduce global emissions as long as these are coupled with an emission tax. But also cost-increasing policy reforms are presented, and conditions derived, such that global emissions fall. This type of analysis is pertinent in the context of environmental agreements where countries may put forward stricter environmental policies on the one hand (e.g., higher emission taxes), but at the same time cost-reducing policies which may induce higher emissions.

The paper is structured as follows. Section 2 presents the building blocks of the model. Section 3 presents the comparative statics analysis with implications for policy reform. Section 4 then looks at the welfare implications of policy reform. In section 5, I conclude by discussing some of the limitations of the analysis and suggesting questions for future research.

2. The Model

This section presents the main building blocks of the model. Consider a home and foreign country where only one firm operates in each country[4]. Firms compete for the production of an imperfect substitute, which is exported to a third market exclusively.

Demand faced by each firm is given by a function $P^k = P^k(q^h, q^f)$, where q^k denotes output in country $k = h, f$; and where (subscripts denote partial derivatives) $P_{q^k} < 0$, $2P_{q^k} + q^k P_{q^k q^k} < 0$, for $k = h, f$. Moreover, as in Dixit (1986) and Lahiri and Symeonidis (2007) I shall assume that the "own effect" is greater than the cross-effect i.e., $2P^h_{q^h} + q^h P^h_{q^h q^h} < P^h_{q^f} + q^h P^h_{q^h q^f} < 0$ and $2P^f_{q^f} + q^f P^f_{q^f q^f} < P^f_{q^h} + q^f P^f_{q^f q^h}$ for $k = h, f$. These will aid to ensure stability in the global equilibrium.

Each firm pollutes the environment and without any loss of generality let e^k denote the pollutant in country $k = h, f$. I follow Requate (2006) in the structure of the cost function for each firm operating in each country $k = h, f$. In particular, consider a cost function $C^k = C^k(q^k, e^k)$ where (subscripts denote partial derivatives) $C^k_{q^k} > 0$, $C^k_{e^k} < 0$, $C^k_{q^k e^k} = C^k_{e^k q^k} < 0$, $C^k_{q^k q^k} > 0$, $C^k_{e^k e^k} > 0$, $C^k_{e^k e^k} C^k_{q^k q^k} - C^{k2}_{q^k e^k} > 0$, and as in Lahiri and Symeonidis (2007) the pollution intensity is defined as the ratio $-C^k_{e^k q^k}/C^k_{e^k e^k} > 0$ for $k =$

[4] By assuming one firm in each country I can focus on the role of asymmetries in abatement costs. The n firm case does not change the key results.

h, f[5].

Each firm faces an emission tax for each unit of pollution it fails to abate. Specifically, the home-country firm faces a per-unit emission tax, t^h, for the level of pollution, e^h, it fails to abate, and analogously the foreign-country firm faces a tax, t^f, which targets e^f.

Firms and governments play a two-stage non-cooperative game. Each country chooses the tax simultaneously taking the other country's tax as given. Firms (home and foreign) then take policy as given and maximize profits by choosing the level of emissions and output 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; Gautier 2014). I assume interior solutions throughout the analysis and the model is solved by backward induction.

In particular, the home country's firm solves

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

where z^h is a positive constant. Larger (smaller) values of z^h capture higher (lower) costs for any q^h and e^h[6]. For example, the firm may face new regulation which in turn reflects on higher production and abatement pollution costs; alternatively, the firm may enjoy lower costs (i.e., a smaller z^h) as a result of cost-reducing technology. The role of z^h is analogous to the role of $R\&D$ in e.g., Montero (2002a), but in the present model this is exogenous.

Maximization of (1) yields the following first-order conditions (subscripts denote par-

[5]For examples of industry/countries with asymmetries in pollution intensities within the US see DOC (2010), and across countries see Sterner and Köhlink (2015: 254).

[6]Gautier (2015) considers a similar type of cost parameter, but specifically on abatement costs and in a closed-economy Cournot setting; here the cost parameter affects not only abatement costs and is presented in an international setting.

tial derivatives)

$$P^h + q^h P^h_{q^h} - z^h C^h_{q^h} = 0 \quad (2)$$

$$-z^h C^h_{e^h} - t^h = 0 \quad (3)$$

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

$$\max_{q^f e^f} \pi^f = P^f q^f - z^f C^f(q^f, e^f) - e^f t^f \quad (4)$$

where z^f is a positive constant and its interpretation is analogous to z^h. From (4), first-order conditions are given by

$$P^f + q^f P^f_{q^f} - z^f C^f_{q^f} = 0 \quad (5)$$

$$-z^f C^f_{e^f} - t^f = 0 \quad (6)$$

Equations (2), (3), (5), (6) implicitly determine the equilibrium level of output and emissions, q^h, q^f, e^h, e^f. Stability for the local and global equilibrium require $\pi^h_{q^h q^h}\pi^f_{q^f q^f} - \pi^h_{q^h q^f}\pi^f_{q^f q^h} > 0$, and $\pi^k_{q^k q^k}\pi^k_{e^k e^k} - \pi^k_{q^k e^k}\pi^k_{e^k q^k} > 0$ for $k = h, f$.

3. Comparative Statics

The comparative static effects of the tax, t^h and t^f, and the cost parameters z^h and z^f, on output on emissions are examined. The analysis of policy reform is then presented.

Total differentiation of (2), (3), (5), (6) yields the following system:

$$\begin{bmatrix} 2P^h_{q^h}+q^hP^h_{q^hq^h}-z^hC^h_{q^hq^h} & P^h_{q^f}+q^hP^h_{q^hq^f} & -z^hC^h_{q^he^h} & 0 \\ -z^hC^h_{e^hq^h} & 0 & -z^hC^h_{e^he^h} & 0 \\ P^f_{q^h}+q^fP^f_{q^fq^h} & 2P^f_{q^f}+q^fP^f_{q^fq^f}-z^fC^f_{q^fq^f} & 0 & -z^fC^f_{q^fe^f} \\ 0 & -z^fC^f_{e^fq^f} & 0 & -z^fC^f_{e^fe^f} \end{bmatrix} \begin{bmatrix} dq^h \\ dq^f \\ de^h \\ de^f \end{bmatrix} = \begin{bmatrix} C^h_{q^h}dz^h \\ C^h_{e^h}dz^h+dt^h \\ C^h_{q^f}dz^f \\ C^h_{e^f}dz^f+dt^f \end{bmatrix}$$

where the determinant of the coefficient matrix is $\mu < 0$. I shall follow Lahiri and Symeonidis (2007: 890) in the definition of pollution intensity, $-C^k_{q^ke^k}/C^k_{e^ke^k} > 0$, for $k = h, f$. Using the above system the effect of the tax and cost parameter z^k (for given tax) on output and emissions is given by

$$\begin{aligned} \Delta dq^h &= \frac{-C^h_{q^he^h}}{C^h_{e^he^h}}\left[-\left(2P^f_{q^f}+q^fP^f_{q^fq^f}\right)+z^f\frac{C^f_{e^fe^f}C^f_{q^fq^f}-C^{f2}_{e^fq^f}}{C^f_{e^fe^f}}\right]dt^h-\frac{C^f_{q^fe^f}}{C^f_{e^fe^f}}\left[P^h_{q^f}+q^hP^h_{q^hq^f}\right]dt^f \\ &+\left(C^h_{q^h}-C^h_{e^h}\frac{C^h_{q^he^h}}{C^h_{e^he^h}}\right)\left[-\left(2P_{q^f}+q^fP_{q^fq^f}\right)+z^f\frac{C^f_{e^fe^f}C^f_{q^fq^f}-C^{f2}_{e^fq^f}}{C^f_{e^fe^f}}\right]dz^h \\ &+\left(C^f_{q^f}-C^f_{e^f}\frac{C^f_{q^fe^f}}{C^f_{e^fe^f}}\right)\left(P^h_{q^f}+q^hP^h_{q^hq^f}\right)dz^f \end{aligned} \tag{7}$$

$$\begin{aligned} \Delta dq^f &= \frac{-C^f_{q^fe^f}}{C^f_{e^fe^f}}\left[-\left(2P^h_{q^h}+q^hP^h_{q^hq^h}\right)+z^h\frac{C^h_{e^he^h}C^h_{q^hq^h}-C^{h2}_{e^hq^h}}{C^h_{e^he^h}}\right]dt^f-\frac{C^h_{q^he^h}}{C^h_{e^he^h}}\left[P^f_{q^h}+q^fP^f_{q^fq^h}\right]dt^h \\ &+\left(C^f_{q^f}-C^f_{e^f}\frac{C^f_{q^fe^f}}{C^f_{e^fe^f}}\right)\left[-\left(2P^h_{q^h}+q^hP^h_{q^hq^h}\right)+z^h\frac{C^h_{e^he^h}C^h_{q^hq^h}-C^{h2}_{e^hq^h}}{C^h_{e^he^h}}\right]dz^f \\ &+\left(C^h_{q^h}-C^h_{e^h}\frac{C^h_{q^he^h}}{C^h_{e^he^h}}\right)\left(P^f_{q^h}+q^fP^f_{q^fq^h}\right)dz^h \end{aligned} \tag{8}$$

where $\Delta := \mu/C^h_{e^he^h}C^f_{e^fe^f}z^hz^f < 0$. In this type of analytical framework the effect of taxes has been examined in the literature (e.g., Lahiri and Symeonidis 2007; Gautier 2014, 2016) so here I just make a few remarks. First, 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; the firm in the other country reacts strategically by raising output. Moreover, global output, $q^h + q^f$, falls from a tax increase since by assumption the own effect dominates the cross effect.

The effect of the tax on emissions works through changes in output and the abatement induced by the tax. Results on the effects of the tax on emissions are analogous to those in the literature: 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, global emissions, $e^h + e^f$, fall with a tax increase at home if the home country is pollution intensive vis-à-vis the foreign country; global emissions rise otherwise if the foreign country exhibits a sufficiently large pollution intensity. The notion of a relative (and sufficient) pollution-intensive country is clearly defined later on.

It is noteworthy that an increase in the tax in the home country raises abatement in that country exclusively (i.e., the term $\Delta/z^h C^h_{q^h e^h}$ in equation 9), thereby lowering emissions in that country. As a result, a change in the tax in one country impacts emissions in that country via changes in output and abatement, whereas the impact on emissions in the other country works exclusively via changes in output.

In particular, the effect of taxes on foreign and home emissions is given by

$$\Delta de^h = \frac{-C^h_{q^h e^h}}{C^h_{e^h e^h}} \left[\frac{-C^h_{q^h e^h}}{C^h_{e^h e^h}} \left(-\left(2P^f_{q^f} + q^f P^f_{q^f q^f}\right) + z^f \frac{C^f_{e^f e^f} C^f_{q^f q^f} - C^{f2}_{e^f q^f}}{C^f_{e^f e^f}} \right) + \Delta/z^h C^h_{q^h e^h} \right] dt^h$$

$$+ \frac{C^h_{q^h e^h}}{C^h_{e^h e^h}} \frac{C^f_{q^f e^f}}{C^f_{e^f e^f}} \left(P^h_{q^f} + q^h P^h_{q^h q^f}\right) dt^f \qquad (9)$$

$$\Delta de^f = \frac{-C^f_{q^f e^f}}{C^f_{e^f e^f}} \left[\frac{-C^f_{q^f e^f}}{C^f_{e^f e^f}} \left(-\left(2P^h_{q^h} + q^h P^h_{q^h q^h}\right) + z^h \frac{C^h_{e^h e^h} C^h_{q^h q^h} - C^{h2}_{e^h q^h}}{C^h_{e^h e^h}} \right) + \Delta / z^f C^f_{q^f e^f} \right] dt^f$$

$$+ \frac{C^f_{q^f e^f}}{C^f_{e^f e^f}} \frac{C^h_{q^h e^h}}{C^h_{e^h e^h}} \left(P^f_{q^h} + q^f P^f_{q^f q^h} \right) dt^h \qquad (10)$$

where $\mu < 0$, $\Delta := \mu / C^h_{e^h e^h} C^f_{e^f e^f} z^h z^f$, the term $\Delta / z^k C^k_{q^k e^k}$ denotes the abatement induced by the emission tax, and the term $-(2P^k_{q^k} + q^k P^k_{q^k q^k}) + z^k (C^k_{e^k e^k} C^k_{q^k q^k} - C^{k2}_{e^k q^k}) / C^k_{e^k e^k}$ captures changes in emissions via changes in output for $k = h, f$.

Next, I look into the effects of the cost parameters z^h and z^f on home/foreign emissions and output.

The effect on home-country output from a change in z^h (for given tax) is given by the second line in (7). There are two opposing effects at play. On the one hand, an increase in z^h raises the cost of an extra unit of output in the home country, $C^h_{q^h}$, thereby lowering output in that country. Since the home country becomes relatively less cost competitive, output rises in the foreign country. On the other hand, an increase in z^h raises the cost of abating an extra unit of pollution in the home country, $-C^h_{e^h} C^h_{e^h q^h} / C^h_{e^h e^h}$, which in turn results in higher output, less abatement and higher emissions in that country; emissions will increase up to the point where marginal abatement costs equal the tax. Since the home country raises output as a result of higher marginal abatement costs, the foreign country reacts strategically by reducing production. Therefore, home (foreign)-country output rises (falls) *if and only if* the effect via the increase in marginal abatement costs is sufficiently large. And global output, $q^h + q^f$, increases under the aforementioned necessary and sufficient condition since the effect of z^h on home output (i.e., the own effect) completely offsets the effect on foreign output.

It is noteworthy that the channel whereby z^h affects the cost of reducing an extra unit of pollution (and thus output and emissions in the home country) depends crucially upon the presence of an emission tax: the upward shift in the marginal abatement cost of the home firm, resulting from an increase in z^h, induces the home firm to increase output and emissions up to the point where the new marginal abatement cost curve meets the emission tax in that country. Without the emission tax this effect vanishes and therefore the term $-C^h_{e^h}C^h_{e^hq^h}/C^h_{e^he^h}$ becomes negligible. An analogous analysis applies to the emission tax in the foreign country and changes in z^f.

Next, I analyze the effects on home and foreign emissions resulting from changes in z^k (for given tax). An increase in z^k exhibits the two opposing effects on output aforementioned with the corresponding effects on emissions. For instance, an increase in z^h raises costs for each extra unit of output, $C^h_{q^h}$, which lowers output and consequently emissions in the home country; as a result, emissions in the foreign country rise as the foreign firm reacts by increasing output. Additionally, an increase in z^h raises the costs of abating an extra unit of pollution which results in an increase in output and thus emissions in the home country; as a result, foreign emissions fall as the foreign firm reacts by lowering output.

It is noteworthy that the term $\Delta C^h_{e^h}/z^hC^h_{q^he^h}$ in equation (11) captures the effect of z^h on emissions, e^h, via abatement: higher abatement costs result in less abatement which in turn reflects on higher emissions; this effect compensates changes in emissions via changes in output as long as the effect via marginal abatement costs in the home country is sufficiently large (i.e., $C^h_{q^h} < C^h_{e^h}C^h_{q^he^h}/C^h_{e^he^h}$).

In particular, the change in home and foreign emissions arising from a change in z^k, $k = h, f$, is given by

$$\Delta de^h = -\frac{C^h_{q^h e^h}}{C^h_{e^h e^h}} \left[\left(C^h_{q^h} - C^h_{e^h} \frac{C^h_{q^h e^h}}{C^h_{e^h e^h}} \right) \left(-\left(2P^f_{q^f} + q^f P^f_{q^f q^f} \right) + z^f \frac{C^f_{e^f e^f} C^f_{q^f q^f} - C^{f2}_{e^f q^f}}{C^f_{e^f e^f}} \right) + C^h_{e^h} \Delta / z^h C^h_{q^h e^h} \right] dz^h$$

$$-\frac{C^h_{q^h e^h}}{C^h_{e^h e^h}} \left(C^f_{q^f} - C^f_{e^f} \frac{C^f_{q^f e^f}}{C^f_{e^f e^f}} \right) \left(P^h_{q^f} + q^h P^h_{q^h q^f} \right) dz^f \quad (11)$$

$$\Delta de^f = -\frac{C^f_{q^f e^f}}{C^f_{e^f e^f}} \left[\left(C^f_{q^f} - C^f_{e^f} \frac{C^f_{q^f e^f}}{C^f_{e^f e^f}} \right) \left(-\left(2P^h_{q^h} + q^h P^h_{q^h q^h} \right) + z^h \frac{C^h_{e^h e^h} C^h_{q^h q^h} - C^{h2}_{e^h q^h}}{C^h_{e^h e^h}} \right) + C^f_{e^f} \Delta / z^f C^f_{q^f e^f} \right] dz^f$$

$$-\frac{C^f_{q^f e^f}}{C^f_{e^f e^f}} \left(C^h_{q^h} - C^h_{e^h} \frac{C^h_{q^h e^h}}{C^h_{e^h e^h}} \right) \left(P^f_{q^h} + q^f P^f_{q^f q^h} \right) dz^h \quad (12)$$

The net effect on global emissions, $e^h + e^f$, resulting from a change in z^k depends upon the relative pollution intensities as well as the effects via marginal abatement and production costs. If, for instance, the home country is the more pollution intensive country (i.e., $-C^h_{q^h e^h}/C^h_{e^h e^h} > -C^f_{q^f e^f}/C^f_{e^f e^f}$), then global emissions rise as long as marginal abatement costs in the home country are sufficiently large. This is because with a sufficiently large effect via marginal abatement costs emissions rise at home, which completely offsets the reduction in emissions in the foreign country because the home country is relatively more pollution intensive. But if the foreign country is sufficiently more pollution intensive (i.e., $-C^h_{q^h e^h}/C^h_{e^h e^h}(-(2P^f_{q^f} + q^f P^f_{q^f q^f}) + C^f_{e^f e^f} C^f_{q^f q^f} - C^{f2}_{e^f q^f}/C^f_{e^f e^f}) + \Delta / z^h C^h_{q^h e^h} < C^f_{q^f e^f}/C^f_{e^f e^f}(P^f_{q^h} + q^f P^f_{q^f q^h}))$, then global emissions may fall.

Proposition 3.1. *An increase in costs in the home country, z^h (for given tax): (i) raises* *output in the home country, (ii) lowers output in the foreign country, and (iii) raises global output if and only if the effect via the increase in marginal abatement costs is sufficiently large (i.e.,* $C^h_{q^h} < C^h_{e^h} C^h_{q^h e^h}/C^h_{e^h e^h}$*).*

Proposition 3.2. *Let marginal abatement costs be sufficiently large in the home country as defined in proposition 3.1. Then, an increase in costs in the home country (i.e., increase in* z^h*) increases global emissions, if the home country is at least as pollution intensive as the foreign country (i.e.,* $-C^h_{q^h e^h}/C^h_{e^h e^h} \geq -C^f_{q^f e^f}/C^f_{e^f e^f}$*). Global emissions fall otherwise if the foreign country is sufficiently pollution intensive i.e.,* $-C^h_{q^h e^h}/C^h_{e^h e^h}(-(2P^f_{q^f} + q^f P^f_{q^f q^f}) + C^f_{e^f e^f} C^f_{q^f q^f} - C^{f2}_{e^f q^f}/C^f_{e^f e^f}) + \Delta/z^h C^h_{q^h e^h} < C^f_{q^f e^f}/C^f_{e^f e^f}(P^f_{q^h} + q^f P^f_{q^f q^h})$*.*

One implication of proposition 3.2 is that a sufficiently less pollution intensive country can set regulation resulting in higher costs (e.g., marginal abatement costs) and still yield a reduction in global emissions as long as the role of the emission tax is part of the policy mix.

Next, I analyze the effect of policy reform of the cost parameter z in more detail. The change in global emissions, $E = e^h + e^f$, from a change in the cost parameter z^h and z^f (for given tax), using (11) and (12) yields

$$
\begin{aligned}
\Delta dE \;=\; & \Bigg[\left(C^h_{q^h} - C^h_{e^h}\frac{C^h_{q^h e^h}}{C^h_{e^h e^h}}\right)\Bigg[-\frac{C^h_{q^h e^h}}{C^h_{e^h e^h}}\left(-\left(2P^f_{q^f} + q^f P^f_{q^f q^f}\right) + z^f\frac{C^f_{e^f e^f}C^f_{q^f q^f} - C^{f2}_{e^f q^f}}{C^f_{e^f e^f}}\right) \\
& -\frac{C^f_{q^f e^f}}{C^f_{e^f e^f}}\left(P^f_{q^h} + q^f P^f_{q^f q^h}\right)\Bigg] - \frac{C^h_{q^h e^h}}{C^h_{e^h e^h}} C^h_{e^h}\Delta/z^h C^h_{q^h e^h}\Bigg] dz^h \\
& + \Bigg[\left(C^f_{q^f} - C^f_{e^f}\frac{C^f_{q^f e^f}}{C^f_{e^f e^f}}\right)\Bigg[-\frac{C^f_{q^f e^f}}{C^f_{e^f e^f}}\left(-\left(2P^h_{q^h} + q^h P^h_{q^h q^h}\right) + z^h\frac{C^h_{e^h e^h}C^h_{q^h q^h} - C^{h2}_{e^h q^h}}{C^h_{e^h e^h}}\right) \\
& -\frac{C^h_{q^h e^h}}{C^h_{e^h e^h}}\left(P^h_{q^f} + q^h P^h_{q^h q^f}\right)\Bigg] - \frac{C^f_{q^f e^f}}{C^f_{e^f e^f}} C^f_{e^f}\Delta/z^f C^f_{q^f e^f}\Bigg] dz^f \qquad (13)
\end{aligned}
$$

Consider a policy reform consisting of $dz^h = dz^f = d\tilde{z} < 0$ (i.e., an equal decrease in the cost parameter z across countries) and let $C^h_{q^h} - C^h_{e^h} C^h_{e^h q^h}/C^h_{e^h e^h} = C^f_{q^f} - C^f_{e^f} C^f_{e^f q^f}/C^f_{e^f e^f} \leq 0$ (i.e., cost effects via z are symmetric across countries where the effect via marginal abatement costs is relatively large). Then, (13) yields $dE < 0$ i.e., global emissions fall as a result of lower costs as long as the cross effects in demand are relatively small (e.g., $|P^h_{q^f} + q^h P^h_{q^h q^f}| \leq |2P^h_{q^h} + q^h P^h_{q^h q^h}|$) or equal across countries i.e., $P^h_{q^f} + q^h P^h_{q^h q^f} = P^f_{q^h} + q^f P^f_{q^f q^h}$. This is because equally lower costs (i.e., $d\tilde{z} < 0$) results in lower emissions since the effect via lower marginal costs in each country induces less output, more abatement and therefore lower emissions. It is noteworthy that this result holds even as pollution intensities differ across countries i.e., $-C^f_{e^f q^f}/C^f_{e^f e^f} \neq -C^h_{e^h q^h}/C^h_{e^h e^h}$. In contrast, if the effect via emission taxes on marginal abatement costs is small in each country so that the term $C^k_{e^k} \simeq 0$ becomes negligible (and so $C^h_{q^h} \simeq C^f_{q^f}$), and still under the assumption of relatively small cross effects in demand, then $dE > 0$ and so global emissions rise with policy reform $d\tilde{z} < 0$. This result underscores the importance of coupling cost reduction policies with emission taxes if global emissions are to be tackled.

To further illustrate the role of pollution intensities suppose that the foreign country is sufficiently large as defined in proposition 3.2 and that there is asymmetry in the extent to which the cost parameter, z, affects output in each country i.e., assume $C^h_{q^h} - C^h_{e^h} C^h_{e^h q^h}/C^h_{e^h e^h} > 0$ and $C^f_{q^f} - C^f_{e^f} C^f_{e^f q^f}/C^f_{e^f e^f} < 0$. Then, a policy reform consisting of $dz^h > 0$ and $dz^f > 0$ results in higher global emissions. This is because, on the one hand, higher costs in the foreign country, the relatively more pollution-intensive country, increase emissions in that country because the effect via higher marginal abatement cost is sufficiently large. On the other hand, higher costs in the home country lowers output and emissions in that country (since the effect via higher marginal abatement cost is sufficiently small in the home country), but this is completely offset by the increase in foreign, sufficiently more pollution-intensive output.

Now consider the policy reform $dz^h < 0$ and $dz^f > 0$, and suppose that the foreign country is sufficiently pollution intensive. Further, suppose that in the foreign country only the effect of the tax on marginal abatement costs is negligible (i.e., $C^f_{e^f} \simeq 0$), and in the home country the cost of producing an extra unit of output is large (i.e., $C^h_{q^h} > C^h_{e^h} C^h_{e^h q^h} / C^h_{e^h e^h}$)[7]. As a result, global emissions fall in the case where the pollution intensive country, with no real presence of emission taxes in marginal abatement costs, raises costs; while the relatively less pollution intensive country, with relatively high costs of producing an extra unit of output, reduces costs.

As a final policy reform consider $dz^h > 0$ and $dz^f < 0$. Suppose pollution intensity coefficients and asymmetry in the effects of the cost parameter are as follows: (i) the foreign country is sufficiently pollution intensive, and (ii) the tax-effect, $C^k_{e^k}$, is small in the sense that $C^k_{e^k} \Delta / z^k C^k_{e^k e^k}$ for $k = h, f$ in (13) become negligible, but at the same time the inequality $C^f_{q^f} - C^f_{e^f} C^f_{e^f q^f} / C^f_{e^f e^f} < 0$ still holds because the pollution intensity $-C^f_{e^f q^f} / C^f_{e^f e^f}$ is assumed to be sufficiently large and the inequality $C^h_{q^h} - C^h_{e^h} C^h_{e^h q^h} / C^h_{e^h e^h} > 0$ still holds because $-C^h_{e^h q^h} / C^h_{e^h e^h}$ is assumed to be sufficiently small. Thus, in this case global emissions fall, on the one hand, via the reduction in costs in the foreign country, z^f, but on the other global emissions increase via an increase in z^h. Global emissions can fall if the foreign country, the pollution-intensive country, sets a sufficiently aggressive cost-reducing policy i.e., $dz^f < 0$ and large.

Proposition 3.3. *Suppose there is symmetry across countries in the cost effects via z (i.e., $C^h_{q^h} - C^h_{e^h} C^h_{e^h q^h} / C^h_{e^h e^h} = C^f_{q^f} - C^f_{e^f} C^f_{e^f q^f} / C^f_{e^f e^f}$). Then, in the case where the effects on marginal abatement costs via the tax are negligible (large) in both countries, global emissions rise (fall) with a multilateral cost-reducing policy reform (i.e., $dz^h = dz^f < 0$) as long as the cross effects via demand are relatively small.*

Proposition 3.4. *Let the foreign country be sufficiently pollution intensive as defined in proposition 3.2 and, additionally, let the effects on marginal abatement costs via the tax be*

[7] One cost function which satisfies this latter condition is a cost function of the end-of-pipe $C(q, e) = c(q) + g(a)$, where the first (second) term denotes production (abatement) costs, $a = \delta(q) - e$, $\delta' > 0$,$\delta'' > 0$; and $C_{qe} = C_{eq} < 0$, $C_{qq} > 0$, $C_{ee} > 0$, $C_{ee} C_{qq} - C^2_{qe} > 0$.

negligible in the foreign country (i.e., $C^f_{e^f} \simeq 0$), and the cost of producing an extra unit of output relatively large in the home country (i.e., $C^h_{q^h} > C^h_{e^h} C^h_{e^h q^h} / C^h_{e^h e^h}$). Then a policy reform of lower costs in the home country ($dz^h < 0$) but higher costs in the foreign country ($dz^f > 0$) results in lower global emissions.

Next, I analyze the effects of policy reform of taxes, t^h and t^f, on global emissions, but since the analysis of taxes has been studied in the literature (e.g., Lahiri and Symeonidis 2007; Gautier 2016) here I just make two remarks. Using (9) and (10), the effect of the tax on global emissions, $E = e^h + e^f$, is given by

$$
\begin{aligned}
\Delta dE \;=\; & \frac{-C^h_{q^h e^h}}{C^h_{e^h e^h}} \left[\frac{-C^h_{q^h e^h}}{C^h_{e^h e^h}} \left(-\left(2P^f_{q^f} + q^f P^f_{q^f q^f}\right) + z^f \frac{C^f_{e^f e^f} C^f_{q^f q^f} - C^{f2}_{e^f q^f}}{C^f_{e^f e^f}} \right) + \Delta / z^h C^h_{q^h e^h} \right. \\
& \left. - \frac{C^f_{q^f e^f}}{C^f_{e^f e^f}} \left(P^f_{q^h} + q^f P^f_{q^f q^h} \right) \right] dt^h \\
& \frac{-C^f_{q^f e^f}}{C^f_{e^f e^f}} \left[\frac{-C^f_{q^f e^f}}{C^f_{e^f e^f}} \left(-\left(2P^h_{q^h} + q^h P^h_{q^h q^h}\right) + z^h \frac{C^h_{e^h e^h} C^h_{q^h q^h} - C^{h2}_{e^h q^h}}{C^h_{e^h e^h}} \right) + \Delta / z^f C^f_{q^f e^f} \right. \\
& \left. - \frac{C^h_{q^h e^h}}{C^h_{e^h e^h}} \left(P^h_{q^f} + q^h P^h_{q^h q^f} \right) \right] dt^f \qquad (14)
\end{aligned}
$$

where the first term captures changes in global emissions from changes in output and the term $\Delta / z^k C^k_{q^k e^k}$ captures changes in global emissions arising from the abatement induced by the tax.

Remark 3.5. *Global emissions fall with an increase in the emission tax in the home country, if the home country exhibits a relatively large intensity coefficient or if pollution intensities across countries are equal (i.e., $-C^h_{q^h e^h} / C^h_{e^h e^h} \geq -C^f_{q^f e^f} / C^f_{e^f e^f}$) . Alternatively, global emissions rise if the foreign country exhibits a sufficiently large pollution intensity coefficient as stated in proposition 3.2.*

Remark 3.6. *Let (i) the foreign country be sufficiently pollution intensive as defined in proposition 3.2 and (ii) the cross effect on demand in both countries is either small or equal across countries. Then, a proportional increase in the emission tax in the home and foreign country (i.e., $dt^h = dt^f > 0$) reduces global emissions.*

Up to this point the analysis has looked at policy reform consisting of changes in either taxes or the cost parameters z^k. In order to combine policy reforms it is important to note that policy reform of the cost parameter, z^k, may induce changes in taxes since taxes in equilibrium are a function of the cost parameter i.e., $t^{h*}(z^h, z^f)$, $t^{f*}(z^h, z^f)$. I delve into the characterization of policy in section 4. With this in mind, consider the policy reform of $dz^h < 0$ which gives the possibility of $dt^h > 0$, if $t^h_{z^h} < 0$, or $dt^h < 0$, if $t^h_{z^h} > 0$, where for given z^f, $dt^h = t^h_{z^h} dz^h$. The case where $t^h_{z^h} < 0$ may denote that, with a higher z^h, the government offsets damages from transboundary pollution and losses in welfare via the profit-shifting effect as home firms lose market share as a result of higher cost. In the case where $t^h_{z^h} < 0$ gives, using (13) and (14), that global emissions fall as long as the home country is at least as pollution-intensive as the foreign country (i.e., $-C^h_{q^h e^h}/C^h_{e^h e^h} \geq -C^f_{q^f e^f}/C^f_{e^f e^f}$) and the increase in emissions via lower marginal costs, due to a reduction in z^h, is small (i.e., $C^h_{q^h} < C^h_{e^h} C^h_{q^h e^h}/C^h_{e^h e^h}$). This is because global emissions fall via the reduction in z^h and at the same time via a higher tax, t^h. Global emissions rise otherwise under the same conditions if $dz^h > 0$ and $t^h_{z^h} < 0$, where higher costs, z^h, result in higher global emissions since $C^h_{q^h} < C^h_{e^h} C^h_{q^h e^h}/C^h_{e^h e^h}$, and concomitantly, because the government lowers the emission tax.

As a second policy reform, consider an equal increase in the tax and cost parameter in the home country (i.e., $dt^h = dz^h > 0$). It is noteworthy that this policy reform requires $t^h_{z^h} = 1$. With this in mind it can be shown that global emissions fall as long as the home country is at least as pollution-intensive as the foreign country and the increase in emissions via higher marginal abatement costs, resulting from an increase in z^h, is sufficiently small i.e., the role of the emission tax in the home country is small, $C^h_{e^h} + 1 > 0$. This result is important because it suggests that a pollution-intensive country, with a relatively small role of its emission tax, may reduce global emissions via taxation and higher costs.

In particular, combining (13) and (14) yields

$$\Delta dE \;=\; \left[\left(C^h_{q^h} - \frac{C^h_{e^h q^h}}{C^h_{e^h e^h}}(C^h_{e^h}+1)\right)\eta - \frac{C^h_{e^h q^h}}{C^h_{e^h e^h}}(C^h_{e^h}+1)\Delta/z^h C^h_{e^h e^h}\right] d\alpha \tag{15}$$

where $dt^h = dz^h = d\alpha$ and

$$\eta \;:=\; \frac{-C^h_{q^h e^h}}{C^h_{e^h e^h}}\left(-\left(2P^f_{q^f} + q^f P^f_{q^f q^f}\right) + z^f \frac{C^f_{e^f e^f} C^f_{q^f q^f} - C^{f2}_{e^f q^f}}{C^f_{e^f e^f}}\right) - \frac{C^f_{q^f e^f}}{C^f_{e^f e^f}}\left(P^f_{q^h} + q^f P^f_{q^f q^h}\right)$$

whence $\eta > 0$, if $-C^h_{q^h e^h}/C^h_{e^h e^h} \geq -C^f_{q^f e^f}/C^f_{e^f e^f}$.

Proposition 3.7. *Let the home country be relatively pollution-intensive and suppose that the change in emissions via the cost of an extra unit of output is small. Then, a policy reform consisting of a tax increase ($dt^h > 0$) and reduction in costs ($dz^h < 0$) lowers global emissions.*

Proposition 3.8. *Let the home country be relatively pollution-intensive and assume $t^h_{z^h} = 1$. Then, a policy reform consisting of higher costs and taxation ($dt^h = dz^h > 0$) lowers global emissions as long as the role of the emission tax in the home country is small i.e., $C^h_{e^h}+1 > 0$.*

4. Welfare and Policy Reform

In this section, I examine the impact of policy reform on welfare i.e., how policy reform in one country affects welfare in the other country. The analysis can be thought of as efforts by countries to coordinate multilateral policy. As presented in the literature (e.g., Kayalica and Lahiri 2005; Hatzipanayatou et al. 2005; Gautier 2014) this type of analysis captures the externalities and inefficiencies of the non-cooperative equilibrium.

I shall follow Ulph and Ulph (2007) and Gautier (2014) in the set-up of the welfare function where consumer surplus effects are assumed away. In this way issues of strategic environmental policy, as it pertains to profit-shifting effects, and transboundary pollution can be the focus of the analysis.

Define welfare in the home country as follows

$$W^h = \pi^h + e^h t^h - \varphi^h(E) \tag{16}$$

where φ^h denotes damages from pollution in the home country, which satisfies $\varphi^{h\prime} > 0$, $\varphi^{h\prime\prime} > 0$ and $E = e^h + e^f$ denotes global emissions. Since the function $\varphi^h(\cdot)$ depends on global emissions, damage from pollution in the home country captures also effects via transboundary pollution. An analogous expression applies to W^f, the welfare function of the foreign country. The home and foreign country simultaneously choose the emission tax taking the other country's policy as given. This yields a non-cooperative policy vector $t^{h*}(z^h, z^f)$, $t^{f*}(z^h, z^f)$. I shall assume interior solutions in order to account for the interaction between taxes and the cost parameters in policy reform.

Differentiation of the welfare function for each country yields (subscripts denote partial derivatives)

$$dW^h = \left[q^h P^h_{q^f} \tfrac{\partial q^f}{\partial t^h} - z^h C^h_{e^h} \tfrac{\partial e^h}{\partial t^h} - \varphi^{h\prime} \tfrac{\partial E}{\partial t^h}\right] dt^h + \left[q^h P^h_{q^f} \tfrac{\partial q^f}{\partial t^f} - z^h C^h_{e^h} \tfrac{\partial e^h}{\partial t^f} - \varphi^{h\prime} \tfrac{\partial E}{\partial t^f}\right] dt^f \tag{17}$$

$$dW^f = \left[q^f P^f_{q^h} \tfrac{\partial q^h}{\partial t^f} - z^f C^f_{e^f} \tfrac{\partial e^f}{\partial t^f} - \varphi^{f\prime} \tfrac{\partial E}{\partial t^f}\right] dt^f + \left[q^f P^f_{q^h} \tfrac{\partial q^h}{\partial t^h} - z^f C^f_{e^f} \tfrac{\partial e^f}{\partial t^h} - \varphi^{f\prime} \tfrac{\partial E}{\partial t^h}\right] dt^h \tag{18}$$

where at the Nash equilibrium the first term in (17) and (18) are equal to zero.

I want to see how taxes and the cost parameter in one country affect the other country's welfare, starting at the Nash equilibrium. This is to have a sense of how policy reform affects welfare across countries. To achieve this, I look at the foreign country's welfare, where differentiation of W^f, starting at the Nash equilibrium while keeping in mind that $t^{h*}(z^h, z^f)$, $t^{f*}(z^h, z^f)$, gives (subscripts denote partial derivatives and dropping the "*" superscript for notational simplicity)

$$dW^f \;=\; \left[W^f_{t^h} t^h_{z^h} + W^f_{z^h}\right] dz^h + \left[W^f_{t^h} t^h_{z^f} + W^f_{z^f}\right] dz^f \tag{19}$$

where the term $W^f_{t^h}$ is given by the last term in (18), $W^f_{z^h} = q^f P^f_{q^h} q^h_{z^h} + t^f e^f_{z^h} - \varphi^{f\prime} E_{z^h}$, and $W^f_{z^f} = q^f P^f_{q^h} q^h_{z^f} + t^f e^f_{z^f} - \varphi^{f\prime} E_{z^f}$.

To delve into the analysis of (19), I first characterize optimal policy and then find the expression for $t^h_{z^h}$. In particular, using (17) optimal taxation in the home country satisfies (subscripts denote partial derivatives)

$$t^{h*} \;=\; -\frac{q^h P^h_{q^f} q^f_{t^h}}{e^h_{t^h}} + \varphi^{h\prime} \frac{e^f_{t^h}}{e^h_{t^h}} + \varphi^{h\prime} \tag{20}$$

where $P^h_{q^f} < 0$, $q^f_{t^h} > 0$, $e^f_{t^h} > 0$. An analogous expression applies to t^{f*}. The term $e^h_{t^h}$ could be positive or negative as discussed in previous sections, but for now consider the case where $e^h_{t^h} < 0$. The first term denotes the incentives to set a lower tax to offset the profit-shifting effect arising from the foreign country, the second term also puts a downward pressure on the optimal tax in order to address transboundary pollution coming from the foreign country (a lower tax at home lowers output in the foreign country thereby lowering pollution coming from that country); and the third term addresses damages from pollution arising from emissions in the home country. An analogous analysis applies to t^{f*}.

There are a number of opposing effects on the optimal tax in the home country arising from changes in z^h. First, an increase in z^h may lower output at home which prompts the home country to lower the tax; and second, an increase in z^h may result in an increase in emissions in the foreign country thereby exacerbating damages from transboundary pollution. Third, an increase in global emissions creates additional damages from pollution, and thus adjustments in the tax in the home country, resulting from non-linearities in the damage function in both countries.

To explore these effects further consider a cost function of the end-of-pipe $C(q,e) = \tilde{c}q + (\delta q - e)^2/2$ where the first (second) term denotes production (abatement) costs, abatement is given by $a = \delta q - e$, where δ is a positive constant which denotes pollution intensity, and $C_{qe} = C_{eq} = -\delta < 0$, $C_{qq} = \delta^2 > 0$, $C_{ee} = 1 > 0$, $C_{ee}C_{qq} - C_{qe}^2 = 0$. In this case $C_q - C_e C_{eq}/C_{ee} = \tilde{c} > 0$, $e^h_{t^h} < 0$, $e^f_{t^f} < 0$, $q^f_{t^f} < 0$, $q^h_{t^h} < 0$, $e^h_{t^f} > 0$, $q^h_{t^f} > 0$, $e^f_{t^h} > 0$, $q^f_{t^h} > 0$, $q^f_{z^f} < 0$, $q^h_{z^h} < 0$, $e^h_{z^f} > 0$, $q^h_{z^f} > 0$, $e^f_{z^h} > 0$, $q^f_{z^h} > 0$. Moreover, consider the case of linear demand where $P^h_{q^h} = P^f_{q^f} = -\beta$, $P^h_{q^f} = P^f_{q^h} = -\gamma$, $\beta > \gamma > 0$, where γ denotes the degree of product differentiation: $\beta = \gamma$ captures the case of homogeneous goods, whereas $0 = \gamma$ the case of completely differentiated products. In what follows I shall assume this demand and cost structure to derive results.

Differentiation of (20) and an analogous expression for t^{f*}, with respect to z^h, and using (7)-(12) yields[8]

$$\omega t^h_{z^h} = P^h_{q^f} q^f_{t^h} q^h / z^h - \varphi^{h\prime} e^f_{t^h}/(z^h)^2 + \varphi^{h\prime\prime} e^h_{t^h} E_{t^h} E_{z^h} - \varphi^{f\prime\prime} e^h_{t^h} E_{t^f} E_{z^h} \frac{P^h_{q^f} q^h_{t^h}}{e^f_{t^f} P^f_{q^h} q^h_{t^f}} \qquad (21)$$

[8]The goal here is to analyze unilateral policy by the home country and its impact on welfare of the foreign country without a policy change in the foreign country. This exemplifies cases where countries act unilaterally without any policy response by other countries. Consistent with this goal I assume that the foreign country does not change policy as a result of a unilateral policy change by the home country.

where $e^h_{t^h} < 0$,$e^f_{t^f} < 0$, $q^h_{t^h} < 0$, $q^f_{t^h} > 0$, $\omega = (e^h_{t^h})^2 - e^h_{t^h}(E_{t^h})^2\varphi^{h\prime\prime} > 0$. The first and second terms capture, respectively, reductions in the tax to offset profit-shifting and transboundary pollution. The last two terms could be positive or negative under a number of assumptions about global emission. But if, for example, the last two terms arising from non-linearities in the damage function are negligible (e.g., marginal damage functions are not too convex), then $t^h_{z^h} < 0$. Alternatively, suppose that conditions are such that $E_{t^k} < 0$ for $k = h, f$ and $E_{z^h} > 0$. Then, the third term is positive thus indicating that the tax at home is adjusted upwards with an increase in z^h in order to tackle higher damages at home resulting from higher global emissions. The fourth term is negative thus indicating that the tax at home is lowered with an increase in z^h in order to reduce damages in the foreign country resulting from higher global emissions: specifically, an increase in z^h induces an increase in t^h which lowers damages to the foreign country via transboundary pollution, but this is completely offset by a reduction in t^h in order to reduce emissions in the foreign country and thus damages in that country.

To complete the set-up necessary to analyze policy reform, I make a few remarks about the terms $W^f_{t^h}$ and $W^f_{z^h}$ in (19) assuming a cost function of the end-of-pipe as defined earlier. First, in $W^f_{t^h} = q^f P^f_{q^h} q^h_{t^h} + (t^f - \varphi^{f\prime})e^f_{t^h} - \varphi^{f\prime} e^h_{t^h}$ an increase in the tax in the home country raises welfare in the foreign country via the profit-shifting term, $q^f P^f_{q^h} q^h_{t^h} > 0$, the reduction in transboundary pollution, $-\varphi^{f\prime} e^h_{t^h} > 0$, and lower abatement costs, $t^f e^f_{t^h} > 0$; but welfare in the foreign country falls as a result of higher emissions in the foreign country and thus higher damages from pollution, $-\varphi^{f\prime} e^f_{t^h} < 0$. Second, from the term $W^f_{z^h} = q^f P^f_{q^h} q^h_{z^h} + t^f e^f_{z^h} - \varphi^{f\prime} E_{z^h}$ an increase in z^h raises welfare in the foreign country via profit-shifting, lower abatement costs and lower transboundary pollution as long as higher costs reduce emissions at home; but welfare in the foreign country falls via higher emissions in the foreign country as a result of an increase in z^h i.e. $-\varphi^{f\prime} e^f_{z^h} < 0$.

With the above results in mind and under the assumption of a cost function of the end-of-pipe as defined earlier, the following results are stated. An increase in costs in the home country, z^h, for given tax, raises welfare in the foreign country if global emissions fall with z^h (i.e. $E_{z^h} < 0$) and thus damages from global pollution do not lower welfare in the foreign country i.e., $-\varphi^{f\prime} E_{z^h} > 0$. Alternatively, if $E_{z^h} > 0$ welfare in the foreign country rises if the home country reduces costs (i.e., z^h falls) and the reduction in damages from global pollution is sufficiently large i.e., $-\varphi^{f\prime} E_{z^h} < 0$ and large so that $W^f_{z^h} > 0$. Moreover, an increase in the tax in the home country lowers (raises) welfare in the foreign country if global emissions rise (fall) with the taxi.e., $E_{t^h} > (<) 0$. Therefore, a policy reform consisting of lower costs in the home country raises welfare in the foreign country as long as (i) the reduction in global emissions lowers damages in the foreign country sufficiently (i.e., $E_{z^h} > 0$, $-\varphi^{f\prime} E_{z^h} < 0$ and large), and (ii) the tax in the home country rises as a result (i.e., $t^h_{z^h} < 0$) with a corresponding reduction in global emissions via the tax (i.e., $E_{t^h} < 0$).

Proposition 4.1. *Suppose the cost function is of the end-of-pipe i.e., $C(q, e) = \tilde{c}q + (\delta q - e)^2/2$. And let global emissions fall with an increase in the tax in the home country ($E_{t^h} < 0$) and with a reduction in costs in the home country ($E_{z^h} > 0$). Then, a policy reform consisting of lower costs in the home country ($dz^h < 0$) with a subsequent increase in taxation ($t^h_{z^h} < 0$) increases welfare in the foreign country as long as the reduction in damages from global emissions in the foreign country resulting from the cost reduction is large i.e., $q^f P^f_{q^h} q^h_{z^h} + t^f e^f_{z^h} < \varphi^{f\prime} E_{z^h}$.*

It is important to note that the conditions $E_{z^h} > 0$ and $E_{t^h} < 0$ in proposition 4.1 hold in the case where the pollution intensity coefficient in home country is large $-C^h_{e^h q^h}/C^h_{e^h e^h} > -C^f_{e^f q^f}/C^f_{e^f e^f}$ and the abatement resulting from lower costs is large i.e., the term $-C^h_{e^h} \Delta / C^h_{e^h e^h} z^h$ in (13) is sufficiently large. Additionally, for $E_{z^h} > 0$ and $E_{t^h} < 0$ to be consistent with $t^h_{z^h} < 0$, non-linearities ought be relatively small (i.e., $\varphi^{h\prime\prime}$ and $\varphi^{f\prime\prime}$ small).

5. Conclusion

The analysis of policy reform is timely and relevant. Recent developments in the kind and number of international/regional agreements suggest that regulatory and environmental policies are likely to be adjusted to new environmental challenges, thereby prompting policy reform across countries. This paper considers a two-country model where firms behave in a Cournot fashion and face an emission tax, and countries undertake policy reform of emissions taxes and cost-related regulations associated to production costs and pollution abatement costs. The model allows for asymmetries in abatement cost functions, thereby capturing differences in pollution intensities (i.e., emissions per unit of output) and marginal abatement costs. The analysis indicates, *inter alia*, that the ability of countries to reduce local and global emissions via policy reform depends crucially on these asymmetries. For example, unilateral policy consisting of higher taxes and lower costs by the pollution-intensive country may reduce global emissions. Other multilateral policies are analyzed where the presence of an emission tax to reduce emissions, via the incentives created by the marginal abatement cost function, is crucial in reducing emissions.

Inevitably, the analysis and policy implications depend crucially on the model assumptions, but at the same time the paper presents several important potential lines for future research. First, the analysis can be easily extended to the n-firm case in order to capture aspects of industry size and free-entry and exit of firms. Even though the factors driving the results do not change, incorporating more firms into the analysis can add interesting aspects of firm competition and how this may alter the effectiveness of policy reform. Second, in many cases international agreements force countries to face policy choices to tackle local and global pollutants, while facing pressure to be more competitive in the global market. In this context adding more pollutants to the analysis in the spirit of Amber and Coria (2013), while keeping asymmetries in abatement cost functions, would render the analysis richer and perhaps more pertinent to current environmental agreements. Third, in the current paper the parameter z, which captures exogenous changes in production and pollution abatement costs, can be endogenized. Even though the literature has endogenized this type of cost parameter, the focus has been to think about it in terms of environmental R&D affecting pollution abatement costs (e.g., Montero 2002a, 2002b) or a subsidy to R&D (e.g., Gautier 2014). Fourth, an additional line of research would be to incorporate aspects of political economy in the decision making process determining policy reform, which in the present paper are assumed away but which play an important role in regional/international agreements.

References

Ambec, S. and Coria, J. (2013), "Price vs quantities with multiple pollutants", *Journal of Environmental Economics and Management*, 66: 123- 140.

Barrett, S. (2003), *Environment and statecraft: The strategy of environmental treaty-making*, Oxford: Oxford University Press.

Barrett, S., Carraro, C. and de Melo, J. (2015), *Towards a Workable and Effective Climate Regime*, VOX CEPR's Policy Portal. Available at: http://www.voxeu.org/content/towards-workable-and-effective-climate-regime

Bayındır-Upmann, T. (2003), "Strategic environmental policy under free entry of firms", *Review of International Economics*, 11: 379-396.

Bhattacharya, R.N. and Pal, R. (2010), "Environmental standards as strategic outcomes: A simple model", *Resource and Energy Economics*, 32(3): 408-420.

Carlsson, F. (2000), "Environmental taxation and strategic commitment in duopoly models", *Environmental & Resource Economics*, 15(3): 243-256.

Caplan, A.J. and Silva, E.C.D. (2005), "An efficient mechanism to control correlated externalities: redistributive transfers and the coexistence of regional and global permit markets", *Journal of Environmental Economics and Management*, 49: 68-82.

Dixit, A. (1986), “Comparative statics for oligopoly”, *International Economic Review*, 27(1): 107-122.

DOC (2010), “U.S. carbon dioxide emissions intensities over time: A detailed accounting of industries, government and households”, *Department of Commerce Economics and Statistics Administration*, U.S. Department of Commerce, April.

Elliott, R.J.R. and Zhou, Y. (2013),“Environmental regulation induced foreign direct investment”, *Environmental & Resource Economics*, 55: 141-158.

Gautier, L. (2013), “Multilateral policy reform of emission taxes and abatement subsidies in a two-country model with oligopolistic interdependence”, *Environmental Economics and Policy Studies*, 15(1): 59-71.

Gautier, L. (2014), “Policy reform of emission taxes and environmental research and development incentives in an international Cournot model with product differentiation”, *Environment and Development Economics*, 19(4):440-465.

Gautier, L. (2015), “Horizontal product differentiation, pollution abatement and emission taxes under oligopoly”, in M.G. Fikru and M. Install (eds), *Economics of Environmental Policy in Oligopolistic Markets*, New York: Nova Science Publishers, 1-20.

Gautier, L. (2016), “Emission taxes and product differentiation in the presence of foreign firms”, *Journal of Public Economic Theory*, doi: 10.1111/jpet.12204.

Grether, J.M. and de Melo, J. (2004), “Globalization and dirty industries: Do pollution havens matter?”, in R.E. Baldwing and A. Winters (eds), *Challenges to Globalisation: Analyzing the Economics*, Chicago: University of Chicago Press.

Hatzipanayotou, P., Lahiri, S. and Michael, M.S. (2005),“ Reforms of environmental policies in the presence of cross-border pollution and publicprivate clean-up”, *Scandinavian Journal of Economics*, 107 (2):315-333.

Hoel, M. (1991), “Global environmental problems: The effects of unilateral actions taken by one country”, *Journal of Environmental Economics and Management*, 20(1): 55-70.

Kahn, M.W. (2016), “The climate change adaptation literature”, *Journal of Environmental Economics and Policy*, 10(1): 166-178.

Kayalica, M. Ö. and Lahiri, S. (2005), "Strategic environmental policies in the presence of foreign direct investment", *Environmental & Resource Economics*, 30(1): 1-21.

Lahiri, S. and Symeonidis, G. (2007),"Piecemeal multilateral environmental policy reforms under asymmetric oligopoly", *Journal of Public Economic Theory*, 9(5): 885-899.

Montero, P. (2002a), "Permits, standards, and technology innovation", *Journal of Environmental Economics and Management*, 44(1): 23-44.

Montero, P. (2002b), "Market structure and environmental innovation", *Journal of Applied Economics*, 5 (2): 293-325.

Neumayer, E. (2001),"Pollution havens: An analysis of policy options for dealing with an elusive phenomenon", *Environment and Development Economics*, 10(2): 147-177.

Requate, T. (2006), "Environmental policy under imperfect competition", in T. Tietenberg and H. Folmer (eds), *The international yearbook of environmental and resource economics 2006/2007*, Cheltenham: Edward Elgar Publishing Limited, 120-207.

Silva, E.C.D. and Zhu, X. (2009), "Emissions trading of global and local pollutants, pollution havens and free riding", *Journal of Environmental Economics and Management*, 58(2): 169-182.

Sterner, T. and Köhlink, G. (2015), "Pricing carbon: The challenges", in S. Barrett, C. Carraro, and J. de Melo (eds), *Towards a Workable and Effective Climate Regime*, VOX CEPR's Policy Portal. Available at: http://www.voxeu.org/content/towards-workable-and-effective-climate-regime

Turunen-Red, A. and Woodland, A.D. (2004), "Multilateral reforms on trade and environmental policy", *Review of International Economics*, 12(3): 321-336.

Ulph, A. (1996), "Environmental policy and international trade when governments and producers act strategically", *Journal of Environmental Economics and Management*, 30: 265-281.

Ulph, A. and Ulph, D. (1996), "Trade, strategic innovation and strategic environmental policy a general analysis", in C. Carraro, Y. Katsoulacos and A. Xepapadeas (eds), *Environmental Policy and Market Structure*, Netherlands: Kluwer Academic Publishers, 181-208.

Ulph, A. and Ulph, D. (2007), “Climate change-environmental and technology policies in a strategic context”, *Environmental & Resource Economics*, 37(1): 159-180.

Zarsky, L. (1999), “Havens, halos and spaghetti: Untangling the evidence about foreign direct investment and the environment”, *OECD conference on foreign direct investment and the environment*, 47-73.