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# Working Paper Strategic Export Motives and Linking Emission Markets

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# Strategic Export Motives and Linking Emission Markets

# Abstract

We explore the possibility of achieving a cooperative outcome when governments act noncooperatively in a strategic environmental policy model where emission permit markets are linked. We introduce a specific distribution scheme of the permit revenues between the exporting countries so as to sustain the cooperative outcome as a subgame perfect Nash equilibrium. Participation in the scheme is endogenized and we show that it constitutes a subgame perfect Nash equilibrium as long as the countries are not too asymmetric. Our results are robust once we allow for multiple pollutants, different modes of competition and market power in the permits market.

JEL-Codes: Q580, F120, F180.

Keywords: strategic environmental policy, internationally tradable permits, cross-border pollution, imperfect competition, welfare.

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# 1 Introduction

The recent alarming calls against climate degradation bring forth more vividly than ever before the need for enhanced collective action against this problem, e.g., The Economist (2019). For example, in line with this realization, whereas broad participation has been achieved in the Paris Agreement, adequate collective ambition for national contributions pledged by individual countries has not been met, e.g., Mehling et al. (2018). The reluctance regarding the ratification of the Paris Agreement is indicative of the difficulties in overcoming the consolidated *prisoners' dilemma* situation. The problem is mainly due to two reasons. First, combating climate degradation is difficult due to the potential carbon leakage effect and also because of the presence of free-riding incentives. Second, there are concerns at countries' level of other crucial economic adversities which may emerge as a result of stricter environmental regulations, e.g., the loss of international competitiveness of national exporting firms, the hindrance in inflows of Foreign Direct Investment (FDI), and the weakening of growth and domestic employment prospects (Martin et al., 2014). Such and other scepticism necessitate the search for potential mechanisms that improve the current regulatory schemes in the presence of strategic motives.

The general global trend for  $CO_2$  emissions regulation is to create emission permit markets, initially at a local level and then gradually extend them across different regions and countries (e.g., Schmalensee and Stavins, 2017). There are now numerous active Emission Trading Systems (ETS). The most well known is the European Union Emissions Trading System (EU ETS) that is the oldest and still largest ETS for GHGs operating worldwide. More than 11,000 power plants across different sectors participate and approximately 45% of the EU emissions are covered by this system (ICAP. 2020). In January 2020 the EU ETS became linked to the Swiss ETS. In the other side of the Atlantic the Western Climate Initiative (WCI) is an act of American state and Canadian provincial governments that aimed at developing a joint strategy to reduce GHG emissions via a cap-and-trade program. California, Quebec and Ontario independently established their own systems using the framework developed by the WCI approach and afterwards at different points in time linked their ETS. Many more programs are now present, among others in China, Japan, Mexico, New Zealand and Republic of Korea. An interesting feature that these programs share is that a portion of the permits allocated to the producers are grandfathered, whereas the rest is auctioned (e.g., Phase III of the EU ETS). Then, the revenue generated from the permits auctions is either lump-sum distributed back to the societies or it is earmarked to finance the provision of public goods. By the end of 2018, the EU ETS has raised revenue of 15.8\$ billion, which on the one hand, according to information submitted, has been used by approximately 80% to finance domestic and international climate-related projects, e.g., renewable energy promotion, but also, on the other hand, to finance other non-environmental ones, e.g., innovation and the general budget (ICAP, 2020). One way or another this appears to be at least partially the case in many active tradable permits schemes. For example in the WCI, most of California's revenue from permits auctions goes to the Greenhouse Gas Reduction Fund. As these ETS mature, it is observed that a smaller portion of permits issued is grandfathered to the participants, while their larger portion is auctioned. Then, the incoming auction revenue is distributed back to the jurisdictions in the forms described previously. Naturally, this pattern rises the question of whether these trends, i.e., linkage of permit markets along with targeted auction revenue distribution across jurisdictions, are moving into the right direction, or whether ETS should be modified once the incentives presented above leading to the prisoners' dilemma are accounted for.

The aim of this study is to address these issues. To this end we develop a three-stage game of strategic environmental policy. Prior to the traditional two-stage strategic environmental policy game, we introduce a pre-stage, Stage "0", where countries decide on establishing a tradable permits system where all permits are sold in the market, thus, ruling out a grandfathering scheme. The ensuing revenue from permits sales are then distributed according to the features of our model. For example, in the symmetric case where the countries are the same in terms of abatement technologies and damages from pollution it suffices to guarantee in Stage 0 that all the permit expenses of the local firm will be returned to the residents of that country. Then, in the next stage, Stage "1". the governments decide unilaterally on the level of permits issued. In the final stage of the game, Stage "2", the firms compete in terms of their output in the world market. Under this scheme, we illustrate that there exists an infinite number of subgame perfect Nash equilibria that share a common feature. That is, the aggregate level of pollution is equivalent to the one that maximizes the joint welfare. This result is in sharp contrast with the standard result of the relevant literature, as presented in the following section, where a race to the bottom occurs in environmental regulation when it is used for trade purposes as well. Our results suggest that it suffices to link tradable permit markets across countries without grandfathering and allow for a specific distribution of permit revenues across countries to be defined and the race to the bottom disappears. The reason is that the proposed mechanism removes the strategic incentives of the exporting countries as the marginal abatement costs are always equal to the permit price and thus regulation affects equally the marginal abatement costs of every firm regardless of the firms' location. Moreover, the externality is correctly internalized and the incentive to issue additional permits to extract gains from the permits market disappears because issuing an additional permit affects pollution in the same way in any country. In the full version of the game, where in Stage 0 the countries decide on linking the national ETS or not, we show that under the unanimity rule participation constitutes a subgame perfect Nash equilibrium as the exporting countries do not have a unilateral incentive to deviate.

Our results extend also to asymmetric cases such as the presence of different damages from pollution or different abatement technologies across countries. To achieve this outcome a specific distribution of the permit revenues is required which corresponds to indirect transfers. When the countries differ in terms of damages from pollution the country with the higher marginal damage receives a larger portion of the aggregate permit revenues and thus an indirect transfer from the other country. When the countries differ in terms of abatement costs the country with the lower costs receives a larger proportion of the aggregate permit revenues which translates to an indirect transfer from the rival country. Naturally, the presence of asymmetries in the characteristics of the countries also implies asymmetric outcomes. This, casts doubt regarding participation in the extended version of the game. In Section 6 we discuss the effect of asymmetries over participation by conducting numerical simulations corresponding to different scenarios. We obtain that for a relatively small degree of asymmetries, in technologies or damages from pollution, e.g., 10%, we are still able to sustain the cooperative solution as a subgame perfect Nash equilibrium in the full game. On the contrary, for larger degrees of asymmetries, e.g., 40%, the country that receives the lowest share of the revenues face an incentive to deviate in Stage 0. Interestingly, we show that we can still obtain the cooperative solution as a subgame perfect Nash equilibrium for a relatively large degree of asymmetries when they are positively correlated. In addition, we illustrate that if we impose exogenously that the permit revenues are split equally between countries, it is more likely for our scheme to become implementable and yield welfare gains to the countries relative to a case without this scheme, at the cost of sacrificing efficiency.

Our proposed scheme is sufficiently general to nest different variations of the model. The most important extensions are discussed in Section 7 where we argue that the results can invariably hold regardless of, the number of pollutants, the mode of competition, i.e., quantities or prices, and the presence of market power in the permits market. Remarkably, in the case of multiple pollutants we show that achieving the cooperative solution by implementing a single instrument for the two externalities may be superior to the case where two policy instruments are in place. The rationale is that the governments by integrating tradable permit markets for different pollutants have an incentive to restrain the issuance of an excessive number of allowances as in the main model. On the contrary, if the local pollutant is regulated by a different policy instrument the governments may relax the corresponding regulation further so as to gain a production advantage against the rival country.

The implications of this study are straightforward. We suggest that a scheme which is already implemented (e.g., EU ETS, Ontario, Montreal and California agreements, China), under a careful design may lead to a cooperative outcome even though the countries choose their levels of regulation by pursuing their self-interest.

**Organization of the paper** In Section 2 we present the related literature. Section 3 illustrates the theoretical model. In Section 4 the comparative statics of the model are presented. Then, in Section 5, we focus on the symmetric case and derive the equilibria of the game. In Section 6 we provide the corresponding analysis for the asymmetric cases. In Section 7 we present several extensions, and finally, in Section 8 we conclude with potential implications arising from the current study. The formal proofs are collected in the Appendix. The calculations for the simulations in Section 6 and an example for the case of multiple pollutants are presented in the Supplementary Appendix.

# 2 Related Literature

The environmental policy as a means to affect the competitiveness of the regulated exporting sectors has been explored in the so called "Strategic Environmental Policy" literature, established, among others, by Conrad (1993), Barrett (1994), Kennedy (1994), Rauscher (1994), Ulph (1996) and Neary (2006). In particular, Conrad (1993), Kennedy (1994), Barrett (1994), and Neary (2006) argue that the level of regulation in the form of emission quotas or taxes is set inefficiently low.<sup>1</sup> All these studies conclude that the presence of strategic incentives are welfare detrimental. Antoniou et al. (2014) show that this race to the bottom is reversed if the two exporting countries are linked through a permits market where the firms compete in quantities and initial permit endowments are allocated for free to the exporters. However, regulation remains below the efficient level. In a similar setup but in the presence of multiple pollutants Antoniou and Kyriakopoulou (2019) show that when the transboundary pollutant is regulated through a permits market then the incentives to relax further local regulation are magnified. Lapan and Sikdar (2020) show that when the exporting firms compete over prices then the level of regulation is strengthened but still not at the efficient level. Al Khourdaije and Finus (2020) introduce a strategic trade model and present the conditions under which border carbon adjustments can mitigate free-riding and reduce carbon leakage. Our study shows that the distribution of permit revenues is important for aligning the incentives of the exporting countries and obtain the cooperative outcome irrespective of the number of pollutants or the mode of competition. $^{2,3}$ 

The idea of allowing countries to issue permits unilaterally and then trade them is not new. Early studies in this literature, e.g., Helm (2003), Carbone et al. (2009) and Godal and Holtsmark (2011) explore the possible welfare gains from such a setup. Gersbach and Winkler (2011) introduce a blueprint for an international permit market where the countries issue permits unilaterally and allow both for grandfathering and auctioning of permits. They show that if revenue from auctioning permits is collected to a global fund, and then is distributed back to the participating countries in fixed proportions, all countries tighten their issuance of permits and thus the equilibrium level of welfare is higher. In the symmetric case where there is full auctioning the solution converges to efficiency. Following the mechanism of Gersbach and Winkler (2011), Tsakiris et al. (2018) argue that in a trade model of symmetric countries of perfect competition and perfectly transboundary pollution environmental policy can be tighter. In the absence of this scheme Holtsmark and Sommervoll (2012) and Lapan and Sikdar (2019) find that internationally tradable permits lead to higher pollution compared to non-tradable permits in the case where there is intra-industry trade

<sup>&</sup>lt;sup>1</sup>Nannerup (2001) and Eichner and Pethig (2009) argue that even if regulation is restricted by an international agreement, the governments may favor the exporting against the non-exporting sectors. Pantelaiou et al. (2020) show, among other things, that when production uses a depletable resource and generates cross-border pollution in most cases revenue recycling is an export-contracting but resource preserving policy.

<sup>&</sup>lt;sup>2</sup>A parallel literature (e.g., Ulph and Valentini, 2001; Kayalica and Lahiri, 2005; Tsakiris et al., 2017; Nachtigall, 2019; Richter et al., 2019) attests that the governments tend also to relax regulation to avoid plant relocation.

 $<sup>^{3}</sup>$ The distribution of permit revenues may translate into indirect transfers and their direction may affect the implementability of the scheme as we also examine in our analysis. The use of direct transfers is commonly advocated so as to counter-act free riding incentives in international public good problems (e.g., Kornek and Edenhofer, 2020).

in goods along with trade in emissions permits and countries strategically choose environmental policies. Interestingly, Landry (2021) introduces a general model which nests many different cases presented in the literature and argues that decentralized policy making can lead to efficiency if interjurisdictional trade of permits is allowed and local governments on average think globally in the sense that their revealed social costs of carbon equal the global social cost of carbon on average.

Our aim is to complement the aforementioned literature by introducing an imperfectly competitive market structure which allows for the adoption of strategic export motives that lead to an inefficiently low level of regulation. We show that efficiency can be obtained as a subgame perfect Nash equilibrium given our proposed revenue scheme. On top of that we introduce a participation game under the unanimity rule and illustrate that for a large number of cases the exporting countries are willing to link their ETS.

Interestingly, Helm and Pichler (2015) show that technology transfers among countries tend to reduce aggregate emissions when permits are internationally tradable. Our results in the asymmetric case about the abatement costs are in line with this finding. On top of that, following a loose argument from our examples summarized in Table 1 (Section 6) we show that the most efficient countries may be willing to transfer technology to the less efficient ones and induce participation. Bréchet et al. (2016) argue that the Clean Development Mechanism as introduced by the Kyoto protocol alter the incentives of the countries issuing permits endogenously and this leads to higher emissions. Holtsmark and Midttømme (2019) show that linking permit markets can induce greater low carbon investments and lower emissions.

Our study shares some similarities with the participation games presented in Habla and Winkler (2013; 2018) where they also consider initially a stage where countries decide whether to link their domestic emission permit markets to an international market, which only forms, as in our model, if it is supported by all countries. Then, countries non-cooperatively decide on the number of tradable emission permits. The authors allow for the presence of lobby groups and study the effects of these groups on their desirable policy and the adverse effect of delegation on the attractiveness of linking tradable permit markets.

The literature on the economics of linking (Stevens and Rose, 2002; Flachsland et al., 2009; Pizer and Yates, 2015; Ranson and Stavins, 2016; Doda and Taschini, 2017; Rose et al., 2018; Quemin and de Perthuis, 2019; Borghesi and Zhu, 2020) has emphasized, by and large, in three different types of gains from multilateral linking of permit markets. That is, price convergence, costeffectiveness and the reduction of price volatility. Doda et al. (2019) quantify the efficiency gains by establishing two decompositions of these gains: Effort and risk-sharing gains as well as risk-pooling associated with the uncertainty affecting each group member's demand for permits. We abstract from these effects as our aim is to focus on the strategic motives presented above. Caparrós and Péreau (2017) and Heitzig and Kornek (2018) discuss different game-theoretic models of gradual linking of permit markets.

# 3 The Model

Consider a two country, Home and Foreign, three stage game. Each country is represented by a government and an exporting firm.<sup>4</sup> The timing structure is as follows:

Stage 0: The governments decide whether to establish and participate into a specific scheme of internationally tradable permits.

Stage 1: The governments simultaneously and non-cooperatively choose the number of permits.

Stage 2: The firms compete à la Cournot in a world commodity market and decide on the number of permits to be purchased.

The equilibrium notion of the game is the subgame perfect Nash equilibrium. Without affecting our results we assume that consumption of the goods in the two countries is zero, thus total production by the two firms is exported to the rest of the world. Production for the Home firm is denoted by x, and the production cost is normalized to zero.<sup>5</sup> Total revenue is r(x, X), and we assume that the two outputs are substitutes,  $r_X < 0$ , and that a pollutant, z, associated with production, i.e.,  $z = \theta x$ , adversely affects residents in the two countries;  $\theta$ , the rate of pollution per unit of output produced, is a common positive scalar which is set for simplicity and without affecting our results equal to one.

Each firm is assumed to have a private abatement technology ( $\alpha$ ) which is necessary for removing the extra emissions above the number of allowances (permits) e purchased by the firm from the permits market at a given price  $P^{e,6}$  Given the possibility of purchasing permits, abatement is defined as  $a = x - e \ge 0$ . We assume a convex abatement cost function q(a), where  $q_a > 0$  and  $q_{aa} > 0$ . Profits are defined as:

$$\pi = r(x, X) - q(a) - P^e e.$$
(1)

The government's objective is to maximize social welfare. Welfare in Home is defined by the function:<sup>7</sup>

$$w = \pi (x, X, a, P^e, e) + P^e e - d(e + \phi E) = r(x, X) - q(a) - d(e + \phi E).$$
(2)

Since, by assumption, the two countries are not consumers of their exported good, social welfare does not include any consumers surplus. Social welfare is captured by the sum of firm profits, i.e.,  $\pi$ , plus the expenses for permits purchases  $P^e e$  by the Home firm that are lump-sum rebated to the residents of that country, i.e.,  $P^e e$ , minus the environmental damage caused to domestic households by the production generated transboundary pollution, i.e.,  $d(e + \phi E)$ . The parameter  $\phi \in [0, 1]$ 

<sup>&</sup>lt;sup>4</sup>We opt for the two-dimensional model to preserve clarity. The model can be extended to higher dimensions regarding the number of countries and firms.

 $<sup>^{5}</sup>$ All choice variables and functions of Home (Foreign) and its firm are denoted by lower (upper) case letters. Unless defined differently we only present explicitly the variables and functions of Home and its firm.

<sup>&</sup>lt;sup>6</sup>In a related extension in Section 7, we relax this assumption and show that the main results carry over. Moreover, price-taking behavior in a thick permits market is commonly used in the existing literature (Sartzetakis, 1997; Malueg and Yates, 2009; Meunier, 2011; Antoniou et al., 2014; Antoniou and Kyriakopoulou, 2019; Lapan and Sikdar, 2020).

<sup>&</sup>lt;sup>7</sup>The corresponding Foreign welfare is:  $W = \Pi(X, x, a, P^e, E) + P^e E - D(E + \phi e)$ .

measures the rate of transboundary pollution and  $d_e$ ,  $d_E > 0$ ,  $d_{ee}$ ,  $d_{eE}$ , and  $d_{EE} > 0.8$ 

The permits market clearing condition requires that the total number of permits issued by Home  $(\overline{e})$  and Foreign (E) in Stage 1, must equal the number of permits purchased by their two firms, i.e., e and E, respectively. The permits price,  $P^e$ , follows from the permits market clearing condition:

$$e + E = \overline{e} + \overline{E}.\tag{3}$$

#### **Comparative Statics** 4

In Stage 2 of the game, the firms maximize their profits with respect to output and the number of permits they are willing to purchase subject to the constraint of abatement. Therefore, the first order conditions for the two firms are:<sup>9</sup>

$$\left\{\begin{array}{l}
\pi_{x} = r_{x} - q_{x} = 0 \\
\pi_{e} = -P^{e} - q_{e} = 0 \\
\Pi_{X} = R_{X} - Q_{X} = 0 \\
\Pi_{E} = -P^{e} - Q_{E} = 0
\end{array}\right\}.$$
(4)

The conditions  $\pi_{xX} < 0$  and  $\Pi_{xX} < 0$  ensure that the output reaction functions are downward sloping and that outputs are strategic substitutes.

We now turn to the comparative statics analysis in Stage 2 which focuses on the sign of the so called *strategic effect* that appears in eco-dumping models and leads to the prisoners' dilemma. The strategic effect can be described as the effect that changes in one country's environmental regulation have on the other country firm's Stage 2 equilibrium output. Here, for the purposes of our analysis, we examine the effects of an increase in Home's supply of permits on Foreign firm's Stage 2 equilibrium output, i.e.,  $\frac{\partial X^*}{\partial \overline{e}}$ , where stars denote Stage 2 equilibrium values. In models of standard strategic environmental policy the sign of this derivative is unambiguously negative, e.g., (Barrett, 1994). That is, an increase in the number of permits issued by one country lowers the marginal cost of abatement, and thus it raises local output. The other country's output falls due to the conjecture that the outputs of the two firms are strategic substitutes to each other. Further to this, we also examine the effect of the increase in Home's supply of permits on demand for, i.e., purchases of, permits by both Home and Foreign's firms, i.e.,  $\frac{\partial e^*}{\partial \overline{e}}$  and  $\frac{\partial E^*}{\partial \overline{e}}$ , respectively. The following proposition summarizes these results.<sup>10</sup>

#### **Proposition 1** An increase in the supply of permits by one country, e.g., Home, (a) entails a

<sup>&</sup>lt;sup>8</sup>For the value  $\phi = 0$  pollution is local, while for values  $0 < \phi \leq 1$ , pollution is either perfectly or imperfectly transboundary. For analytical simplicity and clarity of the results, it is assumed that the two countries are subject to the same rate  $(\phi)$  of transboundary pollution.

 $<sup>{}^{9}</sup>$ The second order conditions are satisfied when the Hessian matrix **H** is negative definite. The corresponding Hessian matrix, for the Home firm is  $\mathbf{H} = \begin{bmatrix} \pi_{xx} & \pi_{xe} \\ \pi_{ex} & \pi_{ee} \end{bmatrix}$ . Note that the subscript(s) stand for the partial derivative(s) with respect to the denoted variable(s). For example,  $q_e = \frac{\partial q}{\partial a} \frac{\partial a}{\partial e} = -q_a$ . <sup>10</sup>Proposition 1 extends the results of Antoniou et al. (2014) without permits grandfathering.

positive strategic effect on Foreign's output. The effect on equilibrium outputs in the two countries is the same, i.e.,  $\frac{dX^*}{d\overline{e}} = \frac{dx^*}{d\overline{e}} > 0$ ,

(b) reduces the equilibrium price of permits, i.e.,  $\frac{dP^{e*}}{d\overline{e}} < 0$ ,

(c) increases demand for emission permits by both Home and Foreign firms, i.e.,  $\frac{de^*}{d\bar{e}}, \frac{dE^*}{d\bar{e}} > 0.$ 

The analytical expressions for these results are given by equations (A3) in the Appendix. Proposition 1(a) denotes that a change in the number of permits issued by either country affects equally the Stage 2 equilibrium output of both firms. The reason is simply that the marginal abatement costs are equalized and fixed at the common permits price. The output game converts to a symmetric Cournot game with fixed marginal costs and naturally the emerging equilibrium is a symmetric one.

Proposition 1(b) states that an increase in the supply of permits by either country reduces the equilibrium price of permits. Moreover, a closer look in the corresponding right-hand-side terms of the expression  $\frac{dP^{e*}}{d\bar{e}}$  in the Appendix allows as to infer how sensitive is this derivative with respect to the specificities of the model. For example, in a linear-quadratic specification of the model it can be shown that when the slope of the marginal abatement cost increases our derivative becomes more negative. This implies that the price is more sensitive to supply changes as the firms' demand for permits is more inelastic.

Proposition 1(c) simply illustrates that since an increase in the supply of internationally tradable permits by either country tends to reduce the price of permits, demand for these permits by firms in both countries rises to the point where the marginal abatement costs are equalized. Note that in the symmetric case, where the firms face the same abatement technologies it holds that  $\frac{de^*}{d\bar{e}} = \frac{dE^*}{d\bar{e}}$ , since in equilibrium the abatement levels are equal.

These preliminary results are of use to the analysis of the section to follow. This is to examine the effects of permits trading on the countries' levels of welfare. To this end, first, we consider the case of symmetric countries in terms of their abatement technologies and of the corresponding environmental preferences. Next, we turn to the case of asymmetric countries in terms of the above features. Related to this analysis we also focus on the incentives for the countries decision in Stage 0 to implement a tradable permits scheme.

# 5 Symmetric Case

## 5.1 Welfare Analysis

We begin by examining as a benchmark case the cooperative solution whereby each government chooses the level of permits to issue so as to maximize their joint welfare. We then compare the cooperative solution to the non-cooperative one.

**Cooperative Solution** For the cooperative case, Home (Foreign) chooses the level of permits  $\overline{e}(\overline{E})$  so that  $\frac{d(w+W)}{d\overline{e}} = 0\left(\frac{d(w+W)}{d\overline{E}} = 0\right)$ . Due to our assumption of symmetric countries, it suffices

to examine the effects of Home choosing  $\overline{e}$ , and the exact same results apply to the case of Foreign choosing  $\overline{E}$ . Given that  $\frac{\partial d}{\partial \overline{e}} = \frac{\partial d}{\partial e^*} \frac{\partial e^*}{\partial \overline{e}} + \frac{\partial d}{\partial \overline{E}} \frac{\partial E^*}{\partial \overline{e}}$  and  $\frac{\partial D}{\partial \overline{e}} = \frac{\partial D}{\partial e^*} \frac{\partial e^*}{\partial \overline{e}} + \frac{\partial D}{\partial \overline{E}} \frac{\partial E^*}{\partial \overline{e}}$ , the first order conditions for total welfare maximization are the following:<sup>11</sup>

$$\frac{d(w+W)}{d\overline{e}} = \underbrace{\left(\frac{\partial e^*}{\partial \overline{e}} + \frac{\partial E^*}{\partial \overline{e}}\right) P^{e*}}_{permits \ revenue} + \underbrace{\left(\frac{\partial \pi^*}{\partial X^*} \frac{\partial X^*}{\partial \overline{e}} + \frac{\partial \Pi^*}{\partial x^*} \frac{\partial x^*}{\partial \overline{e}}\right)}_{general} - \underbrace{\left(\frac{\partial d}{\partial \overline{e}} + \frac{\partial D}{\partial \overline{e}}\right)}_{marg.} = 0.$$
(5)  
effect strat. eff. damage  
(+) (-) (+)

and

$$\overline{e} = \overline{E}.\tag{6}$$

Recall that the asterisks denote equilibrium values, and below each term we indicate the partial effect and the sign of changes in  $\overline{e}$  on the corresponding variables. The first right-hand-side term in (5), we call *permits revenue effect*, is positive in sign and it captures the increase in aggregate revenues from sales of internationally tradable permits from the Home country, as a higher number of permits issued, increases the purchases by both firms as described in Proposition 1(c). The second right-hand-side term, we call *general strategic effect*, captures the impact of changes in  $\overline{e}$  on the countries' joint welfare through changes in firms' levels of output and their effect over the profits of the rival firm. By Proposition 1(a), it follows that the overall sign of this term is negative. This implies that it is to the interest of a country to follow a tighter environmental standard, i.e., the issuance of fewer permits. The last right-hand-side term, we call the *marginal damage*, stands for the aggregate marginal environmental damage caused from pollution. It is equal to the effect of the additional number of permits over the damage. Note that the effect of the change in regulation over the permits price, i.e.,  $\frac{dP^{e*}}{d\overline{e}}$ , is absent as the revenues are lump-sum rebated. Equation (6) applies in the fully symmetric as  $\overline{e}$  and  $\overline{E}$  are linearly dependent.

Using the results presented in Proposition 1 and exploiting symmetry, equation (5) is simplified to:

$$\frac{d\left(w+W\right)}{d\overline{e}} = \frac{\partial e^*}{\partial \overline{e}} P^{e*} + \frac{\partial \pi^*}{\partial X^*} \frac{\partial X^*}{\partial \overline{e}} - \frac{\partial d}{\partial \overline{e}} = 0.$$
(7)

Equation (7) determines the level of permits issued by Home so that the countries' joint welfare is maximized.

**Non-cooperative Solution** We now turn to the non-cooperative solution where each government decides on the number of permits to issue so as to maximize its individual welfare, provided that there is an agreement in Stage 0 regarding the implementation of a tradable permits scheme where revenues are lump-sum distributed to the issuing country's households. The welfare maxi-

<sup>&</sup>lt;sup>11</sup>Note that the terms  $\frac{\partial \pi^*}{\partial x^*} \frac{\partial x^*}{\partial \overline{e}} + \frac{\partial \Pi^*}{\partial X^*} \frac{\partial X^*}{\partial \overline{e}} + \frac{\partial \pi^*}{\partial e^*} \frac{\partial e^*}{\partial \overline{e}} + \frac{\partial \Pi^*}{\partial E^*} \frac{\partial E^*}{\partial \overline{e}}$  disappear as the envelope theorem applies. The second order conditions of the problem are satisfied since the problem is concave.

mizing first order condition for the two governments are described by the following equations:

$$\frac{dw}{d\overline{e}} = \frac{\partial e^*}{\partial \overline{e}} P^{e*} + \frac{\partial \pi^*}{\partial X^*} \frac{\partial X^*}{\partial \overline{e}} - \frac{\partial d}{\partial \overline{e}} = 0$$
$$\frac{dW}{d\overline{E}} = \frac{\partial E^*}{\partial \overline{E}} P^{e*} + \frac{\partial \Pi^*}{\partial x^*} \frac{\partial x^*}{\partial \overline{E}} - \frac{\partial D}{\partial \overline{E}} = 0,$$
(8)

where the corresponding terms are similar to the ones analyzed in (5). Notably, here, the right-handsides of (7) and the first equation in (8) coincide. Therefore, we obtain the following proposition:

#### **Proposition 2** Under symmetry the non-cooperative and cooperative solutions coincide.

The reaction functions of the two countries in the non-cooperative solution in (8) coincide which implies that there exist a continuum of subgame perfect Nash equilibria in the subgame for  $\overline{e}^*$  and  $\overline{E}^*$ , respectively, such that the aggregate emissions should be equal to the cooperative level of emissions. Yet, the Stage 2 equilibrium values remain unaffected from the exact distribution of  $\overline{e}^*$ and  $\overline{E}^*$  and thus the cooperative solution is obtained for every subgame perfect Nash equilibrium. The establishment of a tradable permits scheme of this kind reverses the strategic incentives as the government realizes that any policy change affects equally both firms' outputs. Therefore, any policy change triggered by a strategic motive to affect output is removed and no adverse effect is imposed on the rival firm. On the contrary, tighter regulation coordinates the two firms towards lower aggregate production which benefits both firms. Moreover, the externality from pollution in the other country is now correctly internalized, as a change in the supply of permits in one country affects the permits purchases of both firms by exactly the same magnitude. Thus, any reduction in the number of permits by Home equally reduces the level of pollution in the other country. A critical factor for achieving the cooperative outcome is that the permits expense from each firm is lump-sum rebated to the residents of that country. The latter feature is absent from the existing literature, e.g., Antoniou et al. (2014), Lapan and Sikdar (2020). In Antoniou et al. (2014) the government permits are grandfathered to the corresponding firms. In Lapan and Sikdar (2020), no grandfathering takes place and the revenues from government permit sales, independently of the recipient firm Home or Foreign, are distributed to the local residents. In our case, the permits revenue distribution scheme removes the unilateral incentive to alter the number of permits in order to exploit any windfall gains through permits trading. In the symmetric equilibrium there are no transfers of permits revenue across countries. Hence, the interesting feature is that in the symmetric case the cooperative solution is implementable and can be sustained as a subgame perfect Nash equilibrium in Stage 0.

## 5.2 Implementability of the permits scheme

Our model resembles the case of countries that are already a part of an economic union such as the European Union or some peripheries which are part of a larger country, e.g., Canada, China and the US. In the case of the EU which is consisted by 27 different member states the decisions are

taken by the unanimity rule. In case one member state disapproves a mandate, then it is abolished from the coalition. Hence, the introduction of the EU ETS in Europe has gained the approval of all member states. The open-ended discussion now in the EU is whether to abolish the unanimity rule and move to qualified majority voting or not, e.g., Yrjö-Koskinen et al. (2019). The voting rule is important regarding the implementability of the scheme in Stage 0 as unanimity requires that all countries must agree in establishing and participating in the tradable permits scheme, whereas this is not true under a majority rule.

To examine implementability we focus on Stage 0 of the game where the two countries must decide on the introduction of the scheme or not. To introduce the scheme both countries must agree on that, otherwise the scheme will be abolished and the game simply reduces to the non-cooperative game described in the standard strategic environmental policy literature. The following proposition summarizes the outcome of Stage 0:

#### **Proposition 3** It is a subgame perfect Nash equilibrium to introduce a permits trading scheme.

Proposition 3 simply states that no country has a unilateral incentive to deviate from the introduction of the tradable permits scheme provided that the other country accepts it. This follows from the fact that the non-cooperative solution yields the maximum welfare benefits. Hence, switching regimes is not at the countries self interest. Under symmetry, i.e., same abatement technologies and same environmental preferences, we obtain subgame perfect Nash equilibria where the race to the bottom present in the standard models of strategic environmental policy disappears. Notably, non-participation of both countries constitutes another subgame perfect Nash equilibrium as there is no incentive to unilaterally deviate from this situation as well. The equilibrium, however, described in Proposition 3 is a *focal point*.

# 6 Asymmetric Cases

#### 6.1 Welfare Analysis

We now turn to the case where Home and Foreign are asymmetric, either in terms of different abatement technologies and/or different environmental preferences, as captured by the environmental damage function. We examine the cooperative and non-cooperative solutions to the countries' problem of issuing internationally tradable emission permits, and we set the conditions under which it is possible for the two solutions to coincide.

**Cooperative Solution** The conditions for the joint welfare maximization are again described by the system of equations (5) and (6). Akin to the symmetric case, condition (6) is not unique. This is because independently of which country issues a permit the effect on either country's welfare is exactly the same. Hence, the number of permits in Home and Foreign are linearly dependent. This implies that there is a continuum of combinations of permits issued by the two countries that yield the same outcome. The necessary condition is that they must add to  $\overline{e}^* + \overline{E}^*$ .

A key feature of the current model which further highlights the importance of the proposed distributive scheme of revenue from permits sales is the following. With asymmetric countries, the cooperative equilibrium level of welfare under the proposed distributive scheme of permits revenue, does not coincide with the corresponding cooperative equilibrium level of welfare when governments implement other types of environmental regulation, e.g., either command and control policies or issue permits which are traded in local emission markets.<sup>12</sup> In particular, when countries are asymmetric, the cooperative level of welfare is lower under the proposed distributive scheme of permits revenue compared to that under the alternative policies of environmental regulation. This result might seem surprising but it holds because the abatement technologies in the two countries are different. Specifically, the proposed scheme of trading permits internationally, dictates the two firms to equalize the marginal abatement costs. Yet, when the abatement technologies differ across firms, then, welfare can increase for allocations where the marginal abatement costs are not equal across firms and the product market is imperfectly competitive. The intuition behind this result follows from the analysis of Salant and Shaffer (1999) where they employ a Cournot model and show that in the case of asymmetric (constant) marginal costs, aggregate profits and welfare are higher compared to the case where both firms face the same marginal costs that are equal to the average marginal costs of the asymmetric case. The rationale for this outcome is based on the fact that while the final allocation of production between the two alternative scenarios is the same, the more efficient firm produces the lion share of the aggregate production and this translates to lower aggregate production costs. Meunier (2011), in a context with distinct product markets also illustrates that linking emission markets may be detrimental.

Non-cooperative Solution The first order condition for welfare maximization of the two countries are described by the set of equations in (8). Unlike the symmetric case, however, these two conditions are not the same and in general they do not coincide. The following lemma presents an important feature for our analysis:

#### **Lemma 1** In the asymmetric case the best response functions of the governments are parallel.

From Proposition 1 it follows that every term of the first order conditions for welfare maximization in the set of equations (8) depends on the aggregate level of emissions, i.e.,  $e + E = \overline{e} + \overline{E}$ , since production and permit purchases by each individual firm do not depend on the country where the allowances are issued. As a result, the best response functions of the governments are parallel.<sup>13</sup> Put it differently, Lemma 1 states that if a subgame perfect Nash equilibrium exists, then it is not obtained by an intersection point reflecting a corner solution. That is, one of the two countries selects to issue zero permits and the other chooses the best response to this strategy.

We now use the above results to address the question of whether and under what conditions, in the case of asymmetric countries, the non-cooperative and cooperative solutions can coincide. For

<sup>&</sup>lt;sup>12</sup>Here we follow a loose descriptive argument. A concrete example can be provided upon request. <sup>13</sup>Only in an accidental case where the two best response functions coincide, that is when,  $\frac{\partial e^*}{\partial \overline{e}}P^{e*} - \frac{\partial d}{\partial \overline{e}} = \frac{\partial E^*}{\partial \overline{E}}P^{e*} - \frac{\partial D}{\partial \overline{E}}$ , as  $\frac{\partial \pi^*}{\partial X^*} \frac{\partial X^*}{\partial \overline{e}} = \frac{\partial \Pi^*}{\partial x^*} \frac{\partial x^*}{\partial \overline{E}}$  from Proposition 1, then the results of the symmetric case still apply.

this, we introduce a mechanism which distributes the revenues across the two countries from permit trading. We set as  $\gamma \left(\overline{e} + \overline{E}\right) P^{e*}$  the permit revenues obtained by Home, while  $(1 - \gamma) \left(\overline{e} + \overline{E}\right) P^{e*}$ are the revenues distributed to Foreign. The coefficient  $\gamma$  stands for the share of the revenues obtained by Home and  $1 - \gamma$  corresponds to the share of the Foreign. From Lemma 1 it follows:

**Lemma 2** There exists a  $\gamma^* = \frac{1}{2} \left( 1 + \frac{(e^* - E^*)\frac{\partial P^{e^*}}{\partial \overline{e}} + \frac{\partial d}{\partial \overline{e}} - \frac{\partial D}{\partial \overline{E}}}{(\overline{e} + \overline{E})\frac{\partial P^{e^*}}{\partial \overline{e}} + P^{e^*}} \right)$  so that the best response functions of the governments coincide.

Given Lemma 2 we state the following Proposition:

# **Proposition 4** For $\gamma^*$ the non-cooperative solution coincides with the cooperative solution.

Proposition 4 states that there exists a  $\gamma^*$ , that is a specific distribution of the permit revenues, that leads the governments to select the cooperative levels of pollution despite the fact that they act unilaterally. This result provides a potential theoretical foundation for the governments' decision in Stage 0 to adopt the scheme of internationally tradable permits, as both forces that lead to the race to the bottom, that is, the strategic motives and the externality problem are endogenously resolved. As in the symmetric case the rationale is that when one government issues pollution allowances it lacks the strategic incentive to relax regulation and it affects permits purchases of the Home and the Foreign firm so as to correctly internalize the externality. For this to hold the two governments need to agree in Stage 0 on the implementation of the scheme and the correct split of the revenue that correspond to the specific value of  $\gamma^*$ .

Interestingly, our scheme suggests that in the symmetric case where  $e^* = E^*$  and  $\frac{\partial d}{\partial \overline{e}} = \frac{\partial D}{\partial \overline{E}}$  it holds  $\gamma^* = \frac{1}{2}$ . That is, the two governments decide to share equally the aggregate permits revenue which corresponds to our solution of the symmetric case where in equilibrium each country simply obtains in a lump-sum manner its own permits revenue. Another, important feature is that even though the regulators are free to select the number of permits without any restriction they do not choose to issue an infinite number of permits so that they profit out of it. As Helm (2003) argues it is the damage from pollution that poses the restriction to the governments. Here, it is also the strategic effect which places an additional constraint on issuing extra permits. Yet, most importantly when a regulator maximizes its own welfare with respect to the number of permits also affects the foreign pollution and thus is able to control for the externality. As a result the cooperative outcome is achieved.

#### 6.2 Implementability of the Permits Scheme

As we have shown the cooperative solution is feasible even when the abatement technologies or the damage from pollution may differ across countries. To achieve the cooperative solution the two countries must agree on the exact level of the permits revenue obtained by each counterpart, i.e.,  $\gamma^*$  and  $(1 - \gamma^*)$  respectively. This implies that one country must accept an indirect form of transfers to the other. Naturally, it is not straightforward to conclude whether this occurs or not in equilibrium. It clearly depends on the unilateral incentives faced by each government and on an alternative policy regulation, e.g., emission standards or taxes, vis-a-vis the permits scheme. As already argued in the beginning of this section, in the case of asymmetric countries it may hold that the cooperative equilibrium welfare level under the present distributive scheme of revenue from permits sales is lower relative to other types of environmental regulations. Hence, the fact that under permits trading the cooperative outcome is achieved does not necessarily imply that the adoption of this scheme is beneficial. On top of that in the asymmetric case the distribution of the benefits from the participation in the proposed scheme is also asymmetric, which in turn implies that possibly one of the two countries is worse-off, to an alternative environmental regulation, and thus has no incentive to participate in the scheme. The latter can be resolved if direct transfers across countries are employed so that the additional gains from the implementation of the permits scheme reach both counterparts in a way that both are better-off with respect to an alternative scheme.

It is important to understand when does the cooperative outcome under the permits scheme yield sufficient gains to offset the welfare gains from an alternative scheme. In the absence of tradable permits, e.g., when each government selects an emissions standard or locally tradable permits, the countries with the relatively lower marginal abatement costs or damage from pollution face higher welfare. When this country decides to participate in a trading scheme acknowledges that marginal abatement costs are equalized across firms and thus its firm loses the cost advantage over the other resulting to lower profits. In order to induce this country to participate to the tradable permits scheme, a side benefit must be provided in exchange. This can be a higher amount of permits revenue from the common pool. However,  $\gamma^*$ , is uniquely determined as presented in Lemma 2.

A closer observation of  $\gamma^*$  is necessary in order to understand the direction of the indirect transfers, i.e., whether  $\gamma^* \geq \frac{1}{2}$ . To keep things simple we focus on the case where the permits revenue increases when the supply of permits increases, i.e.,  $(\overline{e} + \overline{E}) \frac{\partial P^{e*}}{\partial \overline{e}} + P^{e*} > 0$ . This is indeed true in any linear specification. Let us first consider the case where the two countries differ only in terms of marginal damage, i.e., their preferences over environmental quality, that is  $\frac{\partial d}{\partial \overline{e}} \neq \frac{\partial D}{\partial \overline{E}}$ . Then, they purchase the same amount of permits from the permits market and thus the share of revenues reduces to  $\gamma^* = \frac{1}{2} \left( 1 + \frac{\frac{\partial d}{\partial \overline{e}} - \frac{\partial D}{\partial \overline{E}}}{\frac{\partial P^{e*}}{\partial \overline{e}} + P^{e*}} \right)$ . If the marginal damage is higher in Home, i.e.,  $\frac{\partial d}{\partial \overline{e}} > \frac{\partial D}{\partial \overline{E}}$ , then  $\gamma^* > \frac{1}{2}$ . The country that suffers more from pollution is compensated further from the permits revenue. This feature creates a disincentive to its counterpart country regarding its participation to the scheme. On the contrary, when marginal abatement costs differ across countries while the damages from pollution are the same, the share of revenues for the Home country is  $\gamma^* = \frac{1}{2} \left( 1 + \frac{(e^* - E^*) \frac{\partial P^{e*}}{\partial \overline{e}}}{(\overline{e} + \overline{P}) \frac{\partial P^{e*}}{\partial \overline{e}} + P^{e*}} \right)$ . If the marginal abatement cost of Home's firm is lower than the corresponding one of Foreign's, the former purchases less permits relative to the latter at any given price, i.e.,  $e^* < E^*$ . This implies that  $\gamma^* > \frac{1}{2}$ . In this way, Home receives a compensation for participating in the scheme and this makes it more likely to be implementable.

Following our discussion, it is more likely to establish permit markets between countries that differ in terms of their technologies rather than countries that differ in terms of damages from pollution. Moreover, it is important to stress that if the suggested indirect transfers affect negatively the decision regarding participation, then  $\gamma$  can be distorted in a way to improve the welfare of the country that is harmed compared to the non-tradable permits case. Yet, this will take place at the cost that now the cooperative solution is no longer feasible.

Table 1 presents the results of different simulations (the calculations are provided in the Supplementary Appendix in Table 2) that are helpful in understanding the conditions under which our proposed mechanism is implementable. We examine five representative scenarios of asymmetries in firms' marginal abatement costs and/or in the damages from pollution. The first introduces an asymmetry only in the damage from pollution where the corresponding coefficient is 10% larger in Foreign compared to Home. In Stage 0 no country has an incentive to deviate from the tradable permits scheme and thus it constitutes a subgame perfect Nash equilibrium. The share of permits revenue for Home is approximately 48%, whereas 52% accrues to Foreign, the country that suffers the most from pollution. Redistribution is small and is not sufficient to alter Home's incentives that enjoys a lower revenue share. Contrary to this, in the second scenario raises the degree of asymmetry in pollution damage to 40% and the shares of permits revenue are approximately 43%for Home and 57% for Foreign. Now, Home is not willing to participate as is better off under the standard model with non-tradable permits. The third scenario introduces a small asymmetry only in abatement technologies, i.e., abatement cost coefficient is 10% higher in Foreign compared to Home. In this case, Home, the country with lower marginal costs, receives a slightly larger proportion of the total permits revenue equal to approximately 52%. This country is compensated for giving up the lower cost advantage of the Home firm in output competition. Hence, our mechanism remains implementable, since in Stage 0 no country is willing to unilaterally deviate from the tradable permits scheme which again constitutes a subgame perfect Nash equilibrium. Increasing the degree of asymmetry to 40%, as described in the fourth scenario, leads to a higher revenue share for Home which, in turn, induces Foreign to reject the tradable permits scheme. However, even in this case the incentive of Foreign to deviate is rather small. So it suffices for a very small transfer to bring this country into an agreement. Alternatively, Home may transfer some technology and the agreement turns implementable. Our mechanism, suffers when there are large asymmetries. The last scenario introduces asymmetries between the two countries, both in terms of differences in their firms' marginal abatement costs, and in their marginal damages from pollution. Specifically, this scenario suggests than if the asymmetries, in abatement costs and damage functions are positively correlated, then our mechanism may still apply for relatively larger degrees of asymmetries. The rationale is simple. A larger marginal abatement cost in Foreign suggests a larger value for  $\gamma^*$ , while a larger marginal damage requires a lower  $\gamma^*$ . Therefore when these two move in the same direction it is more likely to end up with balanced revenue shares which may lead to an agreement and vice-versa.

	$w^{*} - w_{s}^{*}$	$W^* - W^*_s$	Implementability
$\begin{array}{c} Scenario1 \\ {\rm marginal\ damage\ } \sim +10\% \ {\rm in\ Foreign} \end{array}$	(+)	(+)	$\checkmark$
$\begin{array}{c} {\rm Scenario} \ 2 \\ {\rm marginal} \ {\rm damage} \ {\sim} +40\% \ {\rm in} \ {\rm Foreign} \end{array}$	(-)	(+)	$\mathcal{X}$
Scenario 3 marginal abatement costs $\sim$ +10% in Foreign	(+)	(+)	$\checkmark$
Scenario 4 marginal abatement costs $\sim +40\%$ in Foreign	(+)	(-)	X
Scenario 5 marginal abatement costs ~+20% in Foreign marginal damage ~+20% in Foreign	(+)	(+)	$\checkmark$

Table 1: Results from simulations and implementability of the tradable permits scheme

In the Supplementary Appendix, we present the results of a standardized linear formulation of the model, e.g., Ulph (1996), using alternative values for the parameters of the model. The results are summarized in Tables 2 and 3 of the Supplementary Appendix. Specifically, in Table 3 in the Supplementary Appendix we consider the specific case where the countries agree in Stage 0 to split equally the aggregate revenue, i.e.,  $\gamma = \frac{1}{2}$ . We re-calculate the solutions in the first four scenarios, as the fifth scenario coincides with the one described in Table 2. Splitting the revenue leads to an interesting trade-off. On the one side we depart from efficiency, yet on the flip side, it increases the range of the parameter values where this scheme is implementable and leads to higher welfare compared to alternative schemes of environmental regulation.

# 7 Extensions

## 7.1 Multiple Pollutants

In reality the production of many commodities may emit multiple pollutants and thus determining optimal regulation is more complex (e.g., Ambec and Coria, 2013; 2018; Antoniou and Kyriakopoulou, 2019).<sup>14</sup> It is of some interest to examine whether the cooperative outcome can be achieved when multiple pollutants are present and the corresponding permit markets are integrated (e.g., Montero, 2001; Reeling et al., 2018).

We employ again our assumptions of symmetric countries, and of distribution of revenue from permits sales according to our proposed scheme. Let, however, the production x(X) of Home and Foreign firms, respectively, emit a local and a transboundary pollutant. In this case, following the relevant literature, e.g., Ambec and Coria, (2013; 2018), Antoniou and Kyriakopoulou, (2019), abatement costs are:

$$q(a_1, a_2) = q_1(a_1) + q_2(a_2) + \omega a_1 a_2, \tag{9}$$

<sup>&</sup>lt;sup>14</sup>For example, production may emit small particles such as particulate matters (both  $PM_{10}$  and  $PM_{2.5}$ ) and  $CO_2$  emissions at the same time. A common practice is that regulatory agreements are signed separately and the regulation of each pollutant is self-reliant (see IPCC, 2014).

where the indexes 1 and 2, respectively, stand for the local and transboundary pollutants. Abatement of each pollutant is equal to  $a_i = x - e_i$ , i = 1, 2. The parameter  $\omega \neq 0$  captures the interplay between the abatement efforts, where a negative (positive)  $\omega$  implies that the abatement efforts over one pollutant complement (substitute) the abatement efforts over the other. We assume that the abatement cost is increasing and convex. That is, the Hessian matrix **H** of the abatement costs must be positive definite. The firm's profits are  $\pi = r(x, X) - q(a_1, a_2) - P^e e$ .

Home, in order to maximize social welfare, issues a number of permits,  $\bar{e}$ , to regulate both types of pollutants, i.e., it integrates the permit markets across the different pollutants. Welfare is again defined as the sum of firm profits plus revenue from permits sales, minus the pollution damages, now denoted as  $d(e_1, e_2 + \phi E_2)$ . The damage function is increasing and convex with respect to pollution. Thus, welfare becomes  $w = \pi(x, X, a_1, a_2) + P^e(e_1 + e_2) - d(e_1, e_2 + \phi E_2)$ . We state the following remark.

# **Remark 1** In the symmetric case, with multiple pollutants and an integrated permits market across the different types of pollutants, the non-cooperative solution coincides with the cooperative solution.

The result in Remark 1 states that in the present context of symmetric countries, despite the fact that there are two distinct environmental distortions, one local and the other transboundary, with an integrated permits market where governments issue one type of permits to regulate either form of pollution, leads the two symmetric countries, in the subgame perfect equilibrium (of Stages 2 and 3), to choose non-cooperatively the cooperative level of pollution, thus welfare. The rationale follows along the same lines as in our main model. There is no strategic motive to relax regulation to promote exports. On the contrary, there is an incentive to coordinate production to lower levels. The cross-border externality is correctly internalized and the incentive to relax regulation to exploit gains from the permit market is removed through the distribution of the permits revenue. Again, in the symmetric equilibrium there are no transfers between countries.

The assumption of issuing one type of permits to regulate both local and transboundary pollution, may be viewed as violating the Tinbergen principle of effective policy implementation. That is, in order to successfully target the two types of pollution, at least two types of independent policy instruments, e.g., two types of permits each targeting the different types of pollution, would be required. As Antoniou and Kyriakopoulou (2019) show, when the two pollutants are regulated separately, i.e., the transboundary pollutant through permits and the local one through a quota, the government relaxes further the regulation of the local pollutant to promote exports. Integrating the permit markets across the different pollutants removes this discretion and the race to the bottom for strategic purposes. As we show in a linear-quadratic example in the Supplementary Appendix the removal of the race to the bottom outweighs the loss from discretion, and thus welfare with integrated permit markets is superior compared to the case where the two pollutants are regulated separately. Our simulations show that, at least for the symmetric case, when the pollutants are complements or when they are mildly substitutes to each other, this welfare ranking pertains.<sup>15</sup>

<sup>&</sup>lt;sup>15</sup>Further results for the asymmetric cases can be provided upon request. Even under asymmetry our welfare ranking holds for most of the possible alternative scenarios.

Promoting cooperation provides an additional argument for supporting permit markets integration across different pollutants (e.g., Montero, 2001; Reeling et al., 2018).

#### 7.2 Price Competition

A natural extension to consider, and test the robustness of our main result, is to modify the conjectural variation on the market competition between the two firms. Specifically, retaining our assumptions of symmetric countries, we conjecture that, in Stage 2, firms in order to maximize their profits, compete in prices, i.e., Bertrand competition, instead of quantities in commodity markets, e.g., Lapan and Sikdar (2020). As noted previously, the critical difference between the present study and that of Lapan and Sikdar (2020) is in regard to the distribution of revenue from permits sales. In their study, among others, the revenue from permits sales, independently of whether these permits are purchased by Home of Foreign firms, accrues in its entirety to the country of their issuance. In particular, the permits revenue corresponding to Home are equal to  $P^e e$  or equivalently to  $\gamma^* = \frac{1}{2}$ , whereas in Lapan and Sikdar (2020) are  $P^e \overline{e}$ . This difference suffices to alter the results and sustain once again the cooperative solution as a subgame perfect Nash equilibrium as stated in the following remark.

**Remark 2** Under symmetry and price competition in product market, the non-cooperative and cooperative solutions coincide.

When, in Stage 1, Home's regulator selects the optimal level of permits, i.e.,  $\overline{e}^*$ , does so understanding that cannot distort upwards the number of issued permits in order to gain additional permits revenue as half of these extra permits will be purchased by the rival firm and the corresponding revenue accrues to Foreign. Again the cross-border externality is correctly internalized and the strategic effect is the same for the two countries.

#### 7.3 Market Power

Thus far we have assumed that the firms do not possess market power in the permit market as it is considered to be thick.<sup>16</sup> It is of some interest to relax this assumption and explore of any possible changes in our main findings. In general introducing bilateral market power leads to an indeterminacy caused by the absence of a net supply (demand) function for permits. Our model, is a bit different as the firms resort to the permit repository and purchase permits. Similar difficulties, however, arise also here as the first order condition for profit maximization with respect to the number of permits demanded must include the effect over the permits price, that is  $\frac{\partial P^e}{\partial e}$ . For these reasons and for clearer exposition of this case, we assume a linear specification of the model. We state the following remark.

<sup>&</sup>lt;sup>16</sup>Note that in the present model with two firms we can also resort to Nash bargaining which implies efficiency and thus our main results carry over. Introducing market power in this basic setup aims at exploring the possible implications of such an extension.

**Remark 3** Assuming (i) market power of firms in the permits market, and (ii) a linear specification of the model, then, the non-cooperative and cooperative solutions coincide.

In Remark 3 we employ the notion of supply function equilibria first introduced by Klemperer and Meyer (1989), used among others in studies for permit markets by Lange (2009), Malueg and Yates (2009), Wirl (2009) and Antoniou et al. (2014). Following Wirl (2009) we focus on a linear net demand function which in turn implies that the additional effect  $\frac{\partial P^e}{\partial e} = \lambda > 0$ . That is, the firm by choosing an extra permit increases the permit equilibrium price by  $\lambda$ . In Stage 2 of the game we obtain that the number of permits purchased and the production levels are unaffected compared to the no market power case. The market power effect tends to reduce the demand for permits because the decision of the firms affect positively the permit price. Following this the equilibrium permit market price falls such that the equilibrium values of permits and outputs remain the same as in the no market power case. Naturally, the latter are identical to the ones of the cooperative solution.

# 8 Concluding Remarks

The current study provides a new argument favouring the implementation of tradable emission permits across countries or regions when they face strategic incentives in order to enhance the competitiveness of their exporting firms. The establishment of a trading scheme given a suggested distribution of permit revenues aligns the incentives of the exporting countries and despite the fact that they select the level of pollution unilaterally the cooperative outcome is achieved as a subgame perfect Nash equilibrium. The strategic trade motives and the externality from pollution in the other country are present but are correctly resolved due to the structure of our scheme. This is an additional advantage for integrating permit markets, which are well known for enhancing cost efficiency. We also illustrate that when the countries are symmetric the establishment of an agreement is self-enforcing as it constitutes a subgame perfect Nash equilibrium in the participation game. Interestingly, our main result persists for small asymmetries in the abatement technologies and the damage caused from pollution, or even for a larger degree of asymmetry when the abatement technology and the damage from pollution are positively correlated. Moreover, our results are robust in various directions such as the number of pollutants, the mode of competition, and the presence of market power in the permit market. Hence, we provide an alternative motivation following the recent trend of linking tradable permit markets across different regions (see ICAP, 2020) which however do not differ significantly in terms of preferences over the environment or in terms of technologies. If the countries differ significantly in terms of abatement technology then the transfer of this technology can be beneficial for all parties. Finally, we also provide support for linking permit markets across different pollutants.

Despite the fact that our suggested refunding scheme focuses on lump-sum distribution of the permit revenues across different regions the results carry over if these revenues are used to fund the provision of international public goods, such as innovation, renewable energy promotion and climate-related purposes as described in the Introduction. For our results to hold there should not be any permit grandfathering. Even a small amount of grandfathering suffices to alter the incentives of the exporting countries and depart from the cooperative solution.<sup>17</sup> Instead, all permits should be auctioned and the revenues should be distributed back either in a lump-sum fashion or in other forms as described above.

The current discussion which takes place in the EU is proposing a gradual shift from unanimity to qualified majority voting in the field of taxation. This is supposed to improve effectiveness in environmental issues (see Yrjö-Koskinen et al., 2019). Our results offer an alternative glance and underpin this claim from a different angle. As we have shown, asymmetries can lead some countries to vote against such a scheme despite the fact that it implies large gains on aggregate. Abolishing the unanimity rule can be a remedy so as to reach these sort of agreements and reduce GHG emissions.

Our findings are restricted to the export promotion incentives as summarized in the strategic environmental policy literature (see Section 2). In our view it is also interesting to further extend this mechanism to relevant topics such as plant relocation or even to the literature of environmental agreements and see whether larger coalitions can be sustained.

# Appendix

**Proof of Proposition 1.** (a) Differentiating (3) and the profit-maximizing conditions in (4) it follows that:

$$\begin{bmatrix} \pi_{xx} & \pi_{xX} & \pi_{xe} & 0 & 0 \\ \Pi_{Xx} & \Pi_{XX} & 0 & \Pi_{XE} & 0 \\ \pi_{ex} & 0 & \pi_{ee} & 0 & -1 \\ 0 & \Pi_{EX} & 0 & \Pi_{EE} & -1 \\ 0 & 0 & 1 & 1 & 0 \end{bmatrix} \begin{bmatrix} dx \\ dX \\ de \\ dE \\ dP^e \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \\ 0 \\ 1 \end{bmatrix} d\overline{e}.$$
(A1)

Note that the first order conditions in (4) imply:

$$\begin{aligned} \pi_x &= r_x - P^e = 0 \\ \Pi_X &= R_X - P^e = 0 \end{aligned}.$$

Given that  $\pi_{xX} < 0$  and  $\Pi_{xX} < 0$  and our assumptions about costs (convexity), then following Meunier (2011) it follows directly that the solution is unique. Equilibrium outputs in Stage 3 are

<sup>&</sup>lt;sup>17</sup>Grandfathering still takes place to some extent in different ETS (ICAP, 2020), so our analysis provides an argument against this practice.

equal, i.e.,  $x^*(P^e) = X^*(P^e)$ . Then, the problem in (A1) reduces to:

$$\begin{bmatrix} \pi_{xx} & \pi_{xX} & -\pi_{ee} & 0 & 0 \\ \Pi_{Xx} & \Pi_{XX} & 0 & -\Pi_{EE} & 0 \\ -\pi_{ee} & 0 & \pi_{ee} & 0 & -1 \\ 0 & -\Pi_{EE} & 0 & \Pi_{EE} & -1 \\ 0 & 0 & 1 & 1 & 0 \end{bmatrix} \begin{bmatrix} dx \\ dX \\ de \\ dE \\ dP^e \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \\ 0 \\ 1 \end{bmatrix} d\overline{e}.$$
(A2)

After inverting the matrix (A2) we obtain:

$$\begin{bmatrix} \frac{dx^*}{d\overline{e}} \\ \frac{dX^*}{d\overline{e}} \\ \frac{de^*}{d\overline{e}} \\ \frac{dE^*}{d\overline{e}} \\ \frac{dP^{e^*}}{d\overline{e}} \end{bmatrix} = \begin{bmatrix} \frac{\pi_{ee}\Pi_{EE}}{\Delta} \\ \frac{\pi_{ee}\Pi_{EE}}{\Delta} \\ \frac{(\pi_{ee} + \pi_{xX} + \Pi_{XX} - \Pi_{EE})\Pi_{EE}}{\Delta} \\ \frac{(\pi_{xX} + \Pi_{XX})\pi_{ee}}{\Delta} \\ \frac{(\pi_{xX} + \Pi_{XX})\pi_{ee}}{\Delta} \end{bmatrix},$$
(A3)

where  $\Delta = \frac{1}{\pi_{xX} - \Pi_{XX} + \Pi_{EE}} \Delta^H$ ,  $\Delta^H$  is the determinant of the Hessian matrix. The derivative  $\frac{dX^*}{d\overline{e}} = \frac{\pi_{ee}\Pi_{EE}(\Pi_{X} - \pi_{xx} + \pi_{EE})}{\Delta^H}$ , but given that in equilibrium it holds  $x^*(P^e) = X^*(P^e)$  we obtain  $\frac{dX^*}{d\overline{e}} = \frac{dx^*}{d\overline{e}} = \frac{\pi_{ee}\Pi_{EE}}{\Delta}$ . The latter implies that  $\pi_{xX} - \Pi_{XX} + \Pi_{EE} = \Pi_{xX} - \pi_{xx} + \pi_{EE}$ . Following Bulow et al. (1985) in order to ensure the stability of the equilibrium, the Hessian matrix must be negative definite which implies that  $\Delta^H > 0$  and  $\Delta > 0$ . Given the above and the second order conditions for profit maximization and (A3) it follows that  $\frac{dx^*}{d\overline{e}} = \frac{dX^*}{d\overline{e}} > 0, \frac{d\overline{e}^*}{d\overline{e}} > 0, \frac{dE^*}{d\overline{e}} > 0, and \frac{dP^{e*}}{d\overline{e}} < 0.$ 

**Proof of Proposition 3.** From Proposition 2 it follows that when both countries agree on implementing a permits scheme they achieve the maximum possible welfare. Hence, if one country deviates by non accepting the scheme it will end up with lower welfare. Note that even if we do not allow for a tradable permits scheme the cooperative level of pollution in the symmetric case is the one implied by equation (7). This is because in the non-tradable permits case, the term  $\frac{\partial e^*}{\partial \overline{e}}P^{e*}$  is replaced by the effect of a change on pollution  $\overline{e}$  over marginal abatement costs, i.e.,  $-\frac{\partial e^*}{\partial \overline{e}}q_e$ , where  $\frac{\partial e^*}{\partial \overline{e}} = 1$ . Given that the permits price must be equal to the marginal cost of abatement the two effects are exactly the same. Hence, there is no incentive for unilateral deviation, thus, the introduction of the scheme constitutes a subgame perfect Nash equilibrium.

**Proof of Lemma 1.** Totally differentiating the two first order conditions in (8) we obtain:

$$\left\{\begin{array}{l}
w_{\overline{ee}}d\overline{e} + w_{\overline{e}\overline{E}}d\overline{E} = 0\\
W_{\overline{Ee}}d\overline{e} + W_{\overline{EE}}d\overline{E} = 0\end{array}\right\} \Leftrightarrow \left\{\begin{array}{l}
\frac{d\overline{e}}{d\overline{E}} = -\frac{w_{\overline{e}\overline{E}}}{w_{\overline{e}e}} = -1\\
\frac{d\overline{e}}{d\overline{E}} = -\frac{W_{\overline{EE}}}{W_{\overline{Ee}}} = -1\end{array}\right\}.$$
(A4)

The slopes of the reaction functions in (A4) are equal -1. This is true because all the terms in the first order conditions in (8) depend on the aggregate level of permits, i.e.,  $\overline{e} + \overline{E}$ . This implies that  $w_{\overline{e}\overline{E}} = w_{\overline{ee}}$  and  $W_{\overline{EE}} = W_{\overline{Ee}}$ .

**Proof of Lemma 2.** The corresponding first order conditions described in (8) are now:

$$\frac{dw}{d\overline{e}} = \left[\gamma\left(\overline{e} + \overline{E}\right) - e^*\right] \frac{\partial P^{e*}}{\partial \overline{e}} + \gamma P^{e*} + \frac{\partial \pi^*}{\partial X^*} \frac{\partial X^*}{\partial \overline{e}} - \frac{\partial d}{\partial \overline{e}} = 0$$
  
$$\frac{dW}{d\overline{E}} = \left[(1 - \gamma)\left(\overline{e} + \overline{E}\right) - E^*\right] \frac{\partial P^{e*}}{\partial \overline{E}} + (1 - \gamma)P^{e*} + \frac{\partial \Pi^*}{\partial x^*} \frac{\partial x^*}{\partial \overline{E}} - \frac{\partial D}{\partial \overline{E}} = 0$$
(A5)

Following the same argument as in Lemma 1 these two first order conditions imply that the reaction functions are parallel. The two first order conditions coincide  $iff\left[\gamma\left(\overline{e}+\overline{E}\right)-e^*\right]\frac{\partial P^{e*}}{\partial\overline{e}}+\gamma P^{e*}-\frac{\partial d}{\partial\overline{e}}=\left[\left(1-\gamma\right)\left(\overline{e}+\overline{E}\right)-E^*\right]\frac{\partial P^{e*}}{\partial\overline{E}}+\left(1-\gamma\right)P^{e*}-\frac{\partial D}{\partial\overline{E}}$  as  $\frac{\partial \pi^*}{\partial X^*}\frac{\partial X^*}{\partial\overline{e}}=\frac{\partial \Pi^*}{\partial\overline{x}^*}\frac{\partial x^*}{\partial\overline{E}}$  from Proposition 1. Hence, using that  $\frac{\partial e^*}{\partial\overline{e}}=\frac{\partial e^*}{\partial\overline{E}}, \frac{\partial E^*}{\partial\overline{e}}=\frac{\partial P^{e*}}{\partial\overline{e}}=\frac{\partial P^{e*}}{\partial\overline{E}}$  and solving the former equality with respect to  $\gamma$  we obtain  $\gamma^*=\frac{1}{2}\left(1+\frac{\left(e^*-E^*\right)\frac{\partial P^{e*}}{\partial\overline{e}}+\frac{\partial d}{\partial\overline{e}}-\frac{\partial D}{\partial\overline{E}}}{\left(\overline{e}+\overline{E}\right)\frac{\partial P^{e*}}{\partial\overline{e}}+P^{e*}}\right)$  for which the two first order conditions coincide.

**Proof of Proposition 4.** From our results so far we have  $\frac{\partial e^*}{\partial \overline{e}} = \frac{\partial e^*}{\partial \overline{E}}, \ \frac{\partial E^*}{\partial \overline{e}} = \frac{\partial E^*}{\partial \overline{e}}, \ \frac{\partial P^{e*}}{\partial \overline{e}} = \frac{\partial P^{e*}}{\partial \overline{e}}, \ \frac{\partial P^{e*}}{\partial \overline{e}} = \frac{\partial P^{e*}}{\partial \overline{e}}, \ \frac{\partial e^*}{\partial \overline{e}} = \frac{\partial x^*}{\partial \overline{e}} \Rightarrow \frac{dW}{d\overline{e}} = \frac{dW}{d\overline{e}}.$  Then, given  $\gamma^*$  from Lemma 2 and adding the two first order conditions in (A5) we obtain  $\frac{dw}{d\overline{e}} + \frac{dW}{d\overline{E}} = \frac{dw}{d\overline{e}} + \frac{dW}{d\overline{e}} = \left(\frac{\partial e^*}{\partial \overline{e}} + \frac{\partial E^*}{\partial \overline{e}}\right) P^{e*} + \frac{\partial \pi^*}{\partial X^*} \frac{\partial X^*}{\partial \overline{e}} + \frac{\partial \Pi^*}{\partial x^*} \frac{\partial x^*}{\partial \overline{e}} - \left(\frac{\partial d}{\partial \overline{e}} + \frac{\partial D}{\partial \overline{e}}\right)$ . The latter corresponds to the first order condition in (5).

**Proof of Remark 1.** The first order conditions for profit maximization of the two firms are:

$$\begin{cases} \pi_x = r_x - q_x - \omega\alpha_1 - \omega\alpha_2 = 0 \\ \pi_{e_1} = -P^e - q_{e_1} + \omega\alpha_2 = 0 \\ \pi_{e_2} = -P^e - q_{e_2} + \omega\alpha_1 = 0 \\ \Pi_X = R_X - Q_X - \omega A_1 - \omega A_2 = 0 \\ \Pi_{E_1} = -P^e - Q_{E_1} + \omega A_2 = 0 \\ \Pi_{E_2} = -P^e - Q_{E_2} + \omega A_1 = 0 \\ \begin{cases} \pi_x = r_x - P^e = 0 \\ \Pi_X = R_X - P^e = 0 \end{cases} \end{cases}$$

It follows that Stage 2 equilibrium outputs are always the same, and thus, in equilibrium, permits purchases and abatement levels for each pollutant for the two firms are also the same. The latter implies that the comparative statics must also be exactly the same across the two firms.

The first order condition for Home's welfare maximization is:

$$\frac{dw}{d\overline{e}} = \frac{\partial \left(e_1^* + e_2^*\right)}{\partial \overline{e}} P^{e*} + \frac{\partial \pi^*}{\partial X^*} \frac{\partial X^*}{\partial \overline{e}} - \frac{\partial d}{\partial \overline{e}} = 0, \tag{A6}$$

where  $\frac{\partial d}{\partial \bar{e}} = \frac{\partial d}{\partial e_1^*} \frac{\partial e_1^*}{\partial \bar{e}} + \frac{\partial d}{\partial e_2^*} \frac{\partial e_2^*}{\partial \bar{e}} + \frac{\partial d}{\partial E_2^*} \frac{\partial E_2^*}{\partial \bar{e}}$ . A similar first order condition holds for Foreign's welfare maximization.

The first order conditions for the two countries' joint welfare maximization are:

$$\frac{d(w+W)}{d\overline{e}} = \frac{\partial \left(e_1^* + e_2^* + E_1^* + E_2^*\right)}{\partial \overline{e}} P^{e*} + \frac{\partial \pi^*}{\partial X^*} \frac{\partial X^*}{\partial \overline{e}} + \frac{\partial \Pi^*}{\partial x^*} \frac{\partial x^*}{\partial \overline{e}} - \frac{\partial d}{\partial \overline{e}} - \frac{\partial D}{\partial \overline{e}} = 0$$
(A7)  
and  $\overline{e} = \overline{E}$ .

Given that the comparative statics are identical in Stage 2, then from equations (A6) and (A7), due to symmetry, it follows that  $\frac{d(w+W)}{d\overline{e}} = 2\frac{dw}{d\overline{e}} = 2\frac{dW}{d\overline{E}} = 0$ . **Proof of Remark 2.** Profits for Home's firm are defined as:

$$\pi = \xi(p, P) - q \left[\mu(p, P) - e\right] - P^{e}e,$$

where  $\xi(p, P)$  denote the revenues of the Home firm, p and P respectively denote the prices for Home and Foreign's firms' outputs. We assume  $\xi_P > 0$ . Abatement, defined as  $a = \mu(p, P) - e$ , is replaced directly into the abatement cost function,  $\mu(p, P) = B - p + \vartheta P$ , B > 0 with  $0 < \vartheta < 1$ , stands for the demand function for the Home's product. The two goods are imperfect substitutes and the model is symmetric. Welfare in Home, as defined by equation (2), is:

$$w = \pi + P^e e - d(e + \phi E).$$

The permits market clearing condition is again given by equation (3). The first order conditions for profit maximization of the two firms are:

$$\left\{\begin{array}{l}
\pi_{p} = \xi_{p} - q_{p} = 0 \\
\pi_{e} = -P^{e} - q_{e} = 0 \\
\Pi_{P} = \Xi_{P} - Q_{P} = 0 \\
\Pi_{E} = -P^{e} - Q_{E} = 0
\end{array}\right\} \Rightarrow$$

$$\left\{\begin{array}{l}
\pi_{p} = \xi_{p} - P^{e} = 0 \\
\Pi_{P} = \Xi_{P} - P^{e} = 0
\end{array}\right\}.$$
(A8)

Since countries are symmetric, from (A8) it follows that in equilibrium always  $p^* = P^*$ ,  $e^* = E^* = \frac{\overline{e} + \overline{E}}{2}$ . Implementing the implicit function theorem in the system of equations (A8) we obtain  $\frac{dp^*}{d\overline{e}} = \frac{dP^*}{d\overline{e}} < 0$ ,  $\frac{de^*}{d\overline{e}} = \frac{dE^*}{d\overline{e}} > 0$ , and  $\frac{dP^{**}}{d\overline{e}} < 0$ .

Cooperative solution: In Stage 1 of the game the governments maximize w + W with respect to the number of permits issued by each country. The first order conditions, with respect to  $\overline{e}$  and  $\overline{E}$  for the joint welfare maximization are the following:

$$\frac{d(w+W)}{d\overline{e}} = \left(\frac{\partial e^*}{\partial \overline{e}} + \frac{\partial E^*}{\partial \overline{e}}\right) P^{e*} + \left(\frac{\partial \pi^*}{\partial P^*} \frac{\partial P^*}{\partial \overline{e}} + \frac{\partial \Pi^*}{\partial p^*} \frac{\partial p^*}{\partial \overline{e}}\right) - \left(\frac{\partial d}{\partial \overline{e}} + \frac{\partial D}{\partial \overline{e}}\right) = 0, \quad (A9)$$
$$\overline{e} = \overline{E}.$$

Non-cooperative solution: The welfare maximizing condition for the two governments are de-

scribed by the following equations:

$$\frac{dw}{d\overline{e}} = \frac{\partial e^*}{\partial \overline{e}} P^{e*} + \frac{\partial \pi^*}{\partial P^*} \frac{\partial P^*}{\partial \overline{e}} - \frac{\partial d}{\partial \overline{e}} = 0$$

$$\frac{dW}{d\overline{E}} = \frac{\partial E^*}{\partial \overline{E}} P^{e*} + \frac{\partial \Pi^*}{\partial p^*} \frac{\partial p^*}{\partial \overline{E}} - \frac{\partial D}{\partial \overline{E}} = 0.$$
(A10)

From symmetry and the comparative statics presented above it follows that (A9) reduces to  $\frac{d(w+W)}{d\overline{e}} = \frac{\partial e^*}{\partial \overline{e}} P^{e*} + \frac{\partial \pi^*}{\partial \overline{P}} \frac{\partial P^*}{\partial \overline{e}} - \frac{\partial d}{\partial \overline{e}} = 0$  which corresponds to the first equation in (A10). **Proof of Remark 3.** We introduce a linear specification of our symmetric model. The inverse demand is P = B - b(x+X), where b, B > 0. Abatement cost functions as  $q(a) = \frac{1}{2}ga^2$  and  $Q(A) = \frac{1}{2}gA^2$  for the two firms, where g > 0. Moreover, the damage from pollution in each country is  $d(\overline{e} + \overline{E}) = \frac{1}{2}k(e+E)^2$ , where k > 0. Following Wirl (2009) we focus on a linear strategy for each firm of the form  $e = \kappa - \frac{1}{\lambda}P^e$ , where  $\kappa, \lambda > 0$ .

*Non-cooperative solution*: The first order conditions in Stage 2 for the non-cooperative profit maximization are:

$$\left\{\begin{array}{l}
\pi_{x} = B - 2bx - bX - g\left(x - e\right) = 0\\
\pi_{e} = g\left(x - e\right) - P^{e} - \frac{\partial P^{e}}{\partial e}e = 0\\
\Pi_{X} = B - 2bX - bx - g\left(X - E\right) = 0\\
\Pi_{E} = g\left(X - E\right) - P^{e} - \frac{\partial P^{e}}{\partial E}E = 0\end{array}\right\}.$$
(A11)

From the market clearing condition (3) and after differentiating with respect to the price as implied by the linear strategy defined above we obtain  $\frac{\partial P^e}{\partial e} = \frac{\partial P^e}{\partial E} = \lambda$ . Replacing this value into (A11) and along with (3) we obtain the Stage 2 equilibrium of the game:

$$\begin{cases} x^* = X^* = \frac{2B + g(\bar{e} + \overline{E})}{2(3+g)} \\ e^* = E^* = \frac{\bar{e} + \overline{E}}{2} \\ P^{e*} = \frac{2Bg - [g(\lambda+3)+3\lambda](\bar{e} + \overline{E})}{2(3+g))} \end{cases} \end{cases}.$$
 (A12)

Moving backwards to Stage 1 each country maximizes its own welfare as in (8). Employing (A12) and given the linear strategy defined above we obtain the equilibrium in Stage 1 of our game:

$$\begin{cases} x^* = X^* = \frac{B(3+g)(g+4k)}{g(9+4g)+4(3+g)^2k} \\ e^* = E^* = \overline{e}^* = \overline{E}^* = \frac{Bg(2+g)}{g(9+4g)+4(3+g)^2k} \\ P^{e*} = \frac{Bg[g+12k+4gk-(2+g)\lambda]}{g(9+4g)+4(3+g)^2k} \end{cases}$$
(A13)

Cooperative solution: Given (A12) and using the first order conditions for the cooperative solution given in (5) and (6) we obtain (A13).  $\blacksquare$ 

# Supplementary Appendix

#### **Results of Table 1: A Linear Example**

Here, we provide several outcomes under alternative scenarios for the commonly used linear example, e.g., Ulph (1996). In particular, we assume a linear inverse demand function as P = 100 - (x + X) and quadratic abatement cost functions as  $q(a) = \frac{1}{2}ga^2$  and  $Q(A) = \frac{1}{2}GA^2$  for the two firms. Moreover, the damage from pollution in each country is  $d(e + E) = \frac{1}{2}k(e + E)^2$  and  $D(e + E) = \frac{1}{2}K(e + E)^2$ . Note that g, G, k, and K are the coefficients of the corresponding functions. In the baseline case they are all set equal to unity, i.e., g = G = k = K = 1. Table 2 provides approximations of different scenarios (scenario 1-5) where every time one or two parameters are altered.

Equilibrium	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5
Values	K = 1.1	K = 1.4	G = 1.1	G = 1.4	K, G = 1.2
$P^{e*}, P^{es}$	22.19, -	22.49, -	22.76, -	24.37, -	23.61, -
$e^*, e^s$	3.74, -	3.34, -	2.99, -	0.85, -	1.85, -
$E^*, E^s$	3.74, -	3.34, -	5.06, -	7.81, -	5.79, -
$\overline{e}^*, \overline{e}^s$	3.74, 12.26	3.34, 17.26	4.02, 9.40	4.33, 7.16	3.82, 12.26
$\overline{E}^*, \overline{E}^s$	3.74, 7.70	3.34, 0.77	4.02, 11.74	4.33, 15.00	3.82, 7.90
$x^*, x^s$	25.94, 28.63	25.84, 31.38	25.75, 27.25	25.21, 26.45	25.46, 29.04
$X^*, X^s$	25.94, 26.35	25.84, 23.13	25.75, 27.63	25.21, 27.81	25.46, 25.14
$\gamma^*, \gamma^s$	0.48, -	0.43, -	0.52, -	0.57, -	0.50, -
$w^*, w^s$	971,956	963, 1165	985,847	1015,778	988,987
$W^*, W^s$	974,793	974,575	954,884	901,912	936,730

Table 2: Simulations in five scenarios where the basic values are: g = G = k = K = 1. Every scenario changes one or two parameters denoted below the corresponding caption.

Equilibrium	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Values	K = 1.1	K = 1.4	G = 1.1	G = 1.4
$P^{e*}$	22.08	22.08	22.63	23.88
e*	3.90	3.90	3.16	1.50
E*	3.90	3.90	5.22	8.32
$\overline{e}^*$	7.80	7.80	0	0
$\overline{E}^*$	0	0	8.38	9.82
x*	25.97	25.97	25.79	25.37
X*	25.97	25.97	25.79	25.37
$\gamma$	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$
w*	974	974	981	998
W*	971	971	958	916

Next, Table 3 presents the results from the simulations for the case where  $\gamma = \frac{1}{2}$ . We consider the scenarios 1-4 described above, as scenario 5 coincides.

Table 3: Simulations in four scenarios where the basic values are: g = G = k = K = 1 and  $\gamma = \frac{1}{2}$ . Every scenario changes one parameter denoted below the corresponding caption.

#### Multiple Pollutants-Example

Permits trading-one instrument: Here, we introduce a linear-quadratic example. Specifically we assume a linear inverse demand function as P = B - (x + X) and then following Ambec and Coria (2018) we assume quadratic abatement cost functions as  $q(a) = \frac{1}{2}a_1^2 + \frac{1}{2}a_2^2$  and  $Q(A) = \frac{1}{2}A_1^2 + \frac{1}{2}A_2^2$  for the two firms. In this example the spillovers are set equal to zero. Moreover, the damage from pollution in each country is  $d(e_1, e_2 + E_2) = \frac{1}{2}e_1^2 + \frac{1}{2}(e_2 + E_2)^2$  and  $D(E_1, e_2 + E_2) = \frac{1}{2}E_1^2 + \frac{1}{2}(e_2 + E_2)^2$ .

In Stage 2 the Home firm chooses x,  $e_1$  and  $e_2$  (Foreign firm chooses the corresponding ones). The permits price  $P^e$  clears the permits market  $e_1 + E_1 + e_2 + E_2 = \overline{e} + \overline{E}$ . Thus, the Stage 2 equilibrium values are:

$$\left\{ \begin{array}{l} x^* = X^* = \frac{1}{10} \left( 2B + \overline{e} + \overline{E} \right) \\ e_1^* = E_1^* = e_2^* = E_2^* = \frac{\overline{e} + \overline{E}}{4} \\ P^{e*} = \frac{1}{20} \left[ 4B - 3 \left( \overline{e} + \overline{E} \right) \right] \end{array} \right\}.$$

Given these, the regulators maximize their corresponding welfare through  $\overline{e}$  and  $\overline{E}$ . Hence, the equilibrium values of the subgame are:

$$\left\{\begin{array}{c} x^* = X^* = \frac{35}{159}B\\ e_1^* = E_1^* = e_2^* = E_2^* = \frac{8}{159}B\\ \overline{e}^* = \overline{E}^* = \frac{16}{159}B\\ P^{e*} = \frac{9}{53}B\end{array}\right\}$$

Then equilibrium welfare in each country is  $w^* = W^* = \frac{14}{159}B^2$ .

Permits trading-two instruments: Now the Home (Foreign) regulator selects a binding cap  $\overline{e}_1$  ( $\overline{E}_1$ ) for the local pollutant and issues a number of permits  $\overline{e}_2$  ( $\overline{E}_2$ ) for the transboundary pollutant. Stage 2 equilibrium values are:

$$\left\{ \begin{array}{l} x^{**} = \frac{1}{20} \left[ 4B + 2 \left( \overline{e}_2 + \overline{E}_2 \right) + 7\overline{e}_1 - 3\overline{E}_1 \right], \ X^{**} = \frac{1}{20} \left[ 4B + 2 \left( \overline{e}_2 + \overline{E}_2 \right) - 3\overline{e}_1 + 7\overline{E}_1 \right] \\ e_2^{**} = \frac{1}{4} \left[ 2 \left( \overline{e}_2 + \overline{E}_2 \right) + \overline{e}_1 - \overline{E}_1 \right], \ E_2^{**} = \frac{1}{4} \left[ 2 \left( \overline{e}_2 + \overline{E}_2 \right) - \left( \overline{e}_1 - \overline{E}_1 \right) \right] \\ P^{e^{**}} = \frac{1}{10} \left[ 2B - 4 \left( \overline{e}_2 + \overline{E}_2 \right) + \left( \overline{e}_1 + \overline{E}_1 \right) \right] \end{array} \right\}$$

The damage functions are now  $d(\overline{e}_1, e_2 + E_2) = \frac{1}{2}\overline{e}_1^2 + \frac{1}{2}(e_2 + E_2)^2$  and  $D(\overline{E}_1, e_2 + E_2) = \frac{1}{2}\overline{E}_1^2 + \frac{1}{2}(e_2 + E_2)^2$ . Each government maximizes its own welfare through the local emissions cap and through the number of permits issued. The equilibrium values of the subgame now are:

$$\left\{\begin{array}{c} x^{**} = X^{**} = \frac{25}{104}B\\ e_1^{**} = E_1^{**} = \frac{17}{104}B\\ e_2^{**} = E_2^{**} = \overline{e}_2^{**} = \overline{E}_2^{**} = \frac{1}{26}B\\ P^{e**} = \frac{21}{104}B\end{array}\right\}.$$

Then equilibrium welfare in each country is  $w^{**} = W^{**} = \frac{921}{10816}B^2$ . Comparing the equilibrium welfare levels across the two different scenarios it follows  $w^* - w^{**} > 0$ .

The role of spillovers: In the example presented above we allow for the presence of spillovers. Setting B = 100 and allowing for  $\omega \epsilon$  (-1,1) to capture all possible spillovers such that the abatement cost function is convex we obtain the following figure:



Figure 1: Pollution spillovers and welfare comparisons between permits integration  $(w^*)$  and no integration  $(w^{**})$ 

The results of the simulations show that when the two pollutants are complements, i.e.,  $\omega < 0$ , welfare with an integrated permit market is superior to the case where this is not true (two policy instruments). This holds also when the two pollutants are mildly substitutes, i.e.,  $\omega > 0$ .

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