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Nikos Tsakiris and Nikolaos Vlassis

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A Carbon Leakage Mitigation Reform Strategy: The Role of Border Carbon Adjustments

Nikos Tsakiris* and Nikolaos Vlassis†

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Abstract

This paper sheds light on the unidentified effects of unilateral environmental and trade actions within an international trade framework with two large open economies, transboundary pollution, and Public Pollution Abatement (PPA) activities. When private and public abatement coexists in the exporting country, stricter environmental policy by the importing one magnifies the carbon leakage effect. Pareto efficiency dictates that Border Carbon Adjustment (BCA) should account not only for the difference in carbon taxes between the two countries, but also for the policy's unintended consequences on PPA. More importantly, we argue that a conditional reduction of BCA, subject to stricter environmental policy by the country that exports the polluting good, decreases global pollution and increases countries' welfare. Such reform strategy generates strong incentives for countries with laxer environmental policy to adopt a stricter one.

JEL classifications: F18, H21, H23, Q56.

Keywords: Transboundary Pollution, Carbon Leakage, Border Carbon Adjustment, Environmental Taxation, Public Pollution Abatement.

Declarations of interest: none.

*Department of Economics, University of Ioannina, P.O. Box 1186, 45110 Ioannina, Greece. E-mail: ntsak@uoi.gr

†**Corresponding Author**: Department of Economics, University of Aberdeen Business School, Edward Wright Building, Dunbar Street, Aberdeen AB24 3QY, Scotland, UK. Email: nvlassis@abdn.ac.uk

1 Introduction

On 14 July 2021 European Commission adopted the proposal of a Carbon Border Adjustment Mechanism as part of the European Green Deal (COM 2021). This highlights the risk of carbon leakage (e.g., Fowlie *et al.*, 2016; Larch and Wanner, 2017) arising from the implementation of unilateral environmental policies in line with the Paris Climate Agreement to address environmental degradation. Unilateral actions to address climate change, e.g., EU's Emissions Trading System (ETS) and carbon taxes per tone of CO_2, are part of many countries environmental policy agenda such as EU, UK, Canada, US. As developed countries raise their climate ambition, firms have strong incentives to relocate to countries with less stringent environmental and climate policies. Consequently, production of developed countries may be replaced by more carbon-intensive imports. Both the theoretical and empirical literature provide evidence of carbon leakage as a result of unilateral environmental policies, see, among others, Copeland and Taylor (2005), Kotsogiannis and Woodland (2013), Böhringer *et al.* (2014). These concerns are amplified by the lack of enforcement mechanisms in International Environmental Agreements, e.g., the Paris Climate Agreement and the Kyoto Protocol, to impose binding pollution targets on participating countries.

To address these issues a number of countries consider the implementation of trade measures in the form of *Border Carbon Adjustments* (*BCAs*) alongside environmental policies to mitigate the effects arising from countries' asymmetric environmental standards. A *BCA* will equalise the cost of unilateral environmental regulations between domestic production and imports from countries with laxer ones. This will reduce the risk of emission leakage, ensuring that the country's climate objectives are not undermined, and it also preserves the competitiveness of domestic industries. In addition it aims to encourage countries with laxer environmental standards to adopt stricter ones. For a detailed and recent discussion on issues relevant to *BCA* see Keen *et al.* (2021).

BCAs have been in the political agenda for more than a decade (see among others, Fischer and Fox, 2012; Balistreri et al., 2019 and Keen *et al.*, 2021), despite criticisms concerning the legality, implementation and effectiveness of these policies. According to the WTO provisions, countries can adopt *BCA* type of trade restrictions under GATT Article III; XVI and XX. In March 2021 the

European Parliament (EP 2021) adopted a resolution advocating for a *BCA* mechanism compatible with WTO, similarly recent legislative proposals for carbon taxes in the United States include *BCA* measures.[1]

The theoretical literature supports the effectiveness of *BCAs* alongside environmental policies to mitigate the effects arising from countries' asymmetric environmental standards (see among others, Fischer and Fox, 2012; Keen and Kotsogiannis, 2014; Böhringer *et al.*, 2017; and Balistreri *et al.*, 2019). Al Khourdajie and Finus (2020), in a recent paper, analyse the role of *BCA* as an incentive mechanism for countries to join an environmental agreement, mitigating free-riding effects of stricter unilateral environmental policies. They show that the 'small coalition paradox' is reversed in the presence of *BCA*, resulting in the formation of large stable environmental agreements.

Despite the attention unilateral environmental policies, i.e. carbon taxes or permits and *BCAs*, have received from both the policy makers and the academic community, their design details and features are still debatable. This paper contributes to this ongoing debate of *BCA* design and effectiveness in the presence of *Public Pollution Abatement* (*PPA*) activities, a common strand of many countries' environmental actions, which has been neglected by the relevant literature. Within this setting, we provide the optimal *BCA* structure and we analyse its effectiveness as an incentive mechanism for countries with laxer environmental policies to adopt stricter ones. More specifically, we propose a welfare increasing conditional *BCA* reform strategy which provides clear incentives to the exporter of the polluting good to adopt stricter environmental policy.

The importance of PPA activities

PPA activities are a significant part of the environmental policy of many Organization for Economic Co-operation and Development (OECD) countries with 40%–60% of total pollution and abatement control expenditures financed by public revenues, see Linster *et al.* (2007), Pantelaiou *et al.* (2020). Examples of *PPA* activities such as treatment of air i.e., afforestation and reafforestation, sustainable management of forests; treatment of water pollution i.e., sewerage and waste water treatment, are present in many economies. More specifically, China announce the plantation of 36,000 square kilometers of new forest per year from 2021 to 2025 to combat climate change. These actions are part of the Grain-for-Green Program, the world's largest reforestation scheme which runs for over

[1] See https://joebiden.com/climate-plan

two decades with spending of 5 billion dollars by 2013 (Hua *et al.*; 2016). Similarly, Ethiopia under the Green Legacy Initiative mobilized public sector workers and funds for afforestation activities. Another example of *PPA* activities is the management of wildfires. Wildfires are among the first contributors to climate change accounting for 37.8% of total emissions by natural resources (Yue and Gao; 2018). Wildfire appropriations for US, increased by 82% from 2011 to 2020. In nominal terms in 2020 US allocated \$6.11 billion in wildfire management (Hoover 2020). Similarly, Turkey allocated \$24 million and Portugal \$265 million to prevent and combat forest fires in 2021.

Pollution abatement activities in developed economies are undertaken by both the private and the public sectors, while in developing economies are most likely to be undertaken by the public sector, due to the lack of appropriate institutional structure (e.g., lack of enforcement and monitoring mechanisms). In addition, economies with weaker environmental policies might undertake *PPA* activities as a reaction to "carrot policies" by developed economies and International Organizations, e.g., European Union encourages developing economies to mitigate emissions through tied financial foreign aid, see Schweinberger and Woodland (2008), Hadjiyiannis *et al.* (2013) and Nimubona and Rus (2015). Many economies finance *PPA* activities through pollution charges' revenues – the so-called *tax earmarking* – see, among others, Brett and Keen (2000), Haibara (2009), Hadjiyiannis *et al.* (2013). The 'Database on Policy Instruments for the Environment' of the OECD provides evidence of earmarking of environmental tax revenues for environmental purposes.[2] Similarly, countries in Eastern Europe, Caucasus and Central Asia (EECCA) public environmental tax revenues are earmarked for environmental protection projects (see OECD Environmental Country Reviews, http://www.oecd.org/env/country-reviews/).

Contribution of the paper

To analyse the effectiveness of *BCA* as carbon leakage mitigation mechanism in the presence of *PPA* activities, we develop a general equilibrium model with two large open economies, Home and Foreign, and production generated cross-border pollution. Each country imposes country specific carbon policy in order to control pollution, while Home implements *BCA* to level the difference between the countries' carbon policies. Home's carbon policy revenues are distributed as lump-sum transfers to domestic consumers and Foreign's are earmarked for *PPA* activities.

[2] https://pinedatabase.oecd.org/

We find that when private abatement coexists with public pollution abatement, an increase in Home's carbon tax will induce the expansion of the Foreign's polluting sector, the so-called carbon leakage, increasing carbon tax revenues and thus the country's *PPA* activities. In parallel, the unit cost of *PPA* activities increases due to the competition of private and public sectors for the same factors of production. This implies that, if the unit cost of *PPA* activities is higher than the Foreign's carbon tax, a higher carbon tax by Home will magnify the *carbon leakage effect*. The failure of environmentally concerned countries to account for the unintended consequences of stricter carbon taxes on *PPA* will result in the underestimation of the size of the well-known carbon leakage effect, which is standard to the literature.[3]

Additionally, we show that Pareto efficiency dictates that *BCA* should be present, accounting not only for the difference in carbon taxes between countries, as indicated by the relevant literature, (see, among others, Fischer and Fox, 2012; Keen and Kotsogiannis, 2014; Böhringer *et al.*, 2017) but also for the policy's unintended consequences on *PPA* activities.

More importantly, this paper analyses the effectiveness of *BCA* as an incentive mechanism for countries with laxer environmental standards to adopt stricter ones. To do so, we explore how once *BCAs* are in place their conditional reduction can work as a carrot policy for the exporting country answering the question; Are *BCAs* here to stay? The implementation of *BCA* does not automatically results to the adoption of stricter environmental policy by the exporting country, this will depend on the carbon content of Foreign country's exports and the level of *BCA* charge, see Keen *et al.* (2021). To incentivise countries with laxer environmental policy to adopt a stricter one, we suggest a conditional reduction of *BCA*, which alleviates any concerns on the effectiveness of *BCA*.

Within the suggested framework, we propose a conditional reduction of *BCA* subject to stricter carbon tax by the exporting country in such a way so as to provide neutrality in exporting country's producer price. The particularity of this reform strategy to keep producer's price fixed, creates clear incentives for the exporting countries to comply, as it increases its exports and carbon tax revenues. The suggested reform strategy unambiguously increases the exporting country's welfare through

[3]For an extended discussion on carbon leakage under perfect competition, see, among others, e.g., Fischer and Fox (2012), Jakob *et al.* (2013), Keen and Kotsogiannis (2014), Böhringer *et al.* (2017), while Egger et al. (2021) analyse carbon leakage within an imperfectly competitive framework. Baylis *et al.* (2013, 2014), within a perfectly competitive setting consisting of two sectors and two factors, show that the carbon leakage effect resulting from a stricter unilateral environmental policy can be rendered from positive to negative.

the improvement of its competitiveness in international markets and the reduction of pollution. Such type of reform strategy is consistent with *BCA*'s aim, which is to incentivise countries with laxer environmental policy to adopt a stricter one and prevents its use as a strategic trade policy instrument for rent shifting and thus beggar-thy-neighbour behaviour.

The proposed reform strategy affects carbon leakage as well as the countries' welfare through the trade and the *PPA* channels. The decreased level of *BCA* will result in a lower producer and consumer price in Home which increases demand for imports. Simultaneously, Foreign's production level remains unchanged due to the *producer price-neutrality* aspect of the reform. It follows that carbon tax revenues will increase given the higher carbon tax by Foreign required by the reform. As carbon tax revenues are earmarked for *PPA*, their increase will eventually lead to a higher level of *PPA* activities, decreasing global pollution. The suggested reform strategy remains welfare improving even if carbon tax revenues are not earmarked to *PPA* activities but instead they are lump-sum rebated to consumers.

Finally, we conclude our analysis by discussing the role of *BCA* when Foreign regulates pollution through cap-and-trade instead of carbon taxes. It is argued that when revenues from intra-nationally tradable carbon permits are earmarked for *PPA* activities, *BCA* still plays a role, accounting for its consequences on *PPA* activities. This contradicts the results of the relevant literature which supports that *BCA* serves no purpose other than rent shifting when Foreign uses cap-and-trade policy to control pollution.

The rest of the paper is organized as follows: Sections 2 and 3 describe the model, highlight the role of *PPA* in carbon leakage and derive the optimal level of *BCA*; Section 4 proposes a conditional carbon leakage mitigation reform strategy; Section 5 provides a general discussion on the case of cap-and-trade and Section 6 summarises and concludes.

2 The Model

Consider a perfectly competitive model of international trade with two large open economies, labelled 'Home' and 'Foreign'. Foreign's variables are denoted by an asterisk. In each country there is a perfectly competitive private sector producing two tradeable commodities, $x_1(x_1^*)$ and $x_2(x_2^*)$, and a representative consumer. Production of good 1 generates pollution as a by-product of production, denoted by z (z^*), while production of good 2 is 'clean'. Good 2 is chosen as the numeraire. It is also assumed throughout the paper that the numeraire good is subject to no restrictions. Pollution affects consumer welfare but not firms' production capabilities. Home (Foreign) imports (exports) the polluting good 1 and exports (imports) the clean good 2. Imports by Home are subject to a *BCA* (τ) while Foreign does not impose any trade restriction.[4]

To control pollution, both countries impose carbon taxes, denoted by s (s^*). Home uses the carbon tax revenue as a compensation to consumers for the degradation of environmental quality.[5] Foreign uses the carbon tax revenue to finance *PPA* activities denoted by g^* thus, the *net pollution* arising from Foreign's activities is given by $z^* - g^*$. *PPA* activities can be viewed as an international public good as, given the transboundary nature of pollution, they entail positive externalities to other countries, for a discussion on international public goods see, among others, Karakosta *et al.* (2014), Tsakiris *et al.* (2018), Kotsogiannis and Lopez-Garcia (2021). Global pollution is fully transboundary and is given by

$$k = z + z^* - g^*. \tag{1}$$

The world aggregate production-generated pollution is expected to be higher than abatement, i.e., $z + z^* > g^*$. The opposite is also possible under the assumption of pollution stock as in Kotsogiannis and Woodland (2013). Home's GDP is depicted by the revenue function $r(p, s)$ capturing the maximum value of production at domestic producer prices $p = q + \tau$, where q is the world relative price of good 1. By the properties of the revenue function, $r_p(p, s) = \frac{\partial r}{\partial p} = x_1$ is the supply function of good 1, and $-r_s(p, s) = -\frac{\partial r}{\partial s} = z$ is the level of pollution; see, e.g., Keen and Kotsogiannis (2014).

Foreign's GDP is depicted by the *restricted* revenue function:

$$r^*(p^*, s^*, g^*) = \max\left\{x_2^* + p^* x_1^* - s^* z^* : (x_1, x_2, z^*) \in T^*(v^{p*})\right\},$$

capturing the maximum value of production at domestic producer prices p^* (where $p^* = q$, since Foreign does not implement any trade policy), carbon tax s^* and technology $T^*(v^{p*})$. The domestic

[4]For the effectiveness of *BCA* policy with local pollution see Karakosta (2018).

[5]Alternative specifications of the Home's government budget constraint can be easily introduced with the present analytical apparatus, the tax revenue could instead used to finance *PPA* activities. This specification raises additional algebraic complexities without contributing to the importance and clarity of the results.

factors of production are fixed in supply, internationally immobile and denoted by the vector $v^* = v^{p*} + v^{g*}$. Where v^{p*} and v^{g*} are, respectively, the vectors of factors used in the production of the private goods and the public abatement activities. Factor markets are assumed to be perfectly competitive. The supply function of good 1 for Foreign is given by $r^*_{p^*}(p^*, s^*, g^*) = \frac{\partial r^*}{\partial p^*} = x^*_1$; the level of Foreign country's generated pollution is given by $z^* = -\frac{\partial r^*}{\partial s^*} = -r^*_{s^*}(p^*, s^*, g^*)$; by convexity $r^*_{p^*p^*} > 0$ and $r^*_{s^*s^*} = -\left(\frac{\partial z^*}{\partial s^*}\right) > 0$. The unit cost of producing the public pollution abatement is given by $-r^*_{g^*} = -\frac{\partial r^*}{\partial g^*} > 0$ and $r^*_{g^*g^*} = 0$.[6]

Consumer preferences are represented by the expenditure function $e(p, k, u)$ $[e^*(p^*, k, u^*)]$, at constant consumer prices p (p^*) and global pollution k, given by:

$$e(p, k, u) = \min\{pc_1 + c_2 : \ U(c_1, c_2, k) \geqslant u\}, \tag{2}$$

$$e^*(q, k, u^*) = \min\{qc^*_1 + c^*_2 : \ U^*(c^*_1, c^*_2, k) \geqslant u^*\}. \tag{3}$$

Equations (2) and (3) indicate, respectively, the minimum expenditure of Home and Foreign country's representative consumer in achieving utility level u and u^*, given consumer prices and global pollution level. Standard assumption on homogeneity and concavity apply. Consumer marginal willingness to pay for pollution reduction is given by $e_k = \frac{\partial e}{\partial k} > 0$ $(e^*_k > 0)$, and is positive since pollution confers disutility to consumers. Throughout we assume that each country's income effects attach only to the numeraire commodity, thus, $e_{pu} = e^*_{qu^*} = 0$ and that the level of pollution does not affect consumption, $e_{pk} = e^*_{qk} = 0$, see e.g., Keen and Kotsogiannis (2014), Kotsogiannis and Lopez-Garcia (2021).[7]

Assuming it exists, an equilibrium is characterised by a system of five equations, including (1),

[6]The assumption that $r^*_{g^*g^*} = 0$ implies that *PPA*'s unit cost is not affected by the level of *PPA*. For example, this holds in a conventional Heckscher-Ohlin model where factor prices are determined by commodity prices and are independent of changes in factor endowments. For a detailed discussion of the *restricted* revenue function and its properties see, among others, Raimondos-Møller and Woodland (2006), Kotsogiannis and Lopez-Garcia (2021) for the case of small open economies. Hatzipanayotou and Michael (1995), Chao and Yu (1999), Nimubona and Rus (2015) for the case of large open economies.

[7]This assumption is supported by considering a separable utility function of the type $U(c_1, c_2, k) = f(c_1, c_2) - h(k)$ where c_i, $i = 1, 2$, is the consumption of the good i, $f(c_1, c_2)$ is a quasi-linear function and $h(k)$ is increasing and convex. Relaxation of the separability assumption, i.e.,$e_{pk} \neq 0$, $e^*_{qk} \neq 0$, is possible at the cost of additional notation and assumptions on the complementarity (substitutability) between consumption and pollution, i.e., $e_{pk} > 0$ $(e_{pk} < 0)$.

with five unknowns q, u, u^*, g^*, k. That is,

$$e_q^* - r_{p^*}^* + e_p - r_p = 0, \tag{4}$$

$$e(p, k, u) = r(p, s) + sz + \tau(e_p - r_p), \tag{5}$$

$$e^*(q, k, u^*) = r^*(p^*, s^*, g^*) + s^* z^*, \tag{6}$$

$$- r_{g^*}^* g^* = s^* z^* = -s^* r_{s^*}^*(p^*, s^*, g^*). \tag{7}$$

Equation (4) gives the market clearing condition for the polluting good 1. Home's budget constraint, equation (5), states that Home representative consumer's expenditure equals the income from the production of the traded goods plus the lump-sum distributed carbon tax and *BCA* revenues. Foreign's budget constraint, equation (6), states that Foreign representative consumer's expenditure equals the factor income generated from both the production of private goods and *PPA* activities. Equation (7) captures the Foreign's government budget constraint for providing *PPA*. The following section uses this system to analyze the environmental and welfare effects of the available policies.

3 Carbon Leakage in the presence of PPA

In this section, we examine the impact of Home's policies' changes on global pollution, and we characterise their optimal levels, assuming that Foreign remains passive, i.e., $ds^* = 0$.

To obtain Home's policies' impact on the world relative price of good 1, totally differentiate equation (4)**:**

$$\Delta dq = -(e_{pp} - r_{pp})d\tau + r_{ps} ds, \tag{8}$$

stability requires that $\Delta = (e_{qq}^* - r_{p^*p^*}^* + e_{pp} - r_{pp}) - r_{p^*g^*}^* \left(g^* r_{g^*p^*}^* - s^* r_{s^*p^*}\right)(-r_{g^*}^* + s^* r_{s^*g^*}^*)^{-1} < 0.$[8] Equation (8) indicates that a higher *BCA* by Home reduces the world relative price of the polluting good 1, $\frac{dq}{d\tau} = -(e_{pp} - r_{pp})\Delta^{-1} < 0$. Intuitively, a higher *BCA* from Home will decrease local demand and simultaneously increase local supply, which results in the decrease of the world relative price of the polluting good 1. An increase in Home's carbon tax increases the world relative price of the non-numeraire good, $\frac{dq}{ds} = r_{ps}\Delta^{-1} > 0$, since $r_{ps} (= r_{sp}) = \frac{\partial r_p}{\partial s} < 0$. This is due to the fact that a

[8] Sufficient condition for stability requires a relatively small s^*, so that $\left(g^* r_{g^*p^*}^* - s^* r_{s^*p^*}\right) < 0$.

higher s decreases production of the polluting good in Home and thus its world supply.

Totally differentiating equation (7), using (8), we obtain the Home's policies' impact on the level of *PPA* provided by Foreign. That is,

$$dg^* = \left(-s^* r^*_{s^*p^*} + g^* r^*_{g^*p^*}\right) B^{-1} \frac{dq}{ds} ds + \left(-s^* r^*_{s^*p^*} + g^* r^*_{g^*p^*}\right) B^{-1} \frac{dq}{d\tau} d\tau, \tag{9}$$

where $B = (-r^*_{g^*} + s^* r^*_{s^*g^*})$. By the properties of the *restricted* revenue function, $r^*_{s^*p^*} \left(= r^*_{p^*s^*}\right) = -\frac{\partial z^*}{\partial p^*} < 0$, implying that a higher q increases the production of the polluting good 1, and thus pollution, i.e., $\frac{\partial z^*}{\partial p^*} > 0$. Assuming that the polluting good and the *PPA* activity are substitutes in production, implies $r^*_{s^*g^*} = -\frac{\partial z^*}{\partial g^*} > 0$ and $r^*_{g^*p^*} < 0$, e.g., Chao and Yu (1999). This assumption carries throughout the analysis, thus $B > 0$.[9] Since $\frac{dq}{ds} > 0$, a higher carbon tax by Home exerts a positive impact on Foreign's terms of trade, thus increasing production of good 1, carbon tax revenue at a given tax rate s^*, i.e., $-s^* r^*_{s^*p^*} > 0$, and the level of *PPA* provided by the country. On the other hand, a higher s by Home increases *PPA*'s unit cost, and thus reduces the level of its provision, i.e., $g^* r^*_{g^*p^*} < 0$. Therefore, the overall effect on *PPA* is ambiguous. Similarly, a higher *BCA* by Home entails an ambiguous effect on *PPA* in Foreign.

Totally differentiating equation (1), using (9) and (8), we obtain the Home's policies' impact on the level of global pollution. That is:

$$\begin{aligned} dk = &\left\{ \underbrace{-\left(r_{ss} + r_{sp}\frac{dq}{ds}\right)}_{Domestic\ Output\ Effect-Carbon\ Tax} + \underbrace{\left[r^*_{s^*p^*}\left(r^*_{g^*} + s^*\right) - g^* r^*_{g^*p^*}\left(r^*_{s^*g^*} + 1\right)\right] B^{-1}\frac{dq}{ds}}_{Carbon\ Leakage\ Effect-Carbon\ Tax} \right\} ds \\ &+ \left\{ \underbrace{-r_{sp}\left(1 + \frac{dq}{d\tau}\right)}_{Domestic\ Output\ Effect-BCA} + \underbrace{\left[r^*_{s^*p^*}\left(r^*_{g^*} + s^*\right) - g^* r^*_{g^*p^*}\left(r^*_{s^*g^*} + 1\right)\right] B^{-1}\frac{dq}{d\tau}}_{Carbon\ Leakage\ Effect-BCA} \right\} d\tau. \end{aligned} \tag{10}$$

Equation (10) indicates that changes in Home's policies affect global pollution levels, through domestic output and carbon leakage effects. Home's higher carbon tax entails a direct effect on its pollution (r_{ss}) which dominates the indirect effect arising from the terms of trade adjustments $\left(r_{sp}\frac{dq}{ds}\right)$. The overall *Domestic Output Effect* of a higher carbon tax reduces global pollution, i.e.,

[9] Note that complementarity in production of the polluting good and the *PPA* implies $r^*_{s^*g^*} < 0$ and $r^*_{g^*p^*} > 0$.

$-\left(r_{ss}+r_{sp}\frac{dq}{ds}\right)<0.$

An increase of Home's carbon tax increases the world relative price of the polluting good ($\frac{dq}{ds}>0$) triggering *Carbon Leakage* through the following channels: (i) Foreign's production due to the expansion of the polluting sector, i.e., $r^*_{s^*p^*}$, and (ii) the unit cost of PPA provision, i.e., $r^*_{g^*p^*}$. The expansion of Foreign's polluting sector increases pollution – positive effect on emissions – thereby increasing carbon tax revenues and hence PPA – negative effect on emissions. Assuming that Foreign's carbon tax is lower than PPA's unit cost, i.e., $r^*_{g^*}+s^*<0$, which is a realistic assumption for economies with weak environmental policies, the positive effect dominates. Intuitively, $r^*_{g^*}+s^*<0$ implies that the tax base of PPA does not outweigh the increase in pollution due to the expansion of the polluting sector, resulting in an increase in global pollution, i.e., $r^*_{s^*p^*}\left(r^*_{g^*}+s^*\right)B^{-1}\frac{dq}{ds}>0$.

Through the second channel, the induced increase in q raises the unit cost of PPA and thus pollution, i.e., $-g^*r^*_{g^*p^*}\left(r^*_{s^*g^*}+1\right)B^{-1}\frac{dq}{ds}>0$. Intuitively, the expansion of Foreign's polluting sector increases its demand for factors of production. Given that the polluting good and PPA compete for the same factors of production, since $r^*_{g^*p^*}<0$, the unit cost of PPA increases.

The overall *Carbon Leakage Effect* arising from an increase in Home's carbon tax is positive when $r^*_{g^*}+s^*<0$, which reconfirms the well-known result of the literature, e.g., Fischer and Fox (2012), Keen and Kotsogiannis (2014), Böhringer *et al.* (2017). Interestingly, equation (10) suggests that in the presence of PPA activities the positive *Carbon Leakage Effect* is magnified. This is an interesting finding as it suggests that the failure of the countries adopting stricter environmental policies to account for such unintended consequences on PPA will underestimate the size of the leakage effect.

A higher BCA also entails a *Domestic Output* and *Carbon Leakage Effects* analogous to the carbon tax effects. An increase in Home's BCA entails a direct effect on its own production and pollution, i.e., $-r_{sp}$, which dominates the indirect effect arising from the terms of trade adjustments, i.e., $-r_{sp}\frac{dq}{d\tau}$. The overall *Domestic Output Effect* of a higher BCA increases global pollution, i.e., $-r_{sp}\left(1+\frac{dq}{d\tau}\right)>0$. Additionally, a higher BCA by Home reduces the world price ($\frac{dq}{d\tau}<0$) which contracts Foreign's polluting sector and decreases *PPA's* unit cost. The overall *Carbon Leakage Effect* of Home's BCA is negative when $r^*_{g^*}+s^*<0$. Equation (10) suggests that BCA's *Carbon Leakage Effect* has been underestimated by the existing literature, as it neglects its effect on the unit cost of Foreign's *PPA* activities. To emphasise:

Proposition 1 *When carbon tax is used as Foreign's environmental policy and the revenues are earmarked for PPA activities, an increase in Home's carbon tax magnifies the positive carbon leakage effect, while an increase in BCA magnifies the negative carbon leakage effect.*

The result that the presence of *PPA* magnifies the *Carbon Leakage Effects* arising from Home's policies, alters when Foreign's carbon tax is higher than *PPA*'s unit cost, i.e., $r^*_{g^*} + s^* > 0$. This results in the mitigation of Home's policies' *Carbon Leakage Effects.* The leakage effect arising from higher carbon tax by Home can be rendered negative if its effect on Foreign's originated pollution outweighs the one on *PPA's* unit cost. Analogous, a higher *BCA* by Home can render its leakage effect from negative to positive.

To identify the welfare effects arising from Home country's policies, totally differentiate equations (5) and (6), using (8), (9) and (10), to obtain:

$$\begin{aligned} e_u du &= \left[\tau\left(e_{pp} - r_{pp}\right) + \left(e_k - s\right) r_{sp}\right] d\tau \\ &+ \left\{ \begin{array}{c} \tau\left(e_{pp} - r_{pp}\right) B + \left(e_k - s\right) r_{sp} B \\ -\left(e_p - r_p\right) B - e_k\left[r^*_{s^*p^*}\left(r^*_{g^*} + s^*\right) - g^* r^*_{g^*p^*}\left(r^*_{s^*g^*} + 1\right)\right] \end{array} \right\} B^{-1}\left(\frac{dq}{ds} ds + \frac{dq}{d\tau} d\tau\right), \text{ and} \end{aligned} \tag{11}$$

$$\begin{aligned} e^*_{u^*} du^* &= e^*_k r_{sp} d\tau + e^*_k r_{ss} ds \\ &+ \left\{ \begin{array}{c} -\left(e^*_q - r^*_{p^*}\right) B + e^*_k r_{sp} B \\ +\left[\left(e^*_k - s^*\right) r^*_{s^*g^*} + \left(e^*_k + r^*_{g^*}\right)\right] g^* r^*_{g^*p^*} - e^*_k\left(r^*_{g^*} + s^*\right) r^*_{s^*p^*} \end{array} \right\} B^{-1}\left(\frac{dq}{ds} ds + \frac{dq}{d\tau} d\tau\right). \end{aligned} \tag{12}$$

From equations (11) and (12) it follows that the aggregate welfare is given by:

$$e_u du + e^*_{u^*} du^* = A_\tau d\tau + A_s ds, \tag{13}$$

where the complete definition of A_τ and A_s are given in the Appendix I by (A.1).

Following Balistreri *et al.* (2019), Keen and Kotsogiannis (2014), and Turunen-Red and Woodland (2004), we assume that Home sets its policies so as to maximise the countries' joint welfare. This policy setting is consistent to UNFCCC's principle of 'common but differentiated responsibility'[10] with developed economies undertaking more intensive mitigating actions irrespectively of measures elsewhere. For example, EU's commitment for no net emissions of greenhouse gases by 2050, as described by European Green Deal (COM, 2019), is clearly in line with such cooperative behaviour. This is also reflected by the inclusion of more than 130 environmental targets and objectives to the European Union legislation, see EEA (2013). Such type of behaviour, internalizing the induced externality to and from other countries, is expected by developed economies where consumers' demand for clean environment is relatively high. Setting $\frac{e_u du}{d\tau} + \frac{e^*_{u^*} du^*}{d\tau} = 0$ and $\frac{e_u du}{ds} + \frac{e^*_{u^*} du^*}{ds} = 0$ in (13) and solving simultaneously, we obtain:[11]

$$s^c = e_k + e^*_k, \tag{14}$$

$$\tau^c = \underbrace{(s^c - s^*)\, r^*_{s^*g^*} g^* r^*_{g^*p^*} \Phi^{-1}}_{(a)} + \underbrace{\left\{ \underbrace{\left(e_k + e^*_k + r^*_{g^*}\right) g^* r^*_{g^*p^*} \Phi^{-1}}_{(b_1)} - \underbrace{\left(e_k + e^*_k\right)\left(r^*_{g^*} + s^*\right) r^*_{s^*p^*} \Phi^{-1}}_{(b_2)} \right\}}_{(b)}, \tag{15}$$

where $\Phi = \left(1 + \frac{dq}{d\tau}\right) B\Delta < 0$. Pareto efficiency dictates that the carbon tax is set at its first best Pigouvian level taking into account the cumulative (global) marginal damage caused by an additional unit of carbon generated by Home's production. Equation (15) indicates that in the presence of *PPA* activities, the optimal *BCA* should account not only for the difference between carbon taxes in the two countries, as suggested by the existing literature, but also for the policy's effects on *PPA*. By focusing on the cooperative setting the beggar-thy-neighbour aspect of *BCA* is neutralised; see, among others, Balistreri *et al.* (2019), Keen and Kotsogiannis (2014). The first term (a) is positive, as in Keen and Kotsogiannis (2014).[12] In the absence of *PPA* the second term vanishes and the optimal level of *BCA* accounts only for the difference between carbon taxes in

[10] Principle 1 of Article 3 of United Nations Framework Convention on Climate Change (UNFCCC).

[11] Superscript c denotes the optimal cooperative level of Home's policies.

[12] The implicit assumption is that the carbon tax in Foreign is "too low" relative to the first best Pigouvian level, thus $s^* < e_k + e^*_k$. Intuitively, in countries with weaker environmental policy it is expected that the carbon tax is lower than the domestic carbon marginal damage, i.e, $s^* < e^*_k$.

the two countries. The second term arises due to the coexistence of private and *PPA* activities in Foreign—an important component, insofar overlooked by the existing literature. Home's *BCA* affects Foreign's *PPA* unit cost and the available *PPA* funds, through its effect on Foreign's polluting sector. The first element (b_1) is positive since $e_k + e_k^* + r_{g^*}^* > 0$ capturing the underprovision of *PPA* relative to the Samuelson first best rule.[13] The second element (b_2) is also positive under the assumption that $r_{g^*}^* + s^* < 0$. Thus, the sign of *(b)* is positive. In this case, Pareto efficiency dictates for *BCA* to be present but at a higher level than the one suggested by the relevant literature in the absence of *PPA* activities (see, among others, Fischer and Fox, 2012; Keen and Kotsogiannis, 2014).

Proposition 2 *When Home maximises the countries' joint welfare, with Foreign being passive, Pareto efficiency dictates that the carbon tax is set at its first best Pigouvian level, while BCA accounts for the difference in carbon taxes between the two countries as well as for the unintended consequences on PPA activities in Foreign.*

When $r_{g^*}^* + s^* > 0$ the sign of *(b)* is ambiguous; implying that *BCA* can be positive (import charge) or negative (import subsidy). Intuitively, this result shows that in the presence of *PPA*, Pareto efficiency dictates for *BCA* to be present but at a lower level.

To elaborate further on the characteristics of the policies' optimal cooperative structure it is useful to compare them with their non-cooperative structure. When Home acts non-cooperatively, i.e., $\frac{e_u du}{d\tau} = 0$ and $\frac{e_u du}{ds} = 0$, the optimal carbon tax and *BCA*, in the presence of *PPA* activities are given by:[14]

$$s^{nc} = e_k, \tag{16}$$

$$\tau^{nc} = \left\{ (e_p - r_p) + e_k \left[r_{s^*p^*}^* \left(r_{g^*}^* + s^* \right) - g^* r_{g^*p^*}^* \left(r_{s^*g^*}^* + 1 \right) \right] B^{-1} \right\} (e_{pp} - r_{pp} - \Delta)^{-1} . \tag{17}$$

In contrast to equations (14) and (15) when Home behaves non-cooperatively, optimality dictates to set its environmental policy equal to its own marginal damage caused by an additional unit

[13] Due to the existence of cross-border pollution, the relevant Samuelson rule accounts not only for the marginal willingness to pay for pollution reduction within the polluting country, but also for the marginal willingness to pay for it in the other country. In the absence of lump-sum taxes then public pollution abatement is globally underprovided i.e., $e_k^* + e_k > -r_g$. For countries with weaker environmental policy it is expected that public pollution abatement is also locally underprovided i.e., $e_k^* > -r_g$. When lump-sum taxes are available then the Samuelson first best rule requires that $e_k^* + e_k = -r_g$. For further discussion see Kotsogiannis and Lopez-Garcia (2021).

[14] Superscript nc denotes the optimal non-cooperative level of Home's policies.

of pollution. Accordingly, the BCA's non-cooperative optimal structure should account not only for carbon leakage but also for the terms of trade effect, reflecting the policy's strategic aspect; e.g., Böhringer *et al.* (2017), Jakob *et al.* (2013). Even in the case of many sectors, the non-cooperatively and cooperatively optimal structure of carbon taxes calls for uniformity across sectors, i.e., Böhringer *et al.* (2014), Keen and Kotsogiannis (2014).

4 Are $BCAs$ here to stay? A Carbon leakage mitigation reform strategy

In this Section we examine whether once $BCAs$ are in place their conditional reduction can work as a carrot policy for countries with laxer environmental standards to adopt stricter ones, answering the question; Are $BCAs$ here to stay? To answer this, we assume that Foreign is no longer passive, i.e., $ds^* \neq 0$.[15] In particular, we examine the welfare and global pollution effects of a conditional policy reform where Foreign's carbon tax and Home's BCA are adjusted to leave Foreign's producer price unchanged.[16] This type of reform strategy suggests, starting from an arbitrary level, a conditional reduction of Home's BCA subject to an increase in Foreign's carbon tax. Such type of reform strategy is consistent with $BCAs$*'* aim to incentivise other countries to adopt stricter environmental policies without disadvantaging their private sector. Given that the suggested reform strategy increases Foreign's producer's access in Home's market, it is in line with WTO rules, reducing trade barriers such as $BCAs$ (for a recent discussion on tariff reforms compatible with WTO rules, see Raimondos and Woodland, 2018).

One unit of production generates a units of pollution in Home i.e., $z = ax_1 \Rightarrow -r_s = ar_p$; and a^* units of pollution in Foreign, i.e., $z^* = a^*x_1^* \Rightarrow -r^*_{s^*} = a^*r^*_{p^*}$, thus $r^*_{s^*p^*} = -a^*r^*_{p^*p^*}$ and $r^*_{s^*g*} = -r^*_{p^*g^*}$. Given that Foreign's production is expected to be more pollution intensive than Home's, a^* is greater than a, i.e., $a^* > a$. For analytical convenience we assume that $a^* = 1$ and thus $0 < a < 1$. Foreign's producer price is now given by $p^* = q - s^*$, while Foreign's consumer price is the same with the world price (q). In addition, we assume that Home sets its carbon tax equal to

[15] Equations (8) (9), (10), (11), (12) and (13), which describe the policy effects, are now given in the Appendix II by equations (A.2)-(A.7), respectively.

[16] Policy reforms that leave prices unaffected through appropriate adjustments of consumption and production are common in the literature; see among others, Keen (1989), Bagwell and Staiger (1999), Kreickemeier and Raimondos-Møller (2008), Vlassis (2013), Karakosta *et al.* (2014), Raimondos and Woodland (2018).

its first best Pigouvian level, fully internalising the pollution externality, as indicated by equation (14) and thus $ds = 0$. Assuming that Home's carbon tax is fixed at the first best Pigouvian level, allows us to highlight the welfare and pollution effects of the suggested reform strategy. The results of this Section carry over to the case where Home sets its carbon tax at a lower level than its first best Pigouvian level.

A Foreign's *producer price-neutral* reform strategy, i.e., $dp^* = 0$, requires Home to reduce its BCA ($d\tau < 0$) conditional to Foreign's stricter carbon tax ($ds^* > 0$), according to:[17]

$$d\tau = -(\frac{dq}{ds^*} - 1)\left(\frac{dq}{d\tau}\right)^{-1} ds^*. \tag{18}$$

Intuitively, this reform decreases Home producers' and consumer's price of the polluting good generating an excess demand. In addition, it increases the polluting good's world price and thus Foreign's consumer price, generating an excess supply of the polluting good in Foreign as it does not affect Foreign's producer price. International trade will balanced the excess demand and supply.[18]

Implementing the suggested reform strategy, using equation (A.3) Foreign's PPA is given by:

$$dg^* = -r^*_{s^*} B^{-1} ds^*. \tag{19}$$

Equation (19) implies that the suggested reform strategy increases the level of PPA activities. This is due to the fact that this reform strategy induces an increase in carbon tax revenues as it leaves Foreign's producer price unchanged and thus its production level, while it increases Foreign's carbon tax rate. Consequently, Foreign's production of the polluting good as well as the unit cost of PPA activities remain unchanged.

The suggested reform strategy reduces global pollution. To see this substitute (18) in equation (A.4), then global pollution level is given by:

$$dk = -r_{sp}\Psi ds^* + r^*_{s^*}\left(r^*_{s^*g^*} + 1\right) B^{-1} ds^*. \tag{20}$$

[17] The analytical proof of the suggested reform strategy is provided in Appendix III.

[18] In the case that Foreign is a small open economy not able to affect world prices the reform takes the form of $d\tau = -ds^*$. This is due to the fact that Home has complete control over the world price through BCA i.e., $dq = -d\tau$. Consequently, any changes of BCA are fully absorbed by the Foreign.

where $\Psi = \left[1 - \left(\frac{dq}{ds^*} - 1\right)\left(\frac{dq}{d\tau}\right)^{-1}\right] < 0$.[19] The first term of equation (20) describes the reform's effect on Home's production generated pollution. It decreases Home's producer price, leading to the contraction of its polluting sector and thus of production-generated pollution.[20] The second term describes the reform's effect on Foreign's net pollution. Due to the unchanged output level of the polluting sector and the increased carbon tax, the suggested reform increases the available funds for *PPA*, decreasing Foreign's originated pollution. Clearly, this conditional reduction of *BCA,* as described by equation (18), leads to the mitigation of carbon leakage.

Following previous discussion on Home's objective to maximise joint welfare, we now turn to the effects of the suggested reform strategy on the aggregate welfare. Assuming that Home sets its environmental policy equal to its cooperatively level, according to equation (14), and starting from an arbitrary *BCA* level, the effects of the suggested reform strategy on aggregate welfare are given by:[21]

$$e_u du + e^*_{u^*} du^* = \left\{\tau\left(e_{pp} - r_{pp}\right)\Psi - r^*_{s^*}\left[\left(e^*_k + e_k - s^*\right) r^*_{s^*g^*} + \left(e^*_k + e_k + r^*_{g^*}\right)\right] B^{-1}\right\} ds^*. \tag{21}$$

The terms on the right-hand side of equation (21) indicate the channels through which this conditional reform affects the level of aggregate welfare. The first term captures the reform's effect on welfare through trade distortions. This reform increases Foreign's access to Home's market as it reduces Home's domestic consumer and producer prices. The second term captures the reform's effect on *PPA* activities. Given the underlying assumptions regarding the underprovision of *PPA* ($e_k + e^*_k + r^*_{g^*} > 0$) and that the carbon tax in Foreign is 'too low' relative to the first best Pigouvian level ($e_k + e^*_k - s^* > 0$), the reform increases the aggregate welfare. Intuitively, the suggested reform strategy has a positive impact on global environmental quality through the resulted higher level of *PPA*, which clearly benefits both countries.

Proposition 3 *A reform strategy that requires a conditional reduction of Home's BCA subject to stricter carbon tax by Foreign, so as to provide neutrality in Foreign's producer price, described by (18), reduces global pollution and increases aggregate welfare.*

[19] The proof of $\Psi < 0$ is given in Appendix IV.

[20] The proof that the reform strategy results in the reduction of Home's producer price, $dp < 0$, is given in Appendix IV.

[21] To obtain equation (21), substitute equation (18) in (A.7) with $ds = 0$.

To understand Foreign's incentive to comply with such a reform strategy, which increases its carbon tax, we need to isolate the reform's effect on its own welfare. To do so, substitute equation (18) in (A.6), for $ds = 0$, to obtain:

$$e^*_{u^*} du^* = \left\{ - \left(e^*_q - r^*_{p*} \right) + e^*_k r_{sp} \Psi - r^*_{s^*} \left[\left(e^*_k - s^* \right) r^*_{s^* g^*} + \left(e^*_k + r^*_{g^*} \right) \right] B^{-1} \right\} ds^*. \tag{22}$$

The terms of the right-hand-side of equation (22) describe the positive impact of the suggested reform strategy on Foreign's welfare. In turn, the first term denotes the direct terms of trade effect which is positive (i.e., $- \left(e^*_q - r^*_q \right) ds^* > 0$) given that Foreign exports the polluting good ($e^*_q - r^*_q < 0$); The suggested reform strategy reduces BCA and thus, benefits Foreign through increased access in Home's market. The second and third terms indicate the reform's effect on welfare through pollution. The second term ($e^*_k r_{sp} \Psi ds^* > 0$) captures the increase in Foreign's welfare through the reduction of Home's production-generated pollution. The third term ($-r^*_{s^*} \left[\left(e^*_k - s^* \right) r^*_{s^* g^*} + \left(e^*_k + r^*_{g^*} \right) \right] B^{-1} ds^* > 0$) captures the reform's positive effect in Foreign's welfare through its effect on *PPA,* given that for developing economies $\left(e^*_k - s^* \right) > 0$ and $\left(e^*_k + r^*_{g^*} \right) > 0$ (for further discussion see footnotes 12 and 13); This conditional reform increases carbon tax revenues earmarked for *PPA,* reducing Foreign's net pollution level and consequently global pollution. This implies that Foreign's welfare increases unambiguously as a result of a stricter environmental policy.

If carbon tax revenues in Foreign are not earmarked to *PPA* activities but instead they are lump-sum rebated to consumers, the suggested reform strategy remains welfare improving for Foreign. In this case, Foreign's incentive to comply with the suggested reform strategy and increase its carbon tax arises through the reduction of Home's BCA, which improves Foreign's terms of trade and its government revenues through carbon tax.

Further we can show that even in the case that Home behaves non-cooperatively, as described by equations (16) and (17), both countries have an incentive to comply with the suggested reform strategy. Assuming that Home sets its environmental policy equal to its non-cooperatively level, according to equation (16), and starting from an arbitrary BCA level we can prove that the suggested reform strategy, as described by (18), can deliver a strict Pareto improvement increasing the welfare of each country individually. To see this substitute equation (18) in (A.5) and (A.6), for

$s = e_k$ and $ds = 0$, to obtain, respectively, the effects of the reform on Home and Foreign country's welfare:

$$e_u du = \left[\tau \left(e_{pp} - r_{pp}\right) \Psi - e_k r^*_{s^*} \left(r^*_{s^* g^*} + 1\right) B^{-1} - \left(e_p - r_p\right)\right] ds^*, \tag{23}$$

$$e^*_{u^*} du^* = \left\{- \left(e^*_q - r^*_{p^*}\right) + e^*_k r_{sp} \Psi - r^*_{s^*} \left[\left(e^*_k - s^*\right) r^*_{s^* g^*} + \left(e^*_k + r^*_{g^*}\right)\right] B^{-1}\right\} ds^*. \tag{24}$$

Equation (23) indicates that the suggested conditional reform strategy is affecting Home's welfare: (i) positively through trade distortions alleviations, (ii) positively through the reduction of global pollution due to the higher level of *PPA* activities and (iii) negatively through terms of trade deterioration. The reform's overall effect on Home's welfare depends on the relative strength of the opposing effects. When the first two effects dominate the third one, then this reform increases Home's welfare. The terms of trade effect does not appear in the case of aggregate welfare, equation (21), since the strategic aspect of *BCA* is no longer present. Equation (24) captures the reform's effects on Foreign's welfare, when Home sets its environmental policy non-cooperatively and they are identical to the ones described by equation (22).

Böhringer *et al.* (2017) suggest an alternative scheme to *BCA*, consisting of output-based rebating (OBR) of emission tax payments combined with a consumption tax. They show that such a scheme can be equivalent to *BCA* increasing aggregate welfare, when Foreign is passive. Given the unilateral nature of their scheme, *BCA*'s role in incentivising Foreign country to adopt stricter environmental policy is neglected. As it is clearly shown by equation (22) the suggested reform strategy, described by equation (18), incentivises Foreign to increase carbon tax through its terms of trade and environmental effects. The latter suggests that the reform strategy mitigates the externality arising from Foreign's production, reducing global pollution, benefiting both the Home and the Foreign. Equations (23) and (24) suggests that the reform can deliver a strict Pareto improvement. The role of *BCA* as a carrot policy for Foreign country to follow more stringent environmental actions has also been highlighted in the absence of *PPA* by Böhringer *et al.* (2016) and Sanctuary (2018). Böhringer *et al.* (2016) show that *BCA* as well as the economic performance of the destination markets, i.e., Home, can motivate the exporting country to bear the burden of abatement. Sanctuary (2018) shows that when *BCA*'s revenues are rebated to the exporting country, a *BCA* and the exporter's emission tax can be complements resulting to stricter environmental policies for both countries. Al Khourdajie and Finus (2020) show that *BCA* can be used as a mechanism to incentivise countries to join an environmental agreement. The results of Böhringer *et al.* (2016), Sanctuary (2018) and Al Khourdajie and Finus (2020) highlight important channels through which *BCA* can mitigate free-riding and reduce carbon leakage. We contribute to this debate on the effectiveness of *BCA* by showing that stricter environmental policy, resulted by a conditional reduction of *BCA,* benefits unambiguously the exporting country irrespectively of the use of carbon tax revenue. Furthermore, we highlight the importance of *PPA* as a channel to incentivise both countries to adopt the suggested reform strategy. In the presence of *PPA* activities, both countries benefit from the suggested reform strategy due to its negative effect on global pollution.

5 *BCA* and Cap-and-Trade; A general discussion

In this Section, we extend the discussion on the effectiveness of *BCA* as a carbon leakage mitigation instrument, in the presence of *PPA,* considering the case where Foreign's environmental policy takes the form of cap-and trade such as intra-nationally traded carbon permits.[22]

When Foreign implements intra-nationally traded carbon permits and their revenues are earmarked for *PPA* activities, Pareto efficiency requires *BCA* to be present, despite the fact that it does not affect directly the production-generated pollution by Foreign. *BCA* still plays a role since it affects *PPA* activities in Foreign. This contradicts the results of the relevant literature which supports that *BCA* serves no purpose other than rent shifting when Foreign uses cap-and-trade policy, e.g., carbon permits or quotas, to control pollution (see, among others, Panagariya *et al.* 2004; Keen and Kotsogiannis, 2014).

In this case, a higher *BCA* leads to negative(positive) carbon leakage, given that Home policy's effect on Foreign's unit cost of *PPA* dominates(dominated) by the one on revenues generated by the carbon permit market. Intuitively, a higher *BCA* decreases the polluting good's world price which shrinks Foreign's polluting sector's demand for intra-national tradable carbon permits**.** This reduces the carbon permit price in Foreign, given their fixed supply when Foreign is passive, and consequently the available funds for *PPA*. On the other hand, the unit cost of *PPA* is reduced. The contraction of Foreign's polluting sector decreases its demand for factors of production, which in

[22] Please refer to the Supplementary Material for the detailed derivations of this Section.

turn reduces the unit cost of *PPA* activities, given the assumption of substitutability in production between the polluting good and *PPA*. The direction of *Carbon Leakage Effect* is determined by the relative strength of its two opposing channels. In this setting, a *BCA*'s reform strategy that does not affect production level in Foreign, similar to the one described in Section 4, requires Foreign to remain passive. This is due to the fact that production in Foreign is tied to the number of permits issued by Foreign government.

6 Concluding Remarks

This paper sheds light on unidentified channels through which unilateral environmental policies and *BCA* affect another country's production-generated pollution. The mechanism of these channels lies in Home's policies' unintended consequences on *PPA* activities. We show that the carbon leakage effect of stricter unilateral environmental policy is magnified when private abatement coexists with *PPA*. In this context, Pareto efficiency calls for *BCA* to correct not only for the difference in carbon taxes between the two countries, as predicted by the existing literature, but also for its unintended effects on the other country's *PPA*. In addition, we argue that *BCA* still plays a role, in the presence of *PPA* activities, even when Foreign uses cap-and-trade policy to control pollution. In this case, although *BCA* does not affect Foreign's production-generated pollution it affects its *PPA* activities.

A key finding of this paper is that a conditional reform strategy that requires Home to reduce *BCA* subject to a stricter carbon tax by Foreign, providing neutrality in Foreign's producer price, decreases global pollution and increases countries' welfare. The suggested reform strategy increases Foreign's carbon tax revenues earmarked for *PPA* activities, as it increases carbon tax while it does not affect Foreign's producer price and thus the output level of the polluting good. This reduces pollution and thus increases countries' welfare. The reduction of *BCA* increases Foreign's access to Home's market. These two effects unambiguously improve Foreign's welfare, highlighting its strong incentive to comply with the reform strategy adopting stricter environmental policy. Accordingly, the reform benefits Home not only through the reduction of global pollution but also through trade distortions alleviation. This suggested reform strategy provides additional arguments in favor of the effectiveness of *BCA* policy as it eliminates the strategic aspect of the policy.

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Appendix I

The complete definitions of A_τ and A_s are:

$$\begin{aligned} A_\tau &= \left[\tau\left(e_{pp}-r_{pp}\right)+\left(e_k+e_k^*-s\right)r_{sp}\right]\left(1+\frac{dq}{d\tau}\right) \\ &+\left\{\begin{array}{c} \left[\left(e_k+e_k^*-s^*\right)r^*_{s^*g^*}+\left(e_k^*+e_k+r^*_{g^*}\right)\right]g^*r^*_{g^*p^*} \\ -\left(e_k+e_k^*\right)\left(r^*_{g^*}+s^*\right)r^*_{s^*p^*} \end{array}\right\}B^{-1}\frac{dq}{d\tau}, \end{aligned}$$

$$\begin{aligned} A_s &= \left[-\tau r_{ps}+\left(e_k+e_k^*-s\right)r_{ss}\right]+\left[\tau\left(e_{pp}-r_{pp}\right)+\left(e_k+e_k^*-s\right)r_{sp}\right]\frac{dq}{ds} \\ &+\left\{\begin{array}{c} \left[\left(e_k+e_k^*-s^*\right)r^*_{s^*g^*}+\left(e_k+e_k^*+r^*_{g^*}\right)\right]g^*r^*_{g^*p^*} \\ -\left(e_k+e_k^*\right)\left(r^*_{g^*}+s^*\right)r^*_{s^*p^*} \end{array}\right\}B^{-1}\frac{dq}{ds}. \end{aligned} \tag{A.1}$$

Appendix II

Assuming that $ds^* \neq 0$ and differentiating the commodity market clearing condition, equation (4), we obtain Home's and Foreign's policies' impact on world relative price of good 1:

$$\Delta dq = -(e_{pp}-r_{pp})d\tau + r_{ps}ds + r^*_{p^*s^*}ds^*. \tag{A.2}$$

Totally differentiating equation (7) using (A.2) we obtain policies' impact on PPA:

$$\begin{aligned} dg^* &= \left(-s^* r^*_{s^*p^*} + g^* r^*_{g^*p^*}\right) B^{-1} \frac{dq}{ds} ds + \left(-s^* r^*_{s^*p^*} + g^* r^*_{g^*p^*}\right) B^{-1} \frac{dq}{d\tau} d\tau \\ &\quad + \left[\left(-s^* r^*_{s^*s^*} - r^*_{s^*} + g^* r^*_{g^*s^*}\right) + \left(-s^* r^*_{s^*p^*} + g^* r^*_{g^*p^*}\right) \frac{dq}{ds^*}\right] B^{-1} ds^*. \end{aligned} \tag{A.3}$$

Totally differentiating equation (1) using (A.2) and (A.3) we obtain Home's and Foreign's policies' impact on global pollution:

$$\begin{aligned} dk = &\left\{ \begin{array}{c} -r_{sp}\left(\frac{dq}{ds^*}\right) + \left[r^*_{s^*s^*}\left(r^*_{g^*} + s^*\right) - \left(-r^*_{s^*} + g^* r^*_{g^*s^*}\right)\left(r^*_{s^*g^*} + 1\right)\right] B^{-1} \\ + \left[r^*_{s^*p^*}\left(r^*_{g^*} + s^*\right) - g^* r^*_{g^*p^*}\left(r^*_{s^*g^*} + 1\right)\right] B^{-1} \frac{dq}{ds^*} \end{array} \right\} ds^* \\ &+ \left\{-r_{sp}\left(1 + \frac{dq}{d\tau}\right) + \left[r^*_{s^*p^*}\left(r^*_{g^*} + s^*\right) - g^* r^*_{g^*p^*}\left(r^*_{s^*g^*} + 1\right)\right] B^{-1} \frac{dq}{d\tau}\right\} d\tau \\ &+ \left\{-\left(r_{ss} + r_{sp}\frac{dq}{ds}\right) + \left[r^*_{s^*p^*}\left(r^*_{g^*} + s^*\right) - g^* r^*_{g^*p^*}\left(r^*_{s^*g^*} + 1\right)\right] B^{-1} \frac{dq}{ds}\right\} ds. \end{aligned} \tag{A.4}$$

Following from (5), (6) and (A.2)-(A.4), Home and Foreign welfare effects arising from countries' policies changes are given, respectively, by:

$$\begin{aligned} e_u du = &\left[\tau\left(e_{pp} - r_{pp}\right) + \left(e_k - s\right) r_{sp}\right] d\tau + \left[-\tau r_{ps} + \left(e_k - s\right) r_{ss}\right] ds \\ &- e_k \left[r^*_{s^*s^*}\left(r^*_{g^*} + s^*\right) - \left(g^* r^*_{g^*s^*} - r^*_{s^*}\right)\left(r^*_{s^*g^*} + 1\right)\right] B^{-1} ds^* \\ &+ \left\{ \begin{array}{c} \tau\left(e_{pp} - r_{pp}\right) B + \left(e_k - s\right) r_{sp} B \\ -\left(e_p - r_p\right) B - e_k \left[r^*_{s^*p^*}\left(r^*_{g^*} + s^*\right) - g^* r^*_{g^*p^*}\left(r^*_{s^*g^*} + 1\right)\right] \end{array} \right\} B^{-1} \left(\frac{dq}{ds} ds + \frac{dq}{d\tau} d\tau + \frac{dq}{ds^*} ds^*\right), \end{aligned} \tag{A.5}$$

$$\begin{aligned} e^*_{u^*} du^* = &\, e^*_k r_{sp} d\tau + e^*_k r_{ss} ds + \left\{\left[\left(e^*_k - s^*\right) r^*_{s^*g^*} + \left(e^*_k + r^*_{g^*}\right)\right]\left(g^* r^*_{g^*s^*} - r^*_{s^*}\right) - e^*_k \left(r^*_{g^*} + s^*\right) r^*_{s^*s^*}\right\} B^{-1} ds^* \\ &+ \left\{ \begin{array}{c} -\left(e^*_q - r^*_{p^*}\right) B + e^*_k r_{sp} B \\ + \left[\left(e^*_k - s^*\right) r^*_{s^*g^*} + \left(e^*_k + r^*_{g^*}\right)\right] g^* r^*_{g^*p^*} - e^*_k \left(r^*_{g^*} + s^*\right) r^*_{s^*p^*} \end{array} \right\} B^{-1} \left(\frac{dq}{ds} ds + \frac{dq}{d\tau} d\tau + \frac{dq}{ds^*} ds^*\right). \end{aligned} \tag{A.6}$$

From (A.5) and (A.6) we obtain the aggregate welfare:

$$
\begin{aligned}
e_u du + e^*_{u^*} du^* = {} & \left[\tau\left(e_{pp} - r_{pp}\right) + \left(e_k + e^*_k - s\right) r_{sp}\right] d\tau + \left[-\tau r_{ps} + \left(e_k + e^*_k - s\right) r_{ss}\right] ds \\
& + \left\{\left[\left(e^*_k + e_k - s^*\right) r^*_{s^* g^*} + \left(e^*_k + e_k + r^*_{g^*}\right)\right]\left(g^* r^*_{g^* s^*} - r^*_{s^*}\right) - \left(e^*_k + e_k\right) r^*_{s^* s^*}\left(r^*_{g^*} + s^*\right)\right\} B^{-1} ds^* \\
& + \left\{\begin{array}{c}
\tau\left(e_{pp} - r_{pp}\right) B + \left(e_k + e^*_k - s\right) r_{sp} B \\
-\left(e_k + e^*_k\right) r^*_{s^* p^*}\left(r^*_{g^*} + s^*\right) \\
+\left[\left(e^*_k + e_k - s^*\right) r^*_{s^* g^*} + \left(e^*_k + e_k + r^*_{g^*}\right)\right] g^* r^*_{g^* p^*}
\end{array}\right\} B^{-1}\left(\frac{dq}{ds} ds + \frac{dq}{d\tau} d\tau + \frac{dq}{ds^*} ds^*\right).
\end{aligned}
\tag{A.7}
$$

Appendix III

Reform Strategy

Assuming that one unit of production generates one unit of pollution, i.e., $-r^*_{s^*} = r^*_{p^*}$, it follows that Foreign's producer price, p^*, is defined as:

$$
p^* = q - s^*. \tag{A.8}
$$

Totally differentiate equation (A.8) for fixed Home carbon tax, i.e., $ds = 0$, to get:

$$
dp^* = \frac{dq}{d\tau} d\tau + \frac{dq}{ds^*} ds^* - ds^*.
$$

Set now $dp^* = 0$ to obtain the *producer price-neutral* reform strategy, as described by equation (18),

$$
d\tau = -\left(\frac{dq}{ds^*} - 1\right)\left(\frac{dq}{d\tau}\right)^{-1} ds^*.
$$

Appendix IV

Proof of: $\Psi < 0$

Totally differentiate Home producer's price, given by $p = q + \tau - as$, for fixed Home carbon tax i.e.,$ds = 0$, to get:

$$
dp = \frac{dq}{d\tau} d\tau + \frac{dq}{ds^*} ds^* + d\tau.
$$

Now use the suggested reform strategy (18) to obtain:

$$dp = ds^* + d\tau \Rightarrow dp = \Psi ds^*,$$

where $\Psi = \left[1 - \left(\frac{dq}{ds^*} - 1\right)\left(\frac{dq}{d\tau}\right)^{-1}\right]$. Substituting the terms $\frac{dq}{ds^*}$ and $\frac{dq}{d\tau}$ from equation (A.2) in Ψ, it now becomes:

$$\Psi = -\left[e^*_{qq} - r^*_{p^*g^*}\left(g^* r^*_{g^*p^*} - s^* r_{s^*p^*}\right)\left(-r^*_{g^*} + s^* r^*_{s^*g^*}\right)^{-1}\right]\left(e_{pp} - r_{pp}\right)^{-1}.$$

Given the underlying assumptions, $r^*_{p^*g^*} < 0$, $r^*_{s^*g^*} > 0$, and $\left(g^* r^*_{g^*p^*} - s^* r_{s^*p^*}\right) < 0$, see footnote (8), Ψ is negative and so $|ds^*| < |d\tau|$. This implies that the suggested reform strategy reduces Home country's domestic price ($dp < 0$).

Supplementary Material

Intra-nationally traded carbon permits

Assume that Foreign regulates pollution through intra-nationally traded carbon permits. Foreign government issues Z^* carbon permits which are traded domestically by local producers. The price of each permit is denoted by t^*, determined in the domestic carbon permits market. The sales revenues from the tradable carbon permits, $t^* Z^*$, are earmarked for PPA activities. Foreign's *restricted* revenue function is denoted by $r^*(p^*, t^*, g^*)$ and follows the standard properties. The equilibrium conditions are given by equation (4), (5) and:

- Foreign's representative consumer budget constraint:

$$e^*(q, k, u^*) = r^*(p^*, t^*, g^*) + t^* Z^*. \tag{S.1}$$

- Foreign's government budget constraint:

$$-r^*_{g^*} g^* = t^* Z^*. \tag{S.2}$$

- Foreign's quota market (quota demand = quota supply) :

$$z^* = Z^*. \tag{S.3}$$

- Global pollution:

$$k = z + Z^* - g^*. \tag{S.4}$$

Equations (4), (S.2) and (S.3) produce a system of three equations in (q, g^*, t^*). Differentiating this system with respect to Home's policy variables s and τ , assuming that Foreign is passive, i.e., $dZ^* = 0$, we obtain:

$$\begin{bmatrix} e^*_{qq} - r^*_{p^*p^*} + e_{pp} - r_{pp} & -r^*_{p^*g^*} & -r^*_{p^*t^*} \\ -g^* r^*_{g^*p^*} & -r^*_{g^*} & -(g^* r^*_{g^*t^*} + Z^*) \\ -r^*_{t^*p^*} & -r^*_{t^*g^*} & -r^*_{t^*t^*} \end{bmatrix} \begin{bmatrix} dq \\ dg^* \\ dt^* \end{bmatrix} = \begin{bmatrix} r_{ps} \\ 0 \\ 0 \end{bmatrix} ds + \begin{bmatrix} -(e_{pp} - r_{pp}) \\ 0 \\ 0 \end{bmatrix} d\tau, \tag{S.5}$$

from which we get Home policies effect on international prices, Foreign's *PPA* activities and price of permits are given respectively by the equations:

$$\frac{dq}{ds} = r_{ps}\Gamma\Omega^{-1} > 0, \qquad \frac{dq}{d\tau} = -(e_{pp} - r_{pp})\Gamma\Omega^{-1} < 0, \tag{S.6}$$

$$\frac{dg^*}{ds} = \left[-g^* r^*_{g^*p^*} r^*_{t^*t^*} + r^*_{t^*p^*}(g^* r^*_{g^*t^*} + Z^*)\right] \Gamma^{-1} \frac{dq}{ds}, \tag{S.7}$$

$$\frac{dg^*}{d\tau} = \left[-g^* r^*_{g^*p^*} r^*_{t^*t^*} + r^*_{t^*p^*}(g^* r^*_{g^*t^*} + Z^*)\right] \Gamma^{-1} \frac{dq}{d\tau}, \tag{S.8}$$

$$\frac{dt^*}{ds} = \left[g^* r^*_{g^*p^*} r^*_{t^*g^*} - r^*_{t^*p^*} r^*_{g^*}\right] \Gamma^{-1} \frac{dq}{ds} > 0, \tag{S.9}$$

$$\frac{dt^*}{d\tau} = \left[g^* r^*_{g^*p^*} r^*_{t^*g^*} - r^*_{t^*p^*} r^*_{g^*}\right] \Gamma^{-1} \frac{dq}{d\tau} < 0. \tag{S.10}$$

The determinant of the left-hand-side matrix in equation (S.5) is required to be positive and is given by:

$$\begin{aligned} \Omega = &\left(e^*_{p^*p^*} - r^*_{p^*p^*} + e_{pp} - r_{pp}\right)\Gamma + g^* r^*_{g^*p^*}\left(r^*_{p^*g^*} r^*_{t^*t^*} - r^*_{p^*t^*} r^*_{t^*g^*}\right) \\ &- r^*_{t^*p^*}\left[r^*_{qg^*}\left(g^* r^*_{g^*t^*} + Z^*\right) - r^*_{t^*p^*} r^*_{g^*}\right], \end{aligned}$$

with $\Gamma = r^*_{g^*} r^*_{t^*t^*} - r^*_{t^*g^*}(g^* r^*_{g^*t^*} + Z^*) < 0$.

- Home's policies' impact on world relative price of the polluting good (equation S.6):

  A higher carbon tax by Home increases the world relative price of the polluting good, $\frac{dq}{ds} > 0$. While, a higher BCA by Home reduces the world relative price of the polluting good, $\frac{dq}{d\tau} < 0$.

- Home's policies' impact on Foreign's PPA activities (equations S.7 and S.8):

  A higher carbon tax by Home exerts a positive impact on Foreign's terms of trade, i.e.,$\frac{dq}{ds} > 0$, the unit cost of PPA increases, reducing the level of its provision, i.e., $-g^* r^*_{g^*p^*} r^*_{t^*t^*} \Gamma^{-1} < 0$. On the other hand, a higher carbon tax by Home will increase the world price of the polluting good and thus Foreign's producers' incentives to increase production. This will increase the demand for carbon permits in Foreign and thus their prices t^*, generating higher revenue for PPA, i.e., $r^*_{t^*p^*}(g^* r^*_{g^*t^*} + Z^*)\Gamma^{-1} > 0$. The overall effect of Home's policies on PPA is ambiguous. From equation (S.8) it is obvious that a higher BCA will affect Foreign's PPA activities through the same channels but in opposite direction since $\frac{dq}{d\tau} < 0$.

- Home's policies' impact on the global pollution level:

  Given that intra-national tradable carbon permits are fixed in supply i.e., $dZ^* = 0$, global pollution is affected only by Home's generated pollution and Foreign's PPA activities, i.e., $dk = dz - dg^*$. To obtain Home's policies' impact on the global pollution level totally differentiate equation (S.4), using the system of equations (S.6)-(S.10):

$$dk = \left\{ \underbrace{-\left(r_{ss} + r_{sp}\frac{dq}{ds} \right)}_{Domestic\ Output\ Effect-Carbon\ Tax} + \underbrace{\left[g^* r^*_{g^*p^*} r^*_{t^*t^*} - r^*_{t^*p^*}(g^* r^*_{g^*t^*} + Z^*) \right] \Gamma^{-1} \frac{dq}{ds}}_{Carbon\ Leakage\ Effect-Carbon\ Tax} \right\} ds$$
$$+ \left\{ \underbrace{-r_{sp}\left(1 + \frac{dq}{d\tau} \right)}_{Domestic\ Output\ Effect-BCA} + \underbrace{\left[g^* r^*_{g^*p^*} r^*_{t^*t^*} - r^*_{t^*p^*}(g^* r^*_{g^*t^*} + Z^*) \right] \Gamma^{-1} \frac{dq}{d\tau}}_{Carbon\ Leakage\ Effect-BCA} \right\} d\tau. \quad \text{(S.11)}$$

  Home's policies affect global pollution levels through domestic output and carbon leakage effects.

  Domestic Output Effect: Similar to Section 3 a higher carbon tax reduces global pollution while a higher BCA increases it through the *Domestic Output Effect*.

Carbon Leakage effect:

- A higher carbon tax by home results in positive (negative) *Carbon Leakage Effect* when its effect on *PPA*'s unit cost dominates (dominated) the one on revenues generated by the carbon permit market. Given the fixed supply of permits, in the absence of *PPA* activities, there is no *Carbon Leakage Effect.*
- A higher *BCA* results in *Carbon Leakage Effect* through its impact on *PPA* activities. The effect of *BCA* on the polluting good's world price shrinks Foreign's polluting sector's demand for carbon permits**.** On the one hand, this reduces the carbon permit price and consequently the available funds for *PPA*. On the other hand, the unit cost of *PPA* is reduced. The contraction of Foreign's polluting sector decreases its demand for factors of production, which in turn reduces the unit cost of *PPA* activities, given the assumption of substitutability in production between the polluting good and *PPA*. The direction of *Carbon Leakage Effect* is determined by the relative strength of its two opposing channels.

Totally differentiate equations (5) and (S.1), using (S.3), (S.11), (S.6)-(S.10) to obtain Home's policies' impact on aggregate welfare:

$$e_u du + e^*_{u^*} du^* = \Lambda_\tau d\tau + \Lambda_s ds,$$

where:

$$\begin{aligned}\Lambda_\tau =& \left[\tau\left(e_{pp} - r_{pp}\right) + \left(e_k + e^*_k - s\right) r_{sp}\right]\left(1 + \frac{dq}{d\tau}\right) \\ &+ \left(e^*_k + e_k + r^*_{g^*}\right)\left[-g^* r^*_{g^*p^*} r^*_{t^*t^*} + r^*_{t^*p^*}(g^* r^*_{g^*t^*} + Z^*)\right]\Gamma^{-1}\frac{dq}{d\tau},\end{aligned}$$

- Home's cooperative optimal policies:

$$s^c = e_k + e^*_k,$$

$$\tau^c = \left(e^*_k + e_k + r^*_{g^*}\right)\left[-g^* r^*_{g^*p^*} r^*_{t^*t^*} + r^*_{t^*p^*}(g^* r^*_{g^*t^*} + Z^*)\right]\left[\Omega\Gamma\left(1 + \frac{dq}{d\tau}\right)\right]^{-1},$$

Pareto efficiency dictates that:

- Home's carbon tax is set at its first best Pigouvian level.
- BCA to be present accounting for its effects on Foreign's PPA activities.