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Between a Rock and a Hard Place: A Trade-Theory Analysis of Leakage under Production- and Consumption-Based Policies

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Abstract:

Without a comprehensive global climate agreement, carbon leakage remains a contentious issue. Consumption-based pricing of emissions – which could in practice be implemented with a full border tax adjustment (BTA) – has been forwarded as an option to increase the effectiveness of unilateral climate policy. This paper questions the economic rationale behind this approach, using a theoretical 2x2 trade model in which leakage occurs through terms-of-trade effects. We show analytically, first, that consumption-based pricing of emissions does not necessarily result in less leakage than production-based policies. Second, the sign of the optimal unilateral carbon tariff depends on the carbon intensity differential between the foreign country's exporting and non-exporting sectors, and not the differential between home's and foreign's exporting sectors, as implied by the full BTA approach. Third, based on empirical data for the year 2004, our model implies that full BTA applied by the European Union on e.g. imports from and exports to China would – by shifting China's production from the export sector with a relatively low carbon-intensity towards the more carbon-intensive non-export sector – actually increases leakage.

JEL classifications: F11, F18, Q54, Q56

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1 Introduction

The Kyoto Protocol established upper limits for the greenhouse gas emissions of industrialized (Annex-B) signatories, but exempts developing countries from any binding commitment. Under the Copenhagen Accord, which was adopted at the 2011 Cancún climate summit, all countries are free to choose their own emission targets (including none). In this context of a fragmented policy regime, a frequently discussed issue is the possibility that in response to ambitious reduction targets adopted by some countries, energy intensive industries might migrate to countries with a less stringent or non-existent regulation of emissions (e.g., Van Asselt and Brewer, 2010). Hence, in absence of a global climate agreement, domestic emission reductions of early movers could to a significant extent be offset by increased emissions in other parts of the world, a phenomenon commonly referred to as *carbon leakage* (e.g. Felder and Rutherford, 1993).

Underpinning this concern, empirical studies have recently exposed the large imbalances in ‘embedded’ carbon associated with merchandise and service trade flows between industrialized and developing countries, suggesting that the former have to some extent ‘outsourced’ their emissions to the latter (Caldeira and Davis, 2011). Measures proposed to tackle this issue include approaches in which countries with emission caps are held accountable for their consumption instead of their production-related emissions (Peters and Hertwich, 2008b; Pan et al., 2008), or in which carbon prices are levied on imported goods – and rebated for exports – by means of a border tax adjustment, in the following also referred to as BTA (Ismer and Neuhoff, 2007).

Taking their ability to reduce carbon leakage as granted, much of the political debate on these instruments has focused on two issues: technical feasibility and conformity with international trade law. On the first aspect, it has been pointed out that putting a price on carbon emitted in the production process of imported goods would face a serious obstacle due to the limited availability of information on the total carbon content of goods (Dröge, 2009). Second, international trade legislation (WTO) clearly limits countries’ ability to impose tariffs on imports. However, in certain circumstances it permits collecting taxes to protect the natural environment (Perez, 2005), leading several authors to argue that BTA on carbon embedded in imported goods may be compatible with WTO regulations (Bhagwati and Mavroidis, 2007; WTO-UNEP, 2009).

Economic studies–typically based on CGE simulations–have mostly concluded that BTA could moderately reduce carbon leakage (cf. Section 2), but the theoretical foundations behind this result seem to have received surprisingly little attention. Against this backdrop, the present article re-examines the economic rationale behind the use of carbon-tariffs by employing a stylized 2x2 general equilibrium trade model, which generalizes the framework of Markusen (1975). Within a non-cooperative setting in which only one region ('Home') pursues unilateral climate policy while the rest of the world ('Foreign') does not adopt any policy measures, we study the different effects of production- and consumption-based emission pricing.

After formally reaffirming the equivalence between consumption-based emission pricing and the conventional production-based approach combined with full BTA[1], the model allows to derive three main results: First, it is demonstrated that full BTA and consumption-based pricing of emissions do not constitute (save by chance) optimal unilateral policy instruments. One reason for this is that an optimal carbon tariff depends on the carbon intensity differential between Foreign's exporting and non-exporting sectors, and not on the one between Foreign's and Home's exporting sectors, as would be suggested by the full BTA approach. Second, implementing a consumption-based policy does not generally prevent or even reduce leakage; instead, the effect is shown to be ambiguous and to depend on parameter values. Third, an illustrative empirical application of our model with data for the year 2004 implies that an implementation of BTA by the EU on imports from China would in fact result in an increase of leakage by shifting China's production from the export sector with a relatively low carbon-intensity towards the more carbon-intensive non-export sector.

[1] Throughout this paper, BTA always refers to full BTA, where a price is levied on imports according to their actual carbon content (embodied carbon), and a rebate is granted to exports to exempt them from the domestic carbon price. This corresponds to the definition given by Ismer and Neuhoff (2007, p.140): "exports from one region receive an export compensation based on the CO2 price level in the exporting region and pay an import tariff corresponding to CO2 price level in the importing region ".

From a more general point of view, our results show that influencing international terms-of-trade does provide some leeway for exposing free-riding countries to carbon-pricing, but the drawback of any trade measure is that it only applies to the export sector of these countries. Hence, rather than indirectly establishing an economy-wide price of carbon (as one might perhaps hope), trade measures create a distortion between this country's export and non-export sector, which may or may not lower its emissions.

This article proceeds as follows: Section 2 provides a survey of the relevant literature. Section 3 introduces our theoretical model. Section 4 derives and characterizes the optimal design of unilateral climate policy. Section 5 examines production- and consumption-based policies and shows that the latter is equivalent to a border tax adjustment. Section 6 compares the policy measures examined before. Section 7 confronts our theoretical results with empirical data and discusses the results critically. Section 8 concludes.

2 Literature Review

The literature on unilateral climate policies has identified several channels through which carbon leakage can occur. These include *(i)* free-riding on one actor's provision of the global public good 'abatement' (e.g. Carraro and Siniscalco, 1993; Barrett, 1994), *(ii)* supply side interactions in which reduced demand for fossil fuels in countries that adopt a climate policy depresses their price and results in increased consumption elsewhere (Sinn, 2008), and *(iii)* changes in specialization patterns such that the production of emission intensive goods shifts to countries with a lower (or zero) carbon price (c.f. Siebert, 1979). Since the current debate on competitiveness – and the ensuing calls for 'leveling the carbon playing field' (Houser et al., 2008) – is mainly related to specialization leakage, which also constitutes the most relevant channel in terms-of-trade policy considerations, our analysis will focus on this particular channel of leakage.

Despite the fact that for most industries energy accounts for only a small fraction of total costs and that therefore leakage should not be expected to render unilateral climate policies grossly ineffective (Hourcade et al., 2008), several numerical models have come up with rather high estimates of leakage rates of up to 45% (e.g. Felder and Rutherford, 1993; Babiker and Rutherford, 2005; Elliott et al., 2010). Moreover, empirical studies analyzing the trade flows between industrialized and developing countries repeatedly find that the former are significant net importers of carbon emissions embedded in traded goods, especially with regard to China (Davis and Caldeira, 2010; Peters and Hertwich, 2008a; Wang and Watson, 2008; Shui and Harriss, 2006; Pan et al., 2008). Peters and Hertwich (2008a), for instance, estimate that China's net carbon exports amounted to about 18% of its total carbon emissions in 2001.

As a consequence, it has been suggested that either measures that regulate carbon emissions on a consumption instead of a production basis (Peters and Hertwich, 2008a,b), or policies in which carbon prices are levied on emissions arising from the production of imported goods in the form of border taxes (Ismer and Neuhoff, 2007; Monjon and Quirion, 2010) would be appropriate to address carbon leakage. However, several studies based on calibrated numerical models have found that border tax adjustments would only have a moderate potential to reduce carbon leakage (Babiker and Rutherford, 2005; McKibben et al., 2008; Böhringer et al., 2010): e.g., a systematic comparison of 12 CGE models found that the leakage rate was reduced on average from 12% to 8 % (Böhringer et al. 2012).[2]

The role of trade policy in the presence of transboundary pollution has also been investigated from a theoretical point of view, albeit to lesser extent. Markusen's (1975) seminal analysis of unilateral environmental policy – on which our model is based – emphasizes that the only means to influence foreign producers' emissions by trade policy is through changes in the terms-of-trade. He also derives the result that in general two

[2] Of course, the specific leakage rates depend on how exactly the BTA is implemented and to which sectors it is applied, on model assumptions about the structure of international trade, and, perhaps most of all, on the considered policy scenario. E.g., Burniaux et al. (2010) show that the effectiveness of BTA rapidly declines when climate coalitions become large, as the relative importance of the energy-market (or supply-side) leakage channel–which is not targeted by BTA–becomes higher in that case.

policy instruments (such as a production tax and a tariff) are needed to achieve an optimal outcome. This is confirmed by Hoel (1994) and Golombek et al. (1995), who show that with limited participation in an international climate agreement, the participants' optimal policy mix consists of taxing both the production and consumption of fossil fuels. In a similar vein, Hoel (1996) finds that a differentiation of carbon prices between sectors is not needed as long as one can use import and export tariffs on all traded goods.

One of the few theoretical studies addressing tariffs in proportion to the pollution content of imports is Copeland (1996), who demonstrates that such a tariff is an optimal way for dealing with transboundary pollution whenever the latter arises only from "border-zone production", i.e. from a sector that produces exclusively to meet demand in the importing country. For the case of climate change, of course, such a restriction cannot be applied. This is where the present contribution aims to add to the literature: by building on the theoretical literature cited above, but not restricting the analysis to optimal policies, we study the economic rationale of BTA and consumption-based pricing of emissions and their effect on leakage in a stylized but fairly general setting. .

In contrast to contributions examining the strategic interaction between countries that mutually implement environmental policy and border taxes (e.g. Tsakiris et al., 2011), we focus on the trade theoretic implications of unilateral environmental policy (which may include trade measures), and to this end assume that other countries do not strategically respond – at least for some time – to this policy. This setting is well suited to analyze the motivation of early adopters of climate change legislation (such as the European Union, or a coalition of countries) to complement their domestic policies with trade measures in order to to address carbon leakage.

Finally, with its unilateral framework our analysis also differs from existing work studying similar questions within a cooperative setting, like Keen and Kotsogiannis (2011) or Steckel et al. (2010). Like us, the latter investigate the difference between production- and consumption-based emission accounting and employ a formally similar model, but contrary to our approach they start from the assumption that the world has already adopted a global cap-and-trade system.

3 The Model

In order to study the effects of unilateral climate policies in the presence of international trade, we take the reduced-form general equilibrium trade model employed by Markusen (1975) as a starting point. This two-country, two sector model has the advantage of being general (consistent with both Heckscher-Ohlin and Ricardo-Viner framework) and easily tractable. However, while Markusen adopts the common assumption[3] that pollution arises only in the production of one of the two goods (and with fixed intensity), our model is more general in allowing each sector in each country to have a specific (but also fixed) pollution intensity. As will be shown in the course of this analysis, the more restrictive – and seemingly innocent – assumption of only one polluting sector might lead to unwarranted policy conclusions with regard to measures designed to counteract carbon leakage.

Specifically, let us assume a world with only two regions $r \in \{h, f\}$, Home (h) and Foreign (f), producing two tradable goods, X and Y. Without loss of generality, we may choose X to denote the good exported by Home (to Foreign) and vice versa Y the good exported by Foreign (to Home).

Let X be the numéraire good (i.e. $p_X = 1$), $p = p_Y / p_X = p_Y$ the domestic producer price ratio in Home, and p^* the world market price ratio. For convenience, let us assume that Foreign does not implement any relevant policy so that economic agents in Foreign face the world market price p^*. Both countries' production is described by their production possibility frontier, i.e. the feasible set of combinations of output quantities of X and Y produced by using fixed factor supplies and technologies. Since Home and Foreign generally differ in their production possibility frontiers, each region will have a comparative advantage in the production of one of the goods, here good X for Home and

[3] This assumption is also adopted in, e.g., Copeland (1996) and Elliott et al. (2010).

Y for Foreign.[4] For a formal representation, let us introduce transformation functions T^r describing the output of X as a concave, decreasing function of the output of Y:[5]

$$Q^{Xr} = T^r(Q^{Yr}), \quad T^r_{Q^{Yr}} < 0, \quad T^r_{Q^{Yr}Q^{Yr}} < 0 \tag{1}$$

Because output is implicitly determined by profit maximization of competitive producers, an increase in the price ratio p of good Y relative to good X shifts production towards Y, such that the output ratio Y / X rises. In other words, both Home's and Foreign's supply curves are assumed to be upwards sloping.

As our model is static, we do not allow for international debt and require trade to be balanced. Let E^{Xh} denote Home's exports of X and M^{Yh} its imports of Y. Then balanced trade requires:[6]

$$E^{Xh} - p^* M^{Yh} = 0. \tag{2}$$

The consumption side is characterized by a representative agent in each region drawing utility from the consumption of goods X and Y.[7] For the purpose of this paper, i.e. the analysis of unilateral policies, it is sufficient make specific assumptions only for the Home country, for which we assume homothetic preferences over consumption in form of a concave, increasing function U^h of C^{Xh} and C^{Yh}:

$$U^h(C^{Xh}, C^{Yh}), \quad U^h_{C^{Xh}} > 0, \quad U^h_{C^{Xh}C^{Xh}} < 0, \quad U^h_{C^{Yh}} > 0, \quad U^h_{C^{Yh}C^{Yh}} < 0 \tag{3}$$

From Home's point of view, consumption is related to exports and imports by:

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[4] Note that we assume throughout the paper that Home's unilateral policies do not lead to an inversion of this specialization pattern, which seems reasonable as long as the imposed border-tax remains small in comparison to the price of goods.

[5] We denote derivatives with respect to a certain variable by subscripts throughout the analysis.

[6] This is equivalent to $p^* E^{Yf} - M^{Xf} = 0$ from Foreign's point of view. Our two-region setting naturally implies market clearance on all markets such that $E^{Yf} = M^{Yh}$, $E^{Xf} = M^{Xh}$.

[7] Imported and domestically produced goods are perfect substitutes from the consumer's point of view.

$$C^{Xh} = Q^{Xh} - E^{Xh},\ C^{Yh} = Q^{Yh} + M^{Yh} \tag{4}$$

Next, we introduce the global environmental externality by means of climate change damages *D*. Damages are assumed to reduce the utility drawn from consumption but leave productivity unaffected ('eyesore' pollution). To keep matters simple and transparent, let us assume that Home's welfare function W^h is linearly separable in U^h and *D*, and that damages are a non-negative convex function of global carbon emissions *Z*:[8]

$$W^h = U^h(C^{Xh}, C^{Yh}) - D(Z), \quad D_Z > 0, \quad D_{ZZ} > 0 \tag{5}$$

Global emissions are the sum of emissions in Home and Foreign, which we assume to be a linear combination of the output of *X* and *Y* in each region. Hence, like Steckel et al. (2010) we define sector and country specific emission intensities γ^{Xr}, γ^{Yr} that denote the quantity of carbon emissions per (physical) unit of output:

$$Z = Z^h + Z^f = \gamma^{Xh}Q^{Xh} + \gamma^{Yh}Q^{Yh} + \gamma^{Xf}Q^{Xf} + \gamma^{Yf}Q^{Yf} \tag{6}$$

This assumption generalizes Markusen (1975) and implies that the production of one unit of a certain good in a certain region requires a certain fixed amount of fossil fuel inputs, and that there is no possibility to substitute among inputs to alter this ratio. Of course, long-run changes in production technologies, such as fuel switches and measures to increase energy efficiency, can be expected to influence these emission factors. However, the assumption of fixed emission factors seems plausible for a short-term analysis, and, more importantly, allows us to concentrate on the central general equilibrium aspects.

[8] Since we have adopted a non-cooperative setting and impacts of climate change in Foreign do not influence Home's utility, we only specify a climate damage function for Home.

Finally, we need to require that Home is not a small economy, such that its supply and demand influence world market prices. Assuming Home's policies to have an impact on Foreign's terms-of-trade is a prerequisite for leakage to occur in the first place, and also for the effects of trade policy to be non-trivial.[9] With a unique Foreign excess supply for any world market price p^*, Home's influence on p^* can be represented by a function G^h:[10]

$$\frac{dp^*}{dM^{Yh}} = p^*_{M^{Yh}} \equiv G^h > 0, \quad p^*_{E^{Xh}} > 0 \tag{7}$$

In other words, the price of Y rises (and hence that of X falls) due to increasing demand for imports of Y into Home. Obviously, Home's market power influences Foreign's production and consumption through the change in the relative price p^*. It allows Home to behave strategically by influencing the terms-of-trade, i.e. its imports become a choice variable, which – given the one-to-one correspondence of Foreign demand and price p^* – implicitly determines p^*.

On the other side, let us assume that Foreign – while not ruling out that it has market power – does not act strategically and takes the price p^* as given. This is a reasonable assumption for the scope of our analysis, as we are interested in studying the general-equilibrium effects of unilateral trade policy and not strategic interactions describing, e.g., a trade war. Moreover, the use of unilateral trade policy for environmental objectives could well be compatible with WTO regulations, which would legally preclude retaliation by Foreign.

4 Optimal Unilateral Policies

[9] Leakage, when transmitted through a change in specialization patterns, occurs when a country with climate policy shifts away from the production of emission-intensive goods and, as a consequence, the world price of those goods increases and hence other countries without climate policy shift towards the production of those goods. Accordingly, the shifts of countries' point of production highlighted in this paper should not be seen as a mere long-run phenomenon but as an essential ingredient of carbon leakage.
[10] This is simply the equivalent of Markusen's (1975) assumption of $E_1 < 0$.

From Home's perspective, optimal unilateral policies are those that maximize its own welfare[11] as given in Eq.(5), taking into account Eqs.(1) to (4), as well as the effect of its import choice on the international price p^* and, thereby, on foreign production and emissions (Eq.(7)). After a simple variable replacement for output and exports of good *X*, Home's welfare maximization can be represented by an optimal choice of domestic production and imports of good *Y*:

$$\max_{Q^{Yh},M^{Yh}} W^h = \max_{Q^{Yh},M^{Yh}} \{U^h[T^h(Q^{Yh}) - M^{Yh} p^*(M^{Yh}), Q^{Yh} + M^{Yh}] \\ - D[\gamma^{Xh}T^h(Q^{Yh}) + \gamma^{Yh}Q^{Yh} + \gamma^{Xf}T^f(Q^{Yf}(p^*(M^{Yh}))) + \gamma^{Yf}Q^{Yf}(p^*(M^{Yh}))]\} \tag{8}$$

implying the two first-order conditions *(i)* $\frac{dW^h}{dQ^{Yh}} \overset{!}{=} 0$ and *(ii)* $\frac{dW^h}{dM^{Yh}} \overset{!}{=} 0$.

By evaluating condition *(i)* one obtains:

$$U^h_{C^{Xh}} T^h_{Q^{Yh}} + U^h_{C^{Yh}} = (\gamma^{Xh} T^h_{Q^{Yh}} + \gamma^{Yh}) \cdot D_Z \tag{9}$$

This shows that at Home's optimal point of production, the marginal benefit from producing an additional marginal unit of *Y* (with a corresponding reduction of *X*) balances the associated marginal change in damages.

With profit-maximizing producers, the marginal rate of (technical) transformation of producing goods *X* and *Y* equals the producer price *p* (which, by assumption, is equal to *p** for the foreign country). Therefore, we obtain from Eq.(1):

Producers: $\quad p = -T^h_{Q^{Yh}}\,; \;\; p^* = -T^f_{Q^{Yf}}$ (10)

[11] Differently from e.g. Keen and Kotsiogiannis (2011), we do not analyze policies aimed at global welfare.

In the same manner, utility-maximizing consumers align their marginal rate of substitution to the consumer price, here denoted by q:[12]

Consumers: $$q = \frac{U^h_{C^{Yh}}}{U^h_{C^{Xh}}} \tag{11}$$

Inserting these expressions into Eq.(9) and dividing by $U^h_{C^{Xr}}$ yields:

$$p - q = q^Z (\gamma^{Yh} - p\gamma^{Xh}) \tag{12}$$

with $$q^Z = -\frac{D_Z}{U^h_{C^{Xh}}} \leq 0 \tag{12a}$$

where q^Z denotes the price of the environmental externality in terms of good X.

Condition *(ii)* yields:

$$U^h_{C^{Yh}} - U^h_{C^{Xh}} \left(G^h M^{Yh} + p^* \right) = D_Z \, Q^{Yf}_{p*} \, G^h \left(\gamma^{Yf} + \gamma^{Xf} T^f_{Q^{Yf}} \right) \tag{13}$$

It determines Home's optimal import quantity of good Y, taking into account its impact on Foreign's emissions via changes in the world market price p^*. In the optimum, the marginal benefit from importing an additional unit of Y (and exporting a corresponding amount of X) exactly balances the associated marginal change in damages from additional emissions due to Foreign's changed point of production.

Writing the total differential of Eq.(10) – i.e. of Foreign's point of production – and solving for Q^{Yf}_{p*} allows to further specify Foreign producers' reaction to a change in p^*, the world market price of good Y:

[12] Note that there is no need for a country index in the prices p or q: they always refer to Home, since by assumption Foreign does not employ any policy, and hence all prices in Foreign are given by p^*.

$$Q_{p^*}^{Yf} = -\frac{1}{T_{Q^{Yf}Q^{Yf}}^{f}} \equiv R^f > 0 \tag{14}$$

Finally, inserting Eqs.(10), (12a) and (14) into Eq.(13), dividing by $U_{C^{Xr}}^{h}$, and re-arranging terms yields:

$$p^* - q = -G^h M^{Yh} + q^Z G^h R^f (\gamma^{Yf} - p^* \gamma^{Xf}) \tag{15}$$

We can now determine the optimal production tax as well as the optimal import tariff on good *Y*, assuming that these policies only affect relative prices (i.e. are implemented through lump-sum transfers). The former is given by the difference between domestic consumer and producer prices, Eq.(12), and the latter by the difference between the domestic consumer price and the world market price, Eq.(15). This directly yields the expressions for the optimal tax τ^{opt} on the production of *Y* and the optimal tariff θ^{opt} on imports of *Y*, which are central results of our analysis:

$$\tau^{opt} = q - p = -q^Z (\gamma^{Yh} - p\,\gamma^{Xh}) \tag{16}$$

$$\theta^{opt} = q - p^* = G^h M^{Yh} \underbrace{- q^Z G^h R^f (\gamma^{Yf} - p^* \gamma^{Xf})}_{\theta^Z} \tag{17}$$

$$\theta^Z = -q^Z G^h R^f (\gamma^{Yf} - p^* \gamma^{Xf}) \tag{17a}$$

The interpretation of Eq.(16) is straightforward: As the relative price *p* is the marginal rate of domestic transformation and substitution, respectively, any marginal change along Home's production possibility frontier that increases the production of good *Y* by one unit decreases the production of good *X* by *p* units. This, in turn, increases emissions by $(\gamma^{Yh} - p\,\gamma^{Xh})$ units and decreases utility by $q^Z(\gamma^{Yh} - p\,\gamma^{Xh})$. Hence, Eq.(16) simply states that the optimal production tax τ^{opt} on good *Y* should internalize the emission externality arising from a marginal increase of domestic production of Y. Since $q^Z < 0$, we get $\tau^{opt} > 0$ only if $\frac{\gamma^{Yh}}{p} > \gamma^{Xh}$, i.e. if production in Home's Y sector has a higher carbon intensity (in emissions per output value) than its X sector. [13]

Home's optimal tariff θ^{opt}, as characterized by Eq.(17), consists of two parts: The first part, $G^h M^{Yh}$, does not depend on the environmental externality (as $M^{Yh} > 0$, this expression is non-negative). It represents the gains from influencing the terms-of-trade so as to depress the relative price of Home's imports, which is well known from the so-called 'optimal tariff' literature (c.f. Markusen et al., 1995, Ch.15). The second part, which we call the 'optimal carbon tariff' for the remainder of this paper, θ^Z (Eq. (17a)), captures the environmental externality associated with the import of good Y. According to Eq.(7), one marginal import of Y raises the world market price by G^h. This affects Foreign's production pattern by increasing production of Y by $G^h R^f$ and decreasing production of X by $p^* G^h R^f$ units. Thereby it leads to an increase in global emissions amounting to $G^h R^f (\gamma^{Yf} - p^* \gamma^{Xf})$ and, accordingly, lowers Home's welfare by $q^Z G^h R^f (\gamma^{Yf} - p^* \gamma^{Xf})$. The optimal carbon tariff internalizes this externality caused by a marginal output increase of Y in Foreign by influencing world market prices (i.e. Foreign's terms-of-trade) accordingly, reaffirming Markusen's (1975) assertion that "[o]ne country cannot tax foreign producers, for example, but if the country has monopoly power in trade, it can generally influence foreign production by changing world commodity prices".

Proposition 1: *In the presence of a global environmental externality, Home's optimal carbon tariff θ^Z will be positive (negative) if – in terms of emissions per output value – Foreign's export sector is more (less) carbon intensive than its non-export sector.*

Proof: The proposition follows directly from the expression for θ^Z (Eq.(17a)). ■

[13] The latter condition can perhaps be better understood when written as $\gamma^{Yh}/p_Y > \gamma^{Xh}/p_X$.

In a general equilibrium setting, imposing a positive tariff influences the terms-of-trade such that the relative price of Foreign's exports declines. This shifts Foreign's production from the export sector to the non-export sector and results in lower emissions in Foreign exactly if its export sector is more carbon intensive than its non-export sector. This finding can be regarded as a direct consequence of Leamer (1980), who argues *(i)* that comparing the factor intensity of a country's imports with that of its exports does not allow drawing conclusions regarding its comparative advantage and *(ii)* that trade theory suggests comparing the factor intensities of exports and domestic consumption instead. In particular, comparing emissions embodied in Home's exports with those embodied in its imports does not give an indication of the sign of the optimal carbon tariff. This outcome tends to be overlooked in the current debate, as in a model with only one polluting good (as e.g. Markusen, 1975, or Elliott et al., 2010) comparing exports with imports is – so to say by a fortunate coincidence – identical to comparing exports with domestic consumption.

Corollary 1: *When in both regions emissions are exclusively generated in the production of the good that is imported by Home, then*

(i) *Home's optimal carbon tariff θ^Z will always be positive, and*

(ii) *θ^Z will be strictly proportional to the amount of embodied carbon in the imported good.*

To see this, set the emission intensities of sector X to zero, $\gamma^{Xh} = \gamma^{Xf} = 0$, and again evaluate Eqs.(16) and (17a), leading to $\tau^{opt} = -q^Z \gamma^{Yh}$ and $\theta^Z = -q^Z G^h R^f \gamma^{Yf}$, respectively. This reproduces Markusen's (1975) result, which – in a premature generalization – could be seen to suggest that the optimal carbon tariff depends *always* only on the amount of carbon embodied in the imported good. However, in the case in which all goods cause emissions, this line of reasoning can be misleading.

5 Existing and Proposed Policies: Production and Consumption-Based Emission Pricing

When thinking about actual policy implications, it appears insufficient to exclusively examine Home's optimal carbon tariff. In the case of climate policy the use of market power for environmental purposes could be regarded as being highly controversial in political terms, which might explain why policy-makers have so far refrained from openly pursuing such policies. Instead, they resort to regulating only domestic emissions, such as in the Kyoto Protocol or the European emission trading scheme. However, as already discussed, this policy approach has been criticized for its tendency to induce leakage, and policies based on putting a price on consumed carbon have been forwarded as an alternative. In the following section, we compare production- and consumption-based emission policies and examine their impacts on leakage.

5.1. Production-Based Emission Pricing

In this section, we assume that Home implements a conventional production-based policy targeting domestic emissions, e.g. by setting a carbon tax or using a cap-and-trade system, and characterize the resulting equilibrium of the global economy, in particular the occurrence of leakage. This setting represents the current state under the Kyoto Protocol, which obliges the large majority of industrialized countries to put a cap on the amount of carbon emissions *produced* on their territory.

Formally, let $\overline{Z}^{h}_{prod}$ be the national emission cap adopted by the Home country.[14] Facing this constraint, the market equilibrium arising between profit maximizing competitive firms and utility maximizing consumers is characterized by the solution of the following maximization problem:

[14] We assume the cap to be binding but still being above the (technical) minimum emission level of the economy, which is given by:
$\min_{Q^{Yh}}\left\{\gamma^{Xh}T^{h}(Q^{Yh})+\gamma^{Yh}Q^{Yh}\right\}$.

$$\max_{Q^{Yh}, M^{Yh}} W^h = \max_{Q^{Yh}, M^{Yh}} U^h[T^h(Q^{Yh}) - M^{Yh} p^*, Q^{Yh} + M^{Yh}]$$
$$s.t. \quad \gamma^{Xh} T^h(Q^{Yh}) + \gamma^{Yh} Q^{Yh} \leq \bar{Z}^h_{prod} \tag{18}$$

Eq. (18) determines their point of production (choice of Q^{Yh}) and consumption (choice of M^{Yh}), respectively. Note that in Eq.(18) the price p^* is taken as given, i.e. Home's market power on international markets is not taken into account. The reason is that the only strategic actor (government or regulator) already made its choice – the emission level $\bar{Z}^h_{prod}$ – beforehand, while firms and consumers are modeled as atomistic.[15]

Evaluating Eq.(18) yields the following first-order conditions characterizing the emission-constrained economy's equilibrium

Producers: $$\frac{q - \gamma^{Yh} \mu}{1 - \gamma^{Xh} \mu} = -T^h_{Q^{Yh}} \equiv p \tag{19}$$

Consumers: $$p^* = \frac{U^h_{C^{Yh}}}{U^h_{C^{Xh}}} \equiv q \tag{20}$$

where we introduced μ as the Lagrange multiplier associated with the emission constraint $\bar{Z}^h_{prod}$, i.e. the shadow price of emissions (normalized by the price of the numéraire). It can be interpreted as a per-unit carbon price levied on goods *X* and *Y* proportional to the emissions generated during their production. In this view, Eqs.(19) and (20) represent standard first-order conditions for consumers' marginal rate of substitution and producers' marginal rate of transformation, implying for the wedge between producer and consumer prices for good *Y* in Home:

$$\tau^{prod} \equiv q - p = \mu(\gamma^{Yh} - p\gamma^{Xh}) \tag{21}$$

[15] That is, no single firm or consumer has influence on the world market price.

This expression is identical to the optimal production tax τ^{opt} of Eq.(16) whenever the carbon tax μ corresponds to Home's social costs of carbon, i.e. $\mu = -q^Z$. By Eq.(20) we have $q = p^*$, meaning that there are no other taxes or distortions, and hence a tariff $\theta^{prod} = 0$. By contrast, the optimal tariff described in Eq.(17) is only zero if Home can be considered a small economy, i.e. if $G^h = 0$ (or if by chance the two components of the tariff exactly cancel out).

Corollary 2: *If it has market power on the world market, a production-based emission policy is not optimal for Home.*

Of course, finding that a policy that consists of only one instrument, namely a domestic emission tax (or cap), cannot reproduce the optimal outcome achieved by a combination of two instruments (domestic tax and tariff) is not very surprising. However, the result also implies that a tax equal to marginal damages (i.e. $\mu = -q^Z$) on production-based emissions without any additional tariff *is optimal* for Home if it has no market power. The intuition behind this finding is that without market power, Home has no influence on Foreign's production structure, and as a consequence the optimal unilateral policy is the one that only regulates domestic emissions.

The one-to-one correspondence between the emission constraint $\overline{Z}^h_{prod}$ and the Lagrange multiplier μ implies a relation $\mu(\overline{Z}^h_{prod})$ and, along with Eqs.(19) and (20) and the world market clearing conditions, also $p^*(\overline{Z}^h_{prod})$. The latter implies that Home's choice of $\overline{Z}^h_{prod}$ indirectly influences Foreign's emissions via the resulting p^*. This, of course, is the cause of carbon leakage, i.e. a rise in Foreign emissions in response to a reduction at Home. To understand whether or not production-based carbon pricing causes leakage, we analyse the general equilibrium implications of an increase of μ (equivalent to a decrease of $\overline{Z}^h_{prod}$) on Foreign emissions. The latter are given by:

$$Z^f = \gamma^{Xf} T^f(Q^{Yf}) + \gamma^{Yf} Q^{Yf} \tag{22}$$

Recall Eq.(14) stating $Q^{Yf}_{p*} = R^f > 0$ for the impact of a change in p^* on Foreign's production as well as $-T^f_{Q^{Yf}} = p^*$ from Eq.(10). We thus obtain for the impact of a marginal change in p^* on Foreign's emissions:

$$Z^f_{p*} = \gamma^{Xf} T^f_{Q^{Yf}} Q^{Yf}_{p*} + \gamma^{Yf} Q^{Yf}_{p*} = \left(\gamma^{Yf} - p^* \gamma^{Xf}\right) R^f \tag{23}$$

Lemma 1: *An increase in the relative world market price p^* for Foreign's export good Y will lead to an increase (decrease) in Foreign's emissions if the emission intensity (in terms of emissions per output value) in Foreign's export sector Y is higher (lower) than in its non-export sector X.*

Proof: The term R^f is always positive – producers increase the output of good *Y* if its relative price increases – so that Eq.(23) is positive whenever the term in parenthesis is positive. ■

The general equilibrium effect of an increase in Home's production-based carbon tax μ is captured by the next lemma:

Lemma 2: *The introduction of or an increase in Home's production-based carbon tax μ leads to an increase (decrease) in the relative world market price p^* if Home's Y-sector is more (less) emission intensive than its X-sector.*

Proof: See Appendix.

Intuitively, if Home's *Y*-sector is more carbon intensive than its *X*-sector, the production-based carbon tax shifts Home's production from *Y* to *X*. Instead of demanding the domestic good *Y*, consumers raise their demand for *Y*-imports from Foreign, which raises the relative world market price of *Y*.

Based on Lemma 1 and 2, we can state the conditions under which leakage occurs:

Proposition 2: *Within the previously defined two-sector, two-country model, a unilateral production tax on emissions in Home leads to leakage if in both countries the relatively more emission intensive sector (in terms of emissions per real output value) is the same (e.g. the Y sector). In the opposite case negative leakage occurs.*[16]

Proof: By Lemma 2, if Home increases or introduces a production-based carbon tax μ on the goods produced by Home, the international price of the good with the higher emission intensity increases. By Lemma 1, leakage occurs in case of a price increase of the good that is relatively more emission intensive in Foreign. ■

5.2. Consumption-Based Emission Pricing

In analogy to the formalization of a constraint on production related emissions in Eq.(18), we can derive the market equilibrium under a given consumption-based policy from a welfare maximization problem with a constraint on domestically *consumed* emissions. Under this policy, exported embodied emissions are subtracted and imported embodied emissions are added to Home's emission budget (cf. Peters and Hertwich 2008b). The constraint $\bar{Z}^h_{cons}$ on consumed emissions therefore reads:

$$\gamma^{Xh}\left[T^h(Q^{Yh}) - M^{Yh} p^*\right] + \gamma^{Yh} Q^{Yh} + \gamma^{Yf} M^{Yh} \leq \bar{Z}^h_{cons} \tag{24}$$

Competitive firms and consumers take the constraint as given and choose Q^{Yh} and M^{Yh} so as to maximize their profits and utility, respectively. Hence, they implicitly solve:

$$\begin{aligned} \max_{Q^{Yh},M^{Yh}} W^h = \max_{Q^{Yh},M^{Yh}} & \; U^h[T^h(Q^{Yh}) - M^{Yh} p^*,\, Q^{Yh} + M^{Yh}] \\ s.t. & \;\; \gamma^{Xh}\left[T^h(Q^{Yh}) - M^{Yh} p^*\right] + \gamma^{Yh} Q^{Yh} + \gamma^{Yf} M^{Yh} \leq \bar{Z}^h_{cons} \end{aligned} \tag{25}$$

[16] Negative leakage denotes an emission reduction in Foreign induced by an emission reduction in Home.

Note that this formulation of the problem does not include explicit carbon-based tariffs or border taxes; demand for the Foreign good is only constrained by a purely domestic regulation of emissions embodied in consumption.

Using ρ as the Lagrange-multiplier that denotes the shadow-price of emissions embodied in Home's consumption and defining the corresponding consumption-based carbon tax as $\sigma = \frac{\rho}{U^h_{C^{Xh}}}$, the first-order conditions implied by Eq.(25) which characterize the resulting equilibrium can be written as:

Producers: $$p = \frac{q - \sigma\gamma^{Yh}}{1 - \sigma\gamma^{Xh}} \qquad (26)$$

Consumers: $$p^* = \frac{q - \sigma\gamma^{Yf}}{1 - \sigma\gamma^{Xh}} \qquad (27)$$

Rearranging terms allows examining the wedges that the consumption tax drives between producer and consumer prices and between consumer and world market prices, respectively:

$$\tau^{cons} \equiv q - p = \sigma\left(\gamma^{Yh} - p\ \gamma^{Xh}\right) \qquad (28)$$

$$\theta^{cons} \equiv q - p^* = \sigma\left(\gamma^{Yf} - p^*\ \gamma^{Xh}\right) \qquad (29)$$

Hence, the consumption-based policy can be implemented by a combination of a tax τ^{cons} on the domestic production of *Y* (Eq.(28)) and a tariff θ^{cons} on imports of *Y* (Eq.(29)). If the consumption-based carbon tax σ equals the social cost of carbon, then – as in the previous section – the resulting tax on the domestic production of good *Y* corresponds to the optimal production tax identified in Eq.(16). From the representative consumer's point of view, the consumption-based carbon tax σ puts a price on the externality caused by embodied emissions. This applies to the choice between domestic X and domestic Y goods (Eq.(28)), as well as to the choice between domestic X and imported Y goods (Eq.(29)). In particular, the last equation shows that the tariff θ^{cons} is equivalent to levying the carbon price on emissions embodied in imports ($\sigma\gamma^{Yf}$) and reimbursing it for domestically produced goods that are exported ($-\sigma p^{*}\gamma^{Xh}$). This practice is generally known as a full *border tax adjustment* (BTA).

Corollary 3: *Consumption-based emission pricing is equivalent to a conventional production-based pricing policy supplemented by a full border tax adjustment that puts a price identical to the domestic emission tax on net imports of embodied emissions.*

Hence, a production based carbon tax combined with BTA results in a policy that targets the consumption instead of the production of emissions. However, note that the tariff implied by a consumption-based policy (Eq.(29)) deviates from the optimal carbon tariff (Eq.(17a)) by *(i)* not taking into account the reaction of the world market price (G^h) and of Foreign producers (R^f), as well as by *(ii)* applying the differential in carbon intensity between Home's imports and exports instead of the difference between Foreign's export sector and its non-export sector. Evidently, a tax on carbon intends to internalize the negative impacts brought about by a certain quantity of emissions. The production tax follows this logic. But in a general equilibrium setting the idea of 'putting a price on carbon' cannot be simply transferred to imports. Reducing imports of emissions embodied in traded goods by a certain quantity clearly does not – due to induced changes in Foreign's production and consumption patterns – avoid the same quantity of emissions being released to the atmosphere.

Corollary 4: *A consumption-based emission policy is in general not optimal for Home.*

Obviously, a BTA policy constitutes an optimal instrument to internalize externalities that arise exclusively from *local* consumption. A case in point is, e.g., the taxation of alcohol or tobacco. Here, public health benefits are internalized by taxing domestic consumption, irrespective of where the respective good has been produced. Yet, this argument does not hold for a *global* externality, as in general Home's government has no more leeway to regulate foreign consumers than foreign producers.

To determine the effect of a consumption-based policy with regard to leakage, we first use Eqs.(26) and (27) to state the following Lemma:

Lemma 3: *An introduction of – or increase in – Home's consumption-based carbon tax σ will lead to:*

(i) *an increase (decrease) in the world price p^* for Foreign's export good Y if both Home's X- and Y-sector are more (less) emission intensive than Foreign's export sector Y,*

(ii) *an ambiguous outcome if one of Home's sectors is more and the other less emission intensive than Foreign's export sector Y, and*

(iii) *an increase (decrease) in p^* if the same goods are produced with identical emission intensities in both regions (i.e. the symmetric case $\gamma^{Xh} = \gamma^{Xf}$, $\gamma^{Yh} = \gamma^{Yf}$) and the Y sector has a lower (higher) emission intensity than the X-sector.*

Proof: See Appendix.

With the help of Lemma 3, we can now specify the effects of a consumption-based policy on carbon leakage:

Proposition 3: *Introducing a policy targeting emissions embodied in Home's consumption has the following effect: if Home's X- and Y-sector are both more (less) emission intensive than Foreign's export sector Y, consumption-based emission pricing will raise (lower) the international price of Home's import good Y. Leakage will then occur if Foreign's export sector Y is more (less) emission intensive than its non-export sector X , and negative leakage in the opposite case.*

Proof: Lemma 3 can be used to determine whether the price of the imported good increases or decreases, and Lemma 1 can then be applied to assess Foreign's change of emissions and thus the incidence of leakage. ■

If Home's carbon intensity is higher than Foreign's in both sectors, the consumption-based carbon tax shifts Home's demand from domestic production to imports. As a consequence, production in Foreign shifts from the non-export sector *X* to the export sector *Y*, increasing emissions if the carbon intensity in Foreign's *Y*-sector is higher than in its *X*-sector.

The symmetric case ($\gamma^{Xh} = \gamma^{Xf}$, $\gamma^{Yh} = \gamma^{Yf}$) deserves to be treated separately:

Corollary 5: *If the same goods are produced with identical emission intensities in both regions, and the Y sector is more (less) emission intensive than the X sector, introducing a consumption-based policy in Home will lower (raise) the international price of Y and in all cases lower emissions in Foreign, i.e. induce negative leakage.*

Proof: Applying case *(iii)* of Lemma 3 in combination with Lemma 1. ■

In this special case, consumption based policies affect production in the same direction in both countries due to the assumption of symmetry. Therefore, such policies shift production from the relatively carbon intensive to the less carbon intensive sector in both regions so that leakage is avoided. This result is in accordance with Markusen's (1975) result, who assumes one clean and one dirty sector (i.e. $\gamma^{Xr} = 0$). Corollary 5 generalizes this result to the case of two symmetric sectors with different emission intensities. Internationally symmetric (or very similar) emission intensities are actually encountered for some sectors, e.g. cement production (Monjon and Quirion, 2011). However, the intensity of carbon emissions is in most cases linked both to a sector's specific energy intensity as well as to the economy's overall carbon intensity of energy, and the latter varies significantly between countries. Thus, the applicability of Corollary 5 can be expected to be the exception rather than the rule.

6 Comparison and Discussion of the Policy Measures

Corollaries 2 and 4 have already established that in general neither production- nor consumption-based polices are optimal for Home. But if nevertheless only these two policy instruments are available, which one should be preferred? To begin with, we compare production- and consumption-based pricing of emissions with regard to carbon leakage, first under ‘full information’ – i.e. assuming that emission intensities in Foreign are known (Section 6.1.) – and then under the so-called ‘best available technology approach (Section 6.2.). The section concludes by briefly analyzing the welfare effects of these policies (Section 6.3.).

6.1. Production vs. Consumption-Based Emission Pricing under Full Information

From the discussion in Section 5 it should be clear that neither of the two approaches is *a priori* more effective than the other in addressing leakage, since their effects depend on specific parameter values. To be able to formally quantify their different effects on leakage, we perform the following thought experiment: suppose Home has adopted a conventional production-based policy, i.e. it has put a price μ on all emissions generated on its territory (as described in Section 5.1.). Now imagine that Home – in addition to μ - also introduces a price ϕ on the net import of embodied emissions, i.e. it taxes imported goods in proportion to their carbon-intensity, and likewise reimburses this price for exported goods. Evidently, the case in which this price becomes $\phi = \mu$ corresponds again to a full border-tax adjustment (the case described in Section 5.2.).

The effect of such a continuous transition from production-based towards consumption-based emission pricing on the world price p^* is captured by the following Lemma:

Lemma 4: *Suppose Home has a domestic carbon price* $\mu \geq 0$ *in place. Then, introducing a price* $\phi > 0$ *on net imported emissions embodied in trade will lower (raise) the world market price* p^* *if Home is a net importer (exporter) of embodied emissions*.

Proof: See Appendix.

This leads us to the following proposition:

Proposition 4: *If Home has a domestic carbon price* $\mu \geq 0$ *in place, introducing in addition a price* $\phi > 0$ *on net imported emissions will increase carbon leakage if Home is a net importer (exporter) of embodied emissions, and the carbon intensity of Foreign's export good Y is lower (higher) than the carbon intensity of its non-export good X. Otherwise, carbon leakage will decrease.*

Proof: Proposition 4 directly follows from subsequently applying Lemmas 4 and 1. ■

Therefore – and contrary to what seems to be suggested in some studies (Pan et al., 2008; Peters and Hertwich, 2008a,b) – introducing a price on emissions embodied in trade does not necessarily reduce carbon leakage. In particular, as we have demonstrated in Section 5.2., switching from production- to consumption-based emission pricing is equivalent to imposing a (positive) tariff on Home's import good *Y* whenever home is a net-importer of embodied emissions. However, such a tariff will only reduce carbon leakage if Foreign is actually specialized in the production of carbon-intensive goods, i.e. if its exports are more carbon-intensive than its non-export sector. This analysis also highlights that 'expanding the perimeter of regulated emissions' by subjecting a larger amount of embodied emissions to carbon pricing does not necessarily reduce global emissions, as re-adjustments of production- and consumption patterns in Foreign transmitted by changes in world market prices can work in the opposite direction.

6.2. Border Tax Adjustment Using the Best Available Technology Approach

In view of the substantial informational requirements to successfully implement a consumption-based approach – and to circumvent potential problems related to the WTO-principle of non-discrimination – some alternatives have been proposed. These include the best-available-technology approach, which calculates emissions embodied in imports based on the home country's emission factors, i.e. by assuming that the exporting country employs modern and efficient technologies equivalent to industrialized countries' standards. This approach has the two-fold advantage of imposing considerably lower informational requirements, and being more likely to conform to WTO regulations (Ismer and Neuhoff, 2007).

If we again assume that Home has already implemented a price of carbon μ on domestic emissions, then the following Lemma characterizes the effect of a gradual move of Home towards consumption-based pricing of emissions according to the best available technology approach:

Lemma 5: *Suppose Home has a domestic carbon price* $\mu \geq 0$ *in place. Then, introducing a price* ϕ *> 0 on net imported emissions embodied in trade according to the best available technology approach (i.e. assuming* $\gamma^{Yf} = \gamma^{Yh}$*) will lower (raise) the world market price* p^* *if Home's non-export sector Y has a higher (lower) carbon intensity than its export sector X.*

Proof: See Appendix.

The last lemma directly leads to the following Proposition:

Proposition 5: *If Home has a domestic carbon price* $\mu \geq 0$ *in place, introducing a price* ϕ *> 0 on net imported emissions according to the best available technology approach will increase (decrease) leakage whenever the relatively more carbon-intensive sector in Home and Foreign produce different goods (the same good).*

Proof: Proposition 5 directly follows from subsequently applying Lemmas 5 and 1. ∎

The intuition behind this finding can be easily understood by envisaging the tariff implied by such a policy. Just as in Section 5.2. (in particular Eq.(29)), putting a price on emissions embodied in trade corresponds to a positive (negative) tariff if Home's non-export sector *Y* is more (less) carbon-intensive than its export sector *X*. According to Lemma 1, this will reduce Foreign's emissions if its export sector *Y* is more (less) carbon-intensive than its non-export sector *X*.

6.3. Welfare Analysis

Although in general neither of the two approaches is welfare-optimal, they can both induce the optimal wedge between consumer and producer prices (as implied by Eq.(16)) if the chosen level of the policy corresponds to Home's social costs of carbon (i.e. $\mu = -q^Z$ and $\sigma = -q^Z$). If this is the case – which we will assume in this section – the welfare effects of the two approaches can be assessed by focusing on the different tariffs they imply and compare them to the optimal tariff given by Eq. (17).

As discussed in Section 4, the optimal tariff is the sum of two terms. The first, describing the gains from influencing the terms-of-trade in Home's favour, is unambiguously positive (i.e. it is always welfare improving for Home to artificially constrain the demand for Foreign's export good). The sign of the second term, which captures the environmental externality arising from a change in Foreign's production structure, depends on Foreign's comparative advantage (i.e. the difference between the carbon-intensity of its export sector *Y* and its non-export sector *X*). This double role of Home's tariff makes it hard to draw unambiguous conclusions with respect to welfare.

For instance, if Foreign is specialized in the export of products with a relatively low carbon intensity (i.e. $\gamma^{Yf} < p^* \gamma^{Xf}$), subsidizing imports by means of a negative tariff would reduce carbon leakage. If, however, the absolute value of the first term in Eq.(17) exceeds the one of the second term, the optimal tariff is actually positive, i.e. it maximizes welfare even if at the same time it increases carbon leakage. Consequently, it becomes possible that consumption-based pricing of emissions, even if it violates its main objective of reducing leakage, still increases welfare with respect to a production-based policy due to its effect on Home's terms of trade. Likewise, even if both terms in Eq. (17) are positive, meaning that any positive tariff would in fact decrease carbon leakage, consumption-based pricing may still not raise Home's welfare vis-à-vis the production-based approach without tariff. This is easily understood by comparing Eqs.(17) and (29), which shows that the tariff implied by consumption-based pricing of emissions (Eq.(29)) – even when it has the 'correct' sign – might exceed the optimal tariff (Eq.(18)) to such extent that it would be preferable to have no tariff at all.

Consequently, an unambiguous welfare ranking of production- vs. consumption-based pricing of emissions is only possible for the following special case:

Proposition 6: *Suppose Home has a domestic consumption-based carbon price σ ($\sigma = -q^Z$) in place. Then, if the tariff implied by consumption-based pricing of emissions has the opposite sign of the optimal tariff implied by Eq.(17), the former will lead to lower welfare than conventional production-based emission pricing (with $\mu = -q^Z$) without any tariff. Otherwise, the welfare effects are ambiguous.*

Proof: See Appendix.

7 Practical Implications and Relevance

As an empirical application, this section first explores the implications of our model based on data for the year 2004 (Section 7.1.). Of course, due to its many simplifications, the model cannot be expected to provide rigorous quantitative results, but rather to indicate the direction of what could be called the 'pure' trade effect. An explicit discussion of these simplifications and their implied caveats is provided directly afterwards (Section 7.2.).

7.1. Confronting the Model with Empirical Evidence

In this section, we use the dataset of Davis and Caldeira (2010)[17] which provides the carbon contents of exports, imports and total production as well as the corresponding values of exported, imported and produced goods. Based on their numbers, we computed carbon intensities for the European Union (EU27) and all G20 countries that are not part of the EU, except Saudi Arabia, for which no data on embodied emissions is available. In Table 1, the first four columns show for each country the average carbon intensity of its imports, its exports, its total economy, and whether the carbon intensity of its non-export sector is larger or smaller than the one of its export sector (the exact value of the former cannot be derived based on the present data). The fifth column shows the ratio of the carbon intensity of imports and exports; a value greater than one hence indicates a higher carbon intensity in imports than in exports. Similarly, the last column shows the ratio of the carbon intensities of exports versus the one of the economy as a whole, where a value greater than one indicates a relative specialization on the export of carbon-intensive goods. We focus on an assessment of unilateral trade measures that the European Union or the United States could possibly impose on developing countries that produce rising amounts of carbon emissions (in particular China).

Proposition 1 states that applying a (positive) carbon tariff on a country can only be effective (i.e. reduce leakage) if that country's export sector is relatively more carbon-intensive than its non-export sector. However, the data in Table 1 reveal that for most countries, including China, this is in fact not the case (77 out of 95 countries in the full data base). Therefore, our theoretical model implies that the optimal carbon tariff (Eq.(17a)) on imports from these countries would be negative in the majority of cases, and that imposing a positive carbon tariff would increase carbon leakage.

In terms of Proposition 2, which states that a unilateral production-based policy induces leakage whenever the more carbon-intensive sector is the same for both countries (e.g.

[17] Their supplementary online material provides data for 95 countries. We aggregated the data of the 27 EU member countries contained in the dataset into one EU region. We also follow them in their use of GDP in market exchange rates to derive Table 1. This is compatible with our model, which does not feature non-traded goods. Note that the use of purchasing power parity GDP results in a higher relative carbon intensity of exports for China (Jakob and Marschinski, 2013).

Y), one can expect that – even though the carbon intensity of energy production widely varies – the relative ranking of economic sectors by carbon intensity is to a large extent determined by technological factors and hence in fact similar across countries.[18] Hübler (2009), for example, computes carbon intensities of 30 goods based on the GTAP 7 data and finds a very similar ranking of carbon intensities for China, an aggregate of other developing regions, and an aggregate of industrialized countries. Hence, our theoretical results imply that leakage is likely to occur under production-based emission pricing.

Even though the data used in our table do not specify bilateral trade flows, the considerable difference between the carbon intensities of China's exports and those of the EU or the US, respectively, suggests that imports from China to both of the latter can be expected to be more carbon intensive than their exports to China. In fact, this is confirmed explicitly by Davis and Caldeira (2010), who find both regions to be net importers of emissions from China. Hence, under consumption-based emission pricing a positive carbon tariff would be applied by the EU or US on imports from China. However, according to Proposition 4, our model predicts that this would result in higher leakage than under conventional production-based emission pricing.

Finally, as mentioned above, the relative ranking of sectors in terms of their emission intensity is similar across countries. Thus, the application of Proposition 5 suggests that if consumption-based emission pricing would be based not on actual net imports of embodied emissions but on those calculated under a best-available technology approach, it should be expected to result in less leakage than production-based emission pricing.

7.2. Model Limitations and Caveats

Our model is designed to analyze the 'pure' trade effect of consumption- and production-based climate policies and to this end makes several simplifying assumptions: It only represents trade between two countries in two goods and abstracts from the sectoral

[18] For example, the production of cement or steel is energy intensive and thus carbon intensive in all countries, while the provision of financial services has in general a rather low energy- and carbon-intensity.

composition of traded goods, current account surpluses or deficits, changes in production technologies and factor inputs, strategic interactions, and additional channels of leakage (such as free-rider and supply-side leakage). Complex numerical models – such as computable general equilibrium (CGE) models – implement some of these effects. Due to their likely interaction, it is therefore fully conceivable that in these models BTA can in some instances reduce leakage (cf. Section 2), even though our model would imply the opposite. In this section, we discuss how these stylized assumptions affect our findings.

First, with trade measures based on carbon contents, a model with multiple countries is likely to predict that trade gets redirected and increasingly takes place between those countries that have implemented climate polices on the one hand (trade creation), and between those countries that do not have such policies on the other hand (trade diversion). Hence, one would expect a weaker overall effect of carbon-based border measures in such a setting. Second, when taking the multi-sectoral composition of traded goods into account, a carbon-based tariff can be expected to shift the composition of trade towards goods with lower carbon intensities. It is not a priori clear if in this case a carbon tariff has a stronger or a weaker effect than in a two-sector model. For instance, Fischer and Fox (2012) as well as Kuik and Hofkes (2010) highlight that trade measures could reduce leakage in carbon-intensive sectors (such as iron, steel, or cement) but might have only modest impacts on the overall rate of leakage. Third, an analysis of unbalanced trade could only be conducted within a dynamic model, and the question remains in how far environmental and trade policy are appropriate instruments to tackle underlying macro-economic imbalances. Fourth, our model describes emissions in each region by fixed emission factors. It can be argued that carbon-based tariffs pose an incentive for Foreign to adopt cleaner production technologies or switch to less carbon-intensive fuels or intermediate inputs (e.g. Copeland, 1996), and hence increase the effectiveness of border measures, such as a tariff. Fifth, carbon-based tariffs could not only act as an incentive for Foreign to decarbonize, but also trigger retaliation in the form of countervailing tariffs. Accounting for these strategic interactions would require a game-theoretic framework, which we consider to be beyond the scope of this paper. Sixth, even though additional channels of leakage other than specialization are clearly important, it is far from clear how they are affected by trade policy and how they should be represented in a trade model. But if leakage is seen to be driven mainly through the energy markets channel (e.g. the short-term world supply of fossil fuels could be inelastic), then the effectiveness of trade measures would be further reduced (Boeters and Bollen, 2012).

Finally, the current political debate often focuses on the application of BTA only to so-called energy-intensive, trade-exposed (EITE) sectors (Fischer and Fox, 2011), as these sectors are seen as the most 'vulnerable' to leakage, but also for reasons of practical implementation and transaction costs. According to our analysis, one can expect such a policy to reduce carbon leakage if the production of carbon-intensive exports is substituted by the production of goods with a lower carbon-intensity. Whether this is the case is an empirical question and depends on preferences as well as the production possibility frontier. However, even though it would not constitute an *optimal* policy, applying a BTA only to the *most* carbon-intensive sector of a country without domestic carbon price can very likely be expected to reduce leakage, since in this case a shift of the economy towards more carbon-intensive goods can be excluded.

Overall, these limitations of our theoretical model do not invalidate our main message: The rationale behind environmental policies should be to provide better incentives for firms and consumers by pricing in externalities. As we have demonstrated, trade policies influence patterns of production and consumption through their effect on the terms-of-trade, i.e. on relative prices. The implied – possibly counterproductive – general equilibrium effects are often overlooked in the current debate, leading to an under-appreciation of the practical consequences of measures like consumption-based pricing of emissions and border tax adjustment. In that sense, the simplifications in our model discussed above actually point to further complex issues that should be considered (and understood) before trade policy is used to advance environmental objectives.

8 Summary and Conclusions

This paper employs a reduced form general equilibrium 2x2 trade model to study the implications of unilateral policies in the presence of a global emission externality. To this end, it first derives the welfare optimal unilateral policy and then carries out a comparison with production- and consumption-based pricing of emissions (reaffirming that the latter can be implemented by means of a full border tax adjustment). Finally, it confronts the theoretical results with empirical data.

Our findings point to often neglected general equilibrium effects that may theoretically reduce or even reverse the benefits expected from consumption-based pricing of emissions and BTA: Foreign production can shift from less carbon-intensive production for exporting to more carbon-intensive production for its domestic market. Thus, carbon emissions can potentially rise in the foreign country due to full BTA. Moreover, the employed model clearly illustrates that trade policies can be expected to have an impact on foreign producers only to the extent to which the imposing country is able to influence world market prices (i.e. possesses market power), thereby emphasizing the limited possibilities of one country to influence other countries' domestic production decisions offered by trade policy measures.

The comparison of production- and consumption-based approaches for pricing carbon has shown that in general neither represents an optimal policy. However, imposing the optimal carbon tariff derived in Section 4 might not be feasible under WTO stipulations and, moreover, requires very specific information, such as the elasticity of world market prices with respect to changes in the home country's imports and the price elasticity of the foreign country's production. Therefore, the only choice left to policy makers might be the one between production-based and consumption-based pricing of emissions. Based on year 2004 data for the emission intensities of exports of various countries, our stylized theoretical model implies that if implemented by the EU or the US towards China, carbon leakage is likely to occur under both production-based and consumption-based carbon policies, but the latter would be expected to lead to more leakage than the former. However, it can be expected that consumption-based pricing based on the best-available technology approach would result in less leakage than production-based pricing.

From a policy perspective, the findings presented suggest that the economic effects of implementing consumption-based emission pricing (e.g. by means of full BTA) would be uncertain. This observation does not call into question the general ability of trade measures to reduce carbon leakage. However, it highlights the fact that more sophisticated trade policies, which appropriately take into account all relevant general equilibrium effects, might be required.

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Appendix: Table

Carbon intensity	Imported goods (kg/$)	Export sector (kg/$)	Total economy (kg/$)	Non-export sector (kg/$)	Ratio imports/ exports	Ratio exports/ total economy
Argentina	0.58	1.20	1.04	< 1.04	0.49	1.16
Australia	0.78	0.93	0.53	< 0.53	0.84	1.74
Brazil	0.78	0.78	0.55	< 0.55	1.00	1.41
Canada	0.52	0.57	0.57	0.57	0.92	1.01
China	0.49	2.13	3.05	> 3.05	0.23	0.70
EU27	0.51	0.26	0.32	> 0.32	1.99	0.80
India	0.88	2.06	2.12	> 2.12	0.43	0.97
Indonesia	0.75	0.91	1.26	> 1.26	0.83	0.72
Japan	0.91	0.30	0.28	< 0.28	3.05	1.06
Korea (South)	0.62	0.48	0.73	> 0.73	1.30	0.65
Mexico	0.57	0.43	0.60	> 0.60	1.32	0.72
Russia	0.85	2.43	2.63	> 2.63	0.35	0.92
South Africa	0.60	2.80	1.94	< 1.94	0.22	1.44
Turkey	0.79	0.65	0.77	> 0.77	1.21	0.85
United States	0.77	0.49	0.50	> 0.50	1.56	0.99

Table 1: Average carbon intensities of imports, exports, total production, non-export sector and measured relative to each other for the EU27 and G20 countries not part of the EU27 (excl. Saudi Arabia). Derived from data provided in Davis and Caldeira (2010).

Appendix: Proofs

Proof of Lemma 2:

The market clearing condition for the *Y* world market reads: $M^{Yh} - E^{Yf} = 0$, where both M^{Yh} and E^{Yf} depend upon the world market price p^*. Moreover, the budget balance condition Eq.(2) implies: $p^* M^{Yh} = E^{Xh}$. E^{Xh} depends on p^* as well as μ, which translates into M^{Yh}. This implies for the derivative of the market clearing condition with respect to a change in Home's carbon tax μ (equivalent to a change of the cap $\overline{Z}^h$): $M^{Yh}(p^*, \mu) - E^{Yf}(p^*) = 0$ and thus

$$\frac{\partial M^{Yh}}{\partial \mu} + \frac{\partial M^{Yh}}{\partial p^*}\frac{dp^*}{d\mu} - \frac{dE^{Yf}}{dp^*}\frac{dp^*}{d\mu} = 0 \quad \Rightarrow \quad \frac{dp^*}{d\mu} = \frac{-\dfrac{\partial M^{Yh}}{\partial \mu}}{\left(\dfrac{\partial M^{Yh}}{\partial p^*} - \dfrac{dE^{Yf}}{dp^*}\right)} \tag{A1}$$

Under standard conditions, the denominator is unambiguously negative (note that in the present setting both Home and Foreign behave as price-takers). Hence, we only need to compute the sign of the numerator. Using the fact that preferences over consumption are homothetic, Home's imports, $M^{Yh} = C^{Yh} - Q^{Yh}$, can be rewritten by inserting the standard expressions for the consumption of *Y* derived from utility maximizing given an income budget

$$M^{Yh} = \frac{\overline{\eta}}{q} I^h - Q^{Yh} \tag{A2}$$

where $\eta(q)$ denotes the share of Home's real income, I^h, spent on good *X*, and $\overline{\eta}(q) = 1 - \eta(q)$ denotes the share of Home's real income spent on good *Y*. Consumption of *Y* decreases in the relative consumer price of *Y*, denoted by *q*. Since for the moment there are no consumer taxes in place, it is $q = p^*$. Since both goods, *X* and *Y*, are traded internationally, total income is expressed by applying the international price p^*, i.e. as $Q^{Xh} + p^* Q^{Yh}$, implying:

$$M^{Yh} = \frac{\overline{\eta}}{p^*} Q^{Xh} - \eta Q^{Yh} = \frac{\overline{\eta}}{p^*} T^h(Q^{Yh}) - \eta Q^{Yh} \tag{A3}$$

Since in Eq.(A3) only Q^{Yh} depends explicitly on the production tax, μ, we find

$$\frac{\partial M^{Yh}}{\partial \mu} = \left(\frac{\overline{\eta}}{p^*} T^h_{Q^{Yh}} - \eta \right) \frac{\partial Q^{Yh}}{\partial \mu} = -\left(\overline{\eta} \frac{p}{p^*} + \eta \right) \frac{\partial Q^{Yh}}{\partial \mu} \tag{A4}$$

Differentiating the first and the second part of the producers' efficiency condition in Eq.(19) with respect to μ and solving for $\frac{\partial Q^{Yh}}{\partial \mu}$ yields

$$\frac{\partial Q^{Yh}}{\partial \mu} = \frac{\gamma^{Yh} - q\gamma^{Xh}}{\left(1 - \gamma^{Xh} \mu\right)^2 T^h_{Q^{Yh}Q^{Yh}}} \tag{A5}$$

Confronting the last equation with Eq.(14) shows that it will be negative when $\gamma^{Yh} > q\,\gamma^{Xh}$. Therefore, Eq.(A4) will be positive if and only if $\gamma^{Yh} > p^* \gamma^{Xh}$, where $p^* = q$. In this case, Eq.(A1) will be positive as well. ■

Proof of Lemma 3:

To determine the effect of σ on p^*, we start by differentiating the market clearing condition, obtaining (cf. Eq.(A1)):

$$\frac{dp^*}{d\sigma} = -\frac{\dfrac{\partial M^{Yh}}{\partial \sigma}}{\dfrac{\partial M^{Yh}}{\partial p^*} - \dfrac{\partial E^{Yf}}{\partial p^*}} \tag{A6}$$

Again, the denominator is negative under standard conditions. To determine the sign of the numerator, we start by further specifying Home's consumption. With homothetic preferences, we have:

$$\frac{C^{Xh}}{C^{Yh}} = \frac{\eta(q)\,q}{\overline{\eta}(q)} \tag{A7}$$

where $\overline{\eta} \equiv 1 - \eta$ denotes the share of income spent on good Y, as a function of the domestic consumer price q. Since in equilibrium consumption must exhaust the total real income I^h of home, i.e. $C^{Xh} + p^* C^{Yh} = I^h = Q^{Xh} + p^* Q^{Yh}$, we obtain:

$$C^{Yh} = \frac{\overline{\eta}\, I^h}{\eta\, q + \overline{\eta} p^*} \tag{A8}$$

Using $M^{Yh} = C^{Yh} - Q^{Yh}$, one can simplify M^{Yh} to

$$M^{Yh} = \frac{\overline{\eta}\, Q^{Xh} - \eta\, q\, Q^{Yh}}{\eta\, q + \overline{\eta} p^*} \tag{A9}$$

where the RHS can be expressed completely in terms of p^* and σ, since q and p are dependent via Eqs.(28) and (29). Calculating the derivative $\dfrac{\partial}{\partial \sigma}$ and collecting terms leads to:

$$\frac{\partial M^{Yh}}{\partial \sigma} = \frac{-\left[\frac{\partial Q^{Yh}}{\partial p}\frac{\partial p}{\partial \sigma}\left(\eta\, q+\overline{\eta} p^*\right)\left(\eta\, q+\overline{\eta} p\right)+\frac{\partial q}{\partial \sigma}\left(\eta\overline{\eta}+q\frac{\partial \eta}{\partial q}\right)I^h\right]}{\left(\eta\, q+\overline{\eta} p^*\right)^2} \tag{A10}$$

The derivative of η with respect to q is connected to the elasticity of substitution Σ of U^h by $\frac{\partial \eta}{\partial q}=\frac{(\Sigma-1)\eta\overline{\eta}}{q}$, leading to the final expression:

$$\frac{\partial M^{Yh}}{\partial \sigma} = \frac{-\left[\frac{\partial Q^{Yh}}{\partial p}\frac{\partial p}{\partial \sigma}\left(\eta\, q+\overline{\eta} p^*\right)\left(\eta\, q+\overline{\eta} p\right)+\frac{\partial q}{\partial \sigma}\eta\overline{\eta}\,\Sigma\, I^h\right]}{\left(\eta\, q+\overline{\eta} p^*\right)^2} \tag{A11}$$

While the denominator is always positive, both terms of the numerator can be either positive or negative, depending on the sign of $\frac{\partial p}{\partial \sigma}$ and $\frac{\partial q}{\partial \sigma}$. Since Σ > 0, and $\frac{\partial Q^{Yh}}{\partial p}$ is positive as given by Eq.(14), we have the following three cases: *(i)* Eq.(A11) and hence Eq.(A6) for $\frac{dp^*}{d\sigma}$ are positive, i.e. p^* increases when σ increases, if $\frac{\partial p}{\partial \sigma}<0$ and $\frac{\partial q}{\partial \sigma}<0$ (or if one term is negative and the other term is zero); likewise, Eq.(A11) is negative and hence p^* decreases if $\frac{\partial p}{\partial \sigma}>0$ and $\frac{\partial q}{\partial \sigma}>0$ (or if one term is positive and the other term is zero); *(ii)* the impact of σ on p^* is ambiguous if $\frac{\partial p}{\partial \sigma}$ and $\frac{\partial q}{\partial \sigma}$ have different signs. To determine the signs of $\frac{\partial p}{\partial \sigma}$ and $\frac{\partial q}{\partial \sigma}$, we obtain from Eq.(29):

$$\frac{\partial q}{\partial \sigma} = \gamma^{Yf} - p^*\gamma^{Xh} \tag{A12}$$

while combining Eqs.(28) and (29) yields for p and $\frac{\partial p}{\partial \sigma}$:

$$p = p^* + \sigma \frac{\left(\gamma^{Yf} - \gamma^{Yh}\right)}{\left(1 - \sigma\, \gamma^{Xh}\right)} \quad \Rightarrow \quad \frac{\partial p}{\partial \sigma} = \frac{\left(\gamma^{Yf} - \gamma^{Yh}\right)}{\left(1 - \sigma\, \gamma^{Xh}\right)^2} \tag{A13}$$

Therefore, case *(i)* will hold if both of Home's sectors are either more or less emission intensive than Foreign's export sector *Y*, respectively, and case *(ii)* otherwise. In the symmetric case *(iii)*, i.e. when $\gamma^{Xh} = \gamma^{Xf}$ and $\gamma^{Yh} = \gamma^{Yf}$, $\frac{\partial p}{\partial \sigma}$ will become zero and Eq.(A11) will simplify so that the sign of $\frac{dp^*}{d\sigma}$ only depends on Eq.(A12) for $\frac{\partial q}{\partial \sigma}$. Accordingly, $\frac{dp^*}{d\sigma}$ will be positive if the *Y*-sector is less emission intensive than the *X*-sector and negative if it is more emission intensive. ■

Proof of Lemma 4:

The proof proceeds analogously to the one of Lemma 3. Totally differentiating the market clearing condition $M^{Yh}(p^*, \phi) - E^{Yf}(p^*) = 0$ yields:

$$\frac{dp^*}{d\phi} = -\frac{\frac{\partial M^{Yh}}{\partial \phi}}{\frac{\partial M^{Yh}}{\partial p^*} - \frac{\partial E^{Yf}}{\partial p^*}} \tag{A14}$$

As in Eq.(A9), Home's imports can then again be expressed as:

$$M^{Yh} = \frac{\overline{\eta}\, Q^{Xh} - \eta\, q\, Q^{Yh}}{\eta\, q + \overline{\eta} p^*} \tag{A15}$$

with q, p, and p^* depending on ϕ. Using Eq.(21), to express p in terms of q (and μ, which is constant), and Eq.(29) to express q in terms in terms of p^* and ϕ, the RHS of Eq.(A15) can be written as a function of p^* and ϕ.[19] Therefore, in analogy to Eq.(A11), the sign of Eq.(A14) is determined by the signs of $\frac{\partial p}{\partial \phi}$ and $\frac{\partial q}{\partial \phi}$:

$$\frac{\partial M^{Yh}}{\partial \phi} = \frac{-\left[\frac{\partial Q^{Yh}}{\partial p}\frac{\partial p}{\partial \phi}\left(\eta q+\overline{\eta} p^*\right)\left(\eta q+\overline{\eta} p\right)+\frac{\partial q}{\partial \phi}\eta\overline{\eta}\,\Sigma I^h\right]}{\left(\eta q+\overline{\eta} p^*\right)^2} \tag{A16}$$

As in Eq.(A12), $\frac{\partial q}{\partial \phi}$ follows directly from Eq.(29):

$$\frac{\partial q}{\partial \phi} = \gamma^{Yf} - p^* \gamma^{Xh}. \tag{A17}$$

In order to determine $\frac{\partial p}{\partial \phi}$, we use Eqs.(21) and (29) to obtain:

$$p - p^* = \phi(\gamma^{Yf} - p^* \gamma^{Xh}) - \mu(\gamma^{Yh} - p\gamma^{Xh}) \Rightarrow \frac{\partial p}{\partial \phi} = \frac{\gamma^{Yf} - p^*\gamma^{Xh}}{1-\mu\gamma^{Xh}} \tag{A18}$$

As the denominator of Eq.(A18)–which represents the normalized price of good X minus the price of its ‘embodied’ emissions–is positive, $\frac{\partial p}{\partial \phi}$ and $\frac{\partial q}{\partial \phi}$ bear identical signs. Hence, if Home’s imports are more (less) carbon-intensive than its exports – i.e. it is a net importer (exporter) of emissions – Eq.(A14) is negative (positive). ■

Proof of Lemma 5:

[19] Note that Eq.(21) determines the wedge between the domestic consumer- and producer price for a domestic emission price μ, and Eq.(29) determines the wedge between the domestic consumer price and the world market price for a price ϕ levied on imported emissions.

The proof is basically identical to the one for Lemma 4. By substituting γ^{Yh} for γ^{Yf} in Eqs.(A17) and (A18), we get:

$$\frac{\partial q}{\partial \phi} = \gamma^{Yh} - p^* \gamma^{Xh} \tag{A19}$$

and

$$\frac{\partial p}{\partial \phi} = \frac{\gamma^{Yh} - p^* \gamma^{Xh}}{1 - \mu \gamma^{Yh}} \tag{A20}$$

Therefore, under the best available technology approach, Eq.(A14) will be negative (positive) if Home's export sector is more carbon intensive than its non-export sector. ■

Proof of Proposition 6:

As demonstrated in Section 4, Home's welfare is maximized by setting a domestic production tax τ^{opt} and a tariff θ^{opt}, and, according to Eq.(21), this optimal production tax is equivalent to a domestic carbon price $\mu = -q^Z$. Therefore, given that τ^{opt} is in place, the optimal tariff θ^{opt} has to fulfill the following conditions:

$$\left.\frac{dW^h}{d\theta}\right|_{\theta=\theta^{opt}} = 0 \text{ and } \left.\frac{d^2W^h}{d\theta^2}\right|_{\theta=\theta^{opt}} < 0 \tag{A21}$$

Assuming the welfare maximum to be unique, it directly follows that for any two tariffs θ^A, θ^B that deviate from the optimal tariff in the same direction – i.e. for which *sgn* $(\theta^A - \theta^{opt}) =$ *sgn* $(\theta^B - \theta^{opt})$ – the following has to hold:

$$\operatorname{sgn}\left\{W^h\big|_{\theta=\theta^A} - W^h\big|_{\theta=\theta^B}\right\} = -\operatorname{sgn}\left\{\left|\theta^A - \theta^{opt}\right| - \left|\theta^B - \theta^{opt}\right|\right\} \tag{A22}$$

Obviously, for the case in which the tariff θ^{cons} implied by consumption-based pricing of emissions (Eq.(29)) has the opposite sign of the optimal tariff, the fact that the tariff θ^{prod} implied by production-based emission pricing (Eq.(20)) is zero, Eq.(A22) directly yields:

$$\operatorname{sgn}\left\{W^h\big|_{\theta=\theta^{cons}} - W^h\big|_{\theta=0}\right\} = -1, \quad \text{i.e.} \quad W^h\big|_{\theta=\theta^{cons}} < W^h\big|_{\theta=0} \tag{A23}$$

which proves the first part of the proposition.

The second part of the Proposition results from the observation that without specific assumptions regarding the functional form of W^h, no general conclusions can be drawn for any two tariffs θ^A and θ^B that deviate from the optimal tariff in different directions – i.e. for which *sgn* $(\theta^A - \theta^{opt}) = -$ *sgn* $(\theta^B - \theta^{opt})$. ■