Robust policies to mitigate carbon leakage

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Abstract:

Unilateral climate policy induces carbon leakage through the relocation of emission-intensive and trade-exposed industries to regions without emission regulation. Previous studies suggest that emission pricing combined with border carbon adjustment is a second-best instrument, and more cost-effective than output-based rebating. We show that the combination of output-based rebating and a consumption tax for emission-intensive and trade-exposed goods can be equivalent with border carbon adjustment. Moreover, it is welfare improving for a region that implements emission pricing along with output-based rebating to introduce such a consumption tax. The welfare gain is particularly large if output-based rebating is already implemented for a sector that is not much exposed to leakage, e.g., due to uncertainty about exposure or due to lobbying activities. Thus, supplementing output-based rebating with a consumption tax constitutes robust policies to mitigate carbon leakage.

Keywords: Carbon leakage; output-based rebating; border carbon adjustment; consumption tax

JEL classification: D61, F18, H23, Q54

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1. Introduction

In response to the threat of climate change, many countries consider or have introduced unilateral climate policies. However, greenhouse gases are global pollutants and unilateral action leads to carbon leakage, such as relocation of emission-intensive and trade-exposed (EITE) activities to countries with no or more lenient climate regulations. Unilateral constraints on emissions raise production costs for emission-intensive industries such as steel, cement, and chemical products, reducing their competitiveness in the world market, thereby inducing more production and emissions in unregulated regions.

To mitigate counterproductive leakage, countries have either exempted EITE industries from the regulation, or searched for supplemental anti-leakage measures. As a prime example, EITE industries in the EU, which are regulated under an emissions trading system (EU ETS), have received large amounts of free allowances. Currently, allowances are mainly allocated in proportion to installations' production. Free allowances have also been introduced in other emissions trading systems such as in New Zealand, South Korea and California, and in the regional emissions trading systems in China (World Bank, 2014). Free allowance allocation conditional on output can be interpreted as output-based rebating (OBR) of emission tax payments (e.g., Böhringer et al., 1998; Bernard et al., 2007).

Another potential anti-leakage measure that figures prominently in the economic literature is border carbon adjustment (BCA) with carbon tariffs on imports and rebates on exports of EITE goods. Most studies on carbon leakage suggest that BCA outperform OBR with respect to leakage reduction and cost-effectiveness of reducing global emissions (Monjon and Quirion, 2011a; Fischer and Fox, 2012; Böhringer et al., 2014a). BCA are however politically contentious, and experts differ in their views about whether or not it is compatible with WTO rules (see e.g. Horn and Mavroidis, 2011, Tamiotti, 2011, and Böhringer et al., 2012b).[1] One signal for its limited political feasibility is that – so far – border measures have only been proposed but not

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[1] In 2010, the Indian Environment Minister threatened to "bring a WTO challenge against any 'carbon taxes' that rich countries impose on Indian imports" (ICTSD, 2010). There is also a fear that BCA could trigger a trade war (Holmes et al., 2011). On the other hand, Nordhaus (2015) argues that trade penalties can induce countries to join a "Climate Club" (see also Helm and Schmidt, 2015, and Böhringer et al., 2016).

implemented.[2] According to Monjon and Quirion (2011b), a uniform carbon tariff is more likely to be compatible with the WTO rules than tariffs that differentiate between exporting countries.

Regarding economic incentives, a key difference between OBR and BCA is that whereas the latter dampens foreign supply of EITE goods to the regulated country, the former stimulates domestic production. The reason is that OBR acts as an implicit production subsidy (Böhringer and Lange, 2005). As a consequence, production and consumption of EITE goods will be excessive under OBR, compared to second-best setting with BCA.[3] In other words, the incentives to switch from buying emission-intensive to less emission-intensive products are weakened under OBR. As shown in Böhringer et al. (2014a), whereas BCA automatically becomes inactive as the coalition of regulating countries covers the whole world, OBR continues to stimulate too much output of the EITE goods. Similarly, whereas BCA for goods without trade exposure has little or no impacts, OBR triggers too much production.

In this paper we show that it is welfare improving for a country, that has already implemented a carbon tax (or an emissions trading system) along with OBR to EITE goods, to also impose a consumption tax on the same EITE goods. By consumption tax, we refer to product-specific taxes on all purchases of these goods, i.e., not only on final consumption but also on intermediate use in production. The intuition behind the welfare-improving effect of such a consumption tax is that OBR stimulates excessive use of EITE goods. We also find that even in the case without any rebating, it is welfare improving to implement a consumption tax on EITE goods as it reduces foreign production (and hence emissions) of such goods.

The theoretical trade literature has established the result “that a combination of a production subsidy and a consumption tax at equal rates is tantamount to a tariff if the commodity is being imported, and an export subsidy if it is being exported” (Dixit

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[2] For example, border measures have been included in the American Clean Energy and Security Act of 2009 that passed the U.S. Congress but not the Senate (see https://www.congress.gov/bill/111th-congress/house-bill/2454; Fischer and Fox, 2011). Border measures have also been put forward by the EU Commission (2009) as a possible future alternative to free allowance allocation.

[3] This conclusion may no longer hold in the case of pre-existing market imperfections such as market power, see e.g. Gersbach and Requate (2004) and Fowlie et al. (2016).

1985, p.356). Building on this fundamental idea we show that combining OBR with a consumption tax may be equivalent with BCA (assuming a uniform carbon tariff). The equivalence requires that the consumption tax for an EITE good is equal to the OBR rate, which in turn must equal the carbon tariff and the export rebate.[4] To our best knowledge, this equivalence result has not been shown so far in the context of emission leakage.[5]

For unilateral climate policy design, our finding suggests a viable and probably more robust alternative to contentious BCA,[6] thereby lowering the risk of potentially detrimental trade wars. From a practical point of view, there are no extra administrative costs in determining the consumption taxes as long as benchmarks are already determined for the OBR rates (such as the benchmarks currently used in the EU ETS).

We substantiate our analytical findings with complementary numerical results based on a stylized computable general equilibrium (CGE) model with two regions and four goods, where the goods can be either consumed or used as intermediate input into production. The numerical results are in accordance with our analytical findings. In addition, the simulations demonstrate that the advantage of a consumption tax becomes particularly relevant if the EITE good produced domestically cannot be easily substituted by foreign goods. In this case the potential for leakage is limited, and thus the distortive effects of stimulating output are getting more critical. By combining OBR with a consumption tax, the distortive effect of OBR can be controlled for. Such a strategy becomes particularly policy-relevant if there is

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[4] All instruments are applied in monetary value per unit of the EITE good. For instance, with 100% rebating, i.e., all emission payments from an EITE industry are rebated back to the industry in proportion to firms' output, the equivalence requires that the carbon tariff is based on domestic emission intensities, and that there is 100% export rebating.

[5] Analysis of unilateral climate policy and carbon leakage requires some extensions beyond the well-known basic equivalence mechanism. Specifically, dealing with global pollutants, we need to account for emissions abroad when establishing the equivalence. Our analysis also features endogenous world prices and heterogeneous goods. In a somewhat related context with trade in a homogenous fossil fuel good, Hoel (1994) notes that a climate coalition can improve its terms-of-trade in the fuel market by either introducing an import (export) tariff or a combination of production subsidy (tax) and consumption tax (subsidy) if the coalition is a net importer (exporter) of fossil fuels.

[6] It could be argued that the combination of OBR and consumption tax can also be contentious, as it gives the same outcome as BCA. However, the consumption tax itself should not be contentious as it treats home and foreign firms equally. Another question is whether OBR (or output-based allocation) is WTO compatible, as this favors domestic firms, but such policy has already been implemented as explained above.

uncertainty about leakage exposure for individual sectors. The actual practice in EU climate policy sheds some light on the issue at stake. In the EU ETS, sectors that are "exposed to a significant risk of carbon leakage" receive a high share of free allowances.[7] A majority of industry sectors have been put into this group. In contrast, Sato et al. (2015) find that "vulnerable sectors account for small shares of emission", and Martin et al. (2014) conclude that the current allocation results in "substantial overcompensation for given carbon leakage risk". Note that supplementing OBR with a consumption tax does not only provide a robust strategy against uncertainty on data grounds but also with respect to lobbying activities by industries.

There is a large body of literature on carbon leakage. The seminal paper by Markusen (1975) derives the first-best combination of a domestic emission tax and a tariff on imported goods (in his model, emissions are functions of production only), where the optimal tariff depends on both leakage and terms-of-trade effects. In a similar vein, Hoel (1996) determines an optimal combination of an emission tax and a carbon tariff (or export subsidy), where he also includes the indirect emission effects of the tariff (see also Copeland, 1996, for an early analytical contribution).

Many numerical modeling studies quantify carbon leakage, the bulk of them using multi-region and multi-sector CGE models of the world economy. For policy-relevant parameters on key dimensions – such as the stringency of emission regulation or the size of the abatement coalition – most studies conclude that the leakage rate of a unilateral carbon tax (or emissions trading) is in the range of 5-30%, i.e., a reduction of 100 units of CO_2 in the regulating country leads to an increase of 5-30 units of CO_2 in non-regulating countries (see, e.g., the review by Zhang, 2012, and the special issue edited by Böhringer et al., 2012a). There are, however, a few outliers with negative leakage (Elliott and Fullerton, 2014) or leakage rates above 100% (Babiker, 2005), adopting less conventional assumptions on international factor mobility or market power. Studies that calculate leakage from single EITE industries often find somewhat higher leakage rates (e.g., Ponssard and Walker, 2008, and Fischer and Fox, 2012) since competitiveness losses get relatively more pronounced.

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[7] http://ec.europa.eu/clima/policies/ets/cap/leakage/index_en.htm

Leakage mainly occurs through two intertwined channels. In this paper we focus on leakage through the market for EITE goods, often referred to as the competitiveness channel. The second channel is the so-called fossil-fuel channel: Reduced demand for fossil fuels in climate policy regions depresses international fuel prices, stimulating fuel consumption and thus emissions in other regions (Felder and Rutherford, 1993). The policy debate focuses on leakage through the competitiveness channel, mirroring concerns of regulated EITE industries on adverse competitiveness effects. The policy focus goes also along with broader scope of policy options – such as BCA or OBR – to mitigate leakage through EITE markets rather than through fossil fuel markets.

Our paper also relates to a strand of literature that examines consumption taxes in environmental regulation, either alone or in combination with other instruments. In particular, Holland (2012) shows that adding a consumption tax to an emission intensity standard can improve efficiency of unilateral climate policy, as standards trigger inefficiently high consumption. Tradable intensity targets can be re-interpreted as a combination of an emission price and OBR – in this respect, Holland's finding is comparable with our result on the efficiency gains through supplemental consumption taxes. However, Holland's model includes only one good, with domestic and foreign goods being homogenous, whereas we consider a model with three different types of goods, where domestic and foreign goods can be either homogenous or heterogeneous. Eichner and Pethig (2015a) examine consumption-based taxes as an alternative to production-based (emissions) taxes in a two-period two-country analytical general equilibrium model with a finite stock of fossil fuels, concluding that consumption-based taxes may reduce the cost of unilateral climate policy. In follow-up work, Eichner and Pethig (2015b) show that a combination of production- and consumption-based taxes outperform production-based taxation stand-alone.[8] In both these papers, Eichner and Pethig assume a one-to-one relationship between emissions and production of the emission-intensive good, which is different from our model where EITE producers can reduce emissions without reducing output. This is an important distinction when considering policies to mitigate leakage – the purpose of

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[8] This result is derived under specific functional forms and an emission ceiling that is only slightly lower than laissez-faire emissions.

anti-leakage policies such as OBR and BCA is to reduce emissions in EITE industries without necessarily reducing EITE output (as it is output reductions that induce leakage through the competitiveness channel).

The remainder of this paper is organized as follows. In Section 2 we lay out our theoretical model and analyze the optimal consumption tax in a situation where an emission tax combined with OBR is already in place; we then demonstrate the equivalence between BCA and the combination of OBR and consumption tax. In Section 3, we develop a stylized computable general equilibrium model calibrated to empirical data for the world economy and substantiate our analytical results with numerical simulations. Section 4 concludes.

2. Analytical model

We consider a partial equilibrium model with two regions, $j = \{1,2\}$, and three goods x, y and z. Good x is emission-free and tradable, good y is emission-intensive and tradable, while good z is emission-intensive and non-tradable.[9] Same goods produced in different regions are initially assumed to be homogenous,[10] with no trade cost (for the two tradable goods). At the end of this section we consider the case with heterogeneous goods, showing that our main results still hold (see Corollary 4). We interpret y as emission-intensive and trade-exposed (EITE) sectors where output-based rebating is considered (e.g., chemicals, metal and other mineral production), and z as sectors where leakage is of less concern (e.g. electricity production and transport). The market prices (excluding taxes) of goods x, y and z in region j are denoted p^{xj}, p^{yj} and p^{zj}, respectively.

The representative consumer's utility from consumption in region j is given by $u^j\left(\bar{x}^j, \bar{y}^j, \bar{z}^j\right)$, where $\bar{x}^j$, $\bar{y}^j$ and $\bar{z}^j$ denote consumption of the three goods. The

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[9] Note that we use emission and carbon interchangeably throughout the text, as we want to adhere to the established terms "emission-intensive and trade-exposed (EITE)" and "border carbon adjustment (BCA)".
[10] Thus, only net trade matters for each good in this model.

utility function is twice differentiable, increasing and strictly concave; i.e., we have $u_x^j \equiv \partial u^j / \partial \bar{x}^j > 0, u_y^j > 0, u_z^j > 0$ and the Hessian matrix is negative definite.

Production of good *x* in region *j* is $x^j = x^{1j} + x^{2j}$, where x^{ij} denotes goods produced in region *j* and sold in region *i*. We use similar notation for good *y*. The market equilibrium conditions are then:

$$\begin{aligned} &x^1 + x^2 = \bar{x}^1 + \bar{x}^2 \\ &y^1 + y^2 = \bar{y}^1 + \bar{y}^2 \quad . \\ &z^j = \bar{z}^j \end{aligned} \tag{1}$$

Costs of producing goods *x, y* and *z* are given by region-specific cost functions $c^{xj}\left(x^j\right)$, $c^{yj}\left(y^j, e^{yj}\right)$ and $c^{zj}\left(z^j, \mathrm{e}^{zj}\right)$, respectively, with e^{yj} and e^{zj} denoting emissions. We assume that cost is increasing in production for all goods, and that cost of producing *y* and *z* is decreasing in emissions; more precisely, $c_x^{xj}, c_y^{yj}, c_z^{zj} > 0$ and $c_e^{yj}, c_e^{zj} \leq 0$, with strict inequality when emissions are regulated. Further, cost is assumed to be twice differentiable and strictly convex. Last, all derivatives are assumed to be finite.

2.1 Output-based rebating and consumption tax

For our analysis we assume that region 1 undertakes unilateral emission regulation and disposes of three policy instruments: an emission tax t^1, an output subsidy s^1 to production of good *y*, and a consumption tax v^1 on buying good *y*. Output-based rebating (OBR) is equivalent with an output subsidy, where the subsidy is linked to the emission tax. In particular, if the tax revenues are fully redistributed back to the producers, the implicit subsidy of OBR is $s^1 = t^1 e^{y1} / y^1$, a case we will refer to as 100% OBR.[11] Initially, we assume no climate policy in region 2, i.e., $t^2 = s^2 = v^2 = 0$.

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[11] Most studies of OBR in the literature consider 100% rebating. In the EU ETS, the most leakage-exposed industries, accounting for more than half of total emissions from installations that receive free allowances, have around 100% rebating on average. Note that this does not mean that the allowances they receive cover all their needs, as e^{y1} in the expression above denotes regulated emissions, which typically are lower than baseline emissions. Meunier et al. (2014) argue that the allocation mechanism in the EU ETS may be better characterized by capacity-based allocation, as new (and expansion of existing) installations receive allowances in proportion to their installed capacity.

Competitive producers in region *j* maximize profits:

$$
\begin{aligned}
&\max_{x^{1j},x^{2j}}\left[p^{x1}x^{1j}+p^{x2}x^{2j}-c^{xj}(x^{j})\right] \\
&\max_{y^{1j},y^{2j},e^{yj}}\left[\left(p^{y1}+s^{j}\right)y^{1j}+\left(p^{y2}+s^{j}\right)y^{2j}-c^{yj}(y^{j},e^{yj})-t^{j}e^{yj}\right] . \\
&\max_{z^{j},e^{zj}}\left[p^{zj}z^{j}-c^{zj}(z^{j},e^{zj})-t^{j}e^{zj}\right]
\end{aligned}
$$

This gives the following first-order conditions for an interior solution:

$$
\begin{aligned}
&p^{x1}=p^{x2}=c_{x}^{x1}=c_{x}^{x2} \\
&p^{y1}+s^{1}=p^{y2}+s^{1}=c_{y}^{y1} \quad ; \quad p^{y1}=p^{y2}=c_{y}^{y2} \\
&p^{zj}=c_{z}^{zj} \\
&c_{e}^{y1}=c_{e}^{z1}=-t^{1} \quad ; \quad c_{e}^{y2}=c_{e}^{z2}=0
\end{aligned}
\quad . \tag{2}
$$

Note that an interior solution requires that there is one global price for each of the tradable goods *x* and *y*, as both goods are homogenous with no trade cost (this is not the case with heterogeneous goods, see Corollary 4 and the proof in Appendix A). The domestic emission tax t^1 induces higher cost of producing good *y* in region 1, which implies higher output and emissions in region 2 through the international market for good *y*. The motivation for the subsidy s^1 (or OBR) is to target this leakage by driving a wedge between marginal production cost in region 1 and the market price on good *y*, and hence to stimulate domestic output of this good. The net effect of t^1 and s^1 on y^1 is ambiguous.

The representative consumer in region *j* maximizes utility, given consumer prices and a budget restriction. After constructing the Lagrangian function and then differentiating, we get the following first-order conditions:

$$
u_{x}^{j}=p^{xj} \quad ; \quad u_{y}^{j}=p^{yj}+v^{j} \quad ; \quad u_{z}^{j}=p^{zj} . \tag{3}
$$

We assume that the regions have a balance-of-payment constraint, so that import expenditures must equal export revenues in both regions. The import-export balance as a foreign closure rule is motivated by the notion that regions have to stay on their budget line. We thus impose that there is no change in net indebtedness associated with climate policy interference. Net export for region *j* is equal to production minus consumption in that region, i.e., $x^j - \bar{x}^j$ and $y^j - \bar{y}^j$. Using $p^{y1} = p^{y2} \equiv p^y$ and $p^{x1} = p^{x2} \equiv p^x$ from the first-order conditions (2), we have:

$$p^y\left(y^j - \bar{y}^j\right) + p^x\left(x^j - \bar{x}^j\right) = 0. \tag{4}$$

2.2 The optimal consumption tax under OBR

Regional welfare maximization

We now want to derive the optimal consumption tax on good *y* in region 1, given that the region has already implemented an exogenous emission tax (t^1) on goods *y* and *z*, combined with OBR (implemented as an exogenous subsidy s^1) to good *y*. Welfare in region 1 is given by:

$$W^1 = u^1(\bar{x}^1, \bar{y}^1, \bar{z}^1) - c^{x1}(x^1) - c^{y1}(y^1, e^{y1}) - c^{z1}(z^1, e^{z1}) - \tau(e^{y1} + e^{y2} + e^{z1} + e^{z2}), \tag{5}$$

where we use the composite utility price index as a numeraire and normalize that price to unity. τ is the shadow cost of emissions, which we will refer to as the Pigouvian tax.[12] We assume that emissions abroad are valued by the same shadow cost as emissions at home. This is a reasonable assumption for greenhouse gas emissions, with spatially independent emissions damage.[13] We then have the following result:

Lemma 1. *Let welfare in region 1 be given by equation (5), and assume that region 1 has implemented an emission tax equal to the Pigouvian tax, i.e.,* $t^1 = \tau$*, and an exogenous subsidy* s^1 to good *y*. *Then the welfare maximizing consumption tax* v^{1*} *on good y is given by:*

$$v^{1*} = \underbrace{\left(\frac{\partial \bar{y}^1}{\partial v^1}\right)^{-1}}_{(a)} \left[\underset{(b)}{s^1 \frac{\partial y^1}{\partial v^1}} + \tau\left(\underbrace{\frac{\partial e^{y2}}{\partial y^2}\frac{\partial y^2}{\partial v^1}}_{(c)} + \underbrace{\frac{\partial e^{z2}}{\partial z^2}\frac{\partial z^2}{\partial v^1}}_{(d)} \right) - \underbrace{\frac{\partial p^y}{\partial v^1}\left(y^1 - \bar{y}^1\right) - \frac{\partial p^x}{\partial v^1}\left(x^1 - \bar{x}^1\right)}_{(e)} \right]. \tag{6}$$

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[12] Strictly speaking, the Pigouvian tax refers to the global marginal external costs of emissions. Whether region 1 considers this as its shadow cost of emissions, or only considers own damage costs of emissions, the analytical results are not changed.

[13] If only domestic emissions matter, carbon leakage is by assumption not an issue anymore. If foreign emissions are valued less than τ, the optimal consumption tax declines (cf. discussion of terms *c* and *d* of equation (6) below).

Proof. *See Appendix A.*

The first factor (*a*) in (6) is negative, as a higher consumption tax on good *y* in region 1 reduces consumption of this good in that region (see Appendix A). Hence, the sign of v^{1*} is the opposite of the sign of the square bracket.

Inside the square bracket the first term (*b*) is negative, as reduced demand for good *y* in region 1 reduces the market price of *y* and hence output of good *y* in both regions. This term reflects that the OBR-subsidy, which reduces leakage through depressing foreign production, has a negative side effect as it leads to too much consumption of good *y* (marginal production cost in region 1 exceeds the consumer price in both regions). The optimal consumption tax corrects for this.

The two next terms capture emission effects in region 2, which abstains from emission regulation. Term (*c*) is negative by the same reasoning as for term (*b*), and the fact that emissions are increasing in output. The sign on term (*d*) is a priori ambiguous and depends on the cross derivatives of the utility function in region 2, in particular whether *z* is a complement or a substitute to good *y*. As the consumption tax reduces the price of *y*, consumption of this good in region 2 increases. This will tend to reduce the consumption of other goods, and hence production of the non-tradable *z* good, in region 2 unless *y* and *z* are complements (in consumption). Moreover, because *z* is typically dominated by electricity generation and transport, and electricity is an important input into production of many EITE goods, reduced output of *y* in region 2 will also tend to decrease consumption (and thus production) of *z*. For these two reasons, we find it likely that the sign of $\partial z^2 / \partial v^1$ is negative. In any case, it is very likely that this second-order effect is dominated by the first-order effect (*c*). We will henceforth make the following reasonable assumption:

$$(7) \qquad \frac{\partial e^{y2}}{\partial y^2}\frac{\partial y^2}{\partial v^1} + \frac{\partial e^{z2}}{\partial z^2}\frac{\partial z^2}{\partial v^1} < 0 ,$$

which of course is always true if $\partial z^2 / \partial v^1 < 0$.[14]

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[14] In the simulations in Section 3, the sign of $\partial z^2 / \partial v^1$ is consistently negative.

The last term (*e*) captures terms-of-trade effects. Whereas the price of good *y* (p^y) decreases, the price of good *x* (p^x) will increase due to increased demand. If region 1 is initially a net importer (exporter) of good *y* and net exporter (importer) of good *x*, both last terms are negative (positive). Note that the balance of payments constraint (4) requires that if region 1 imports good *y*, it must export good *x* (and vice versa). Hence, we have shown the following result:

Proposition 1. *Consider a region that combines a Pigouvian tax on emissions with an exogenous subsidy to production of an emission-intensive, tradable good y, and considers a consumption tax on good y. Then we have:*

- *The optimal consumption tax on good y is unambiguously positive if the region is not a net exporter of good y.*
- *If the region is a net exporter of good y, then the optimal consumption tax on good y is positive if and only if the disadvantageous terms-of-trade effects are dominated by the beneficial effects from reducing emissions abroad and excessive production of good y.*

Proof. *The proposition follows from Lemma 1, and the discussion of the sign of equation (6) above (including condition (7)).*

The intuition behind the proposition is that the consumption tax mitigates the negative side effect of the OBR, i.e., excessive use of good *y*, and that it reduces foreign emissions. Obviously, this is a second-best policy, as the first-best policy would be to tax foreign emissions directly, which is not possible for the regulator in region 1.

If region 2 has also implemented (some) climate policies, it is straightforward to show that equation (6) still holds. Thus, Proposition 1 also holds in this case. The intuition is that the consumption tax still reduces emissions in region 2, and that region 1 by assumption is not concerned about welfare effects in the other region.

Global welfare maximization

So far, we have assumed that region 1's policy objective when setting the consumption tax is to maximize welfare in region 1. However, a region's unilateral efforts to reduce global warming may not always be motivated solely by concern for the regions own citizens, but may be driven by the intent to improve on global cost-effectiveness of unilateral climate policy action. To assess unilateral climate policy design from a global welfare perspective, we consider the case where region 1 is concerned about effects on global welfare, including the cost of emissions as before.[15] Global welfare is:

$$W^G = \sum_{j=1,2} \left[u^j(\bar{x}^j, \bar{y}^j, \bar{z}^j) - c^{xj}(x^j) - c^{yj}(y^j, e^{yj}) - c^{zj}(z^j, e^{zj}) - \tau\left(e^{yj} + e^{zj}\right) \right], \tag{8}$$

where we take a weighted utility price index across regions as our numeraire. Given that region 1 has implemented a Pigouvian tax on emissions and an exogenous subsidy to production of good *y*, and there is no climate policies in region 2, the consumption tax v^{1**} that maximizes global welfare (8) is given by (see Appendix A):

$$v^{1**} = \left(\frac{\partial \bar{y}^1}{\partial v^1} \right)^{-1} \left[s^1 \frac{\partial y^1}{\partial v^1} + \tau \left(\frac{\partial e^{y2}}{\partial y^2} \frac{\partial y^2}{\partial v^1} + \frac{\partial e^{z2}}{\partial z^2} \frac{\partial z^2}{\partial v^1} \right) \right] > 0\,. \tag{9}$$

We observe that equation (9) is equal to equation (6) when terms-of-trade effects are zero. Thus, we have the following result:

Proposition 2. *Consider a region that combines a Pigouvian tax on emissions with an exogenous subsidy to production of an emission-intensive, tradable good y. Assume no climate policies outside this region. If the regulator in the region maximizes global welfare, then the optimal consumption tax on good y in this region is unambiguously positive.*

Proof. *The proposition follows from equation (9), and the discussion of the sign of equation (6) above (including condition (7)).*

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[15] For example, in Böhringer et al. (2014a), a coalition of countries concerned about leakage chooses the policy that maximizes global welfare. Böhringer et al. (2014b) decomposes leakage and terms-of-trade motives of differential sector-specific emission pricing, as such pricing can be used as a "beggar-thy-neighbor policy" to exploit terms of trade.

Note that this proposition may no longer hold if region 2 has implemented climate policies, too. For instance, if a Pigouvian tax has been imposed in region 2, further emissions reductions may no longer be desirable from a global welfare perspective.

There are some special cases worth elaborating on. To simplify the discussion, we focus on the global welfare perspective in Proposition 2 and equation (9), in which case there is no terms-of-trade effect. First, the optimal consumption tax on good y obviously increases in the OBR subsidy s^1. However, we also observe that the tax is unambiguously positive also without OBR (i.e., $s^1 = 0$). The reason is that reduced domestic demand for good y reduces imports of y, and hence reduces environmental damages from emissions abroad (emissions at home are already accounted for by the emission tax). Thus, in the case where region 1 has implemented (only) a Pigouvian tax, the region should also tax consumption of emission-intensive, tradable goods. We state this finding in the following corollary:[16]

Corollary 1. *Consider a region that has implemented a Pigouvian tax on emissions. Then the optimal consumption tax on an emission-intensive, tradable good y is unambiguously positive if the regulator in region 1 maximizes global welfare.*

Proof. *The corollary follows directly from Proposition 2.*

Next, we see from equation (9) that if production and consumption in region 2 is unaffected by the consumption tax in region 1, e.g. because of no trade between the two regions, the optimal consumption tax is equal to the OBR subsidy, i.e., $v^{1**} = s^1$. It follows that if domestic production and consumption change much more than foreign production and consumption, the optimal consumption tax is close to the OBR-rate. This could be the case if region 1 is much bigger than region 2.

The reason for this result is that the motivation for OBR is to mitigate emission leakage (and loss in competitiveness) induced by unilateral emission regulation. However, the effects of this policy are not only to shift market shares towards the domestic firm, but also to stimulate excessive use of this good. Thus, the regulator

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[16] A somewhat related result is found by Eichner and Pethig (2015b), who demonstrate that a combination of production-based (i.e., emission) and consumption-based taxes is less expensive than a production-based tax alone.

would want the consumption tax to reduce the demand for good *y*. In this special case, when impacts in region 2 are negligible compared to in region 1, the optimal consumption tax completely offsets the distortion caused by the OBR subsidy. The intuition is straightforward: leakage is not an important issue when the domestic region is much larger than the foreign region. Hence, introducing OBR is not a good idea in the first place, and the optimal consumption tax negates the effects of OBR.

The same result holds if the size of region 2 is more comparable with region 1, but both production and consumption in region 2 are insensitive to the climate policy in region 1. In our model with homogenous goods, this would be the case if, e.g., both the marginal cost and marginal utility for good *y* in region 2 are very steep. In a model with heterogeneous goods (cf. Corollary 4 below, and the simulations in Section 3), the substitution elasticities between domestic and foreign goods are also important for how sensitive foreign consumption and production are to the domestic climate policy.

In policy practice, it may be difficult to determine how exposed a sector really is to leakage and, correspondingly, whether or not it should be included in an OBR regime. The above results suggest that a policy which combines OBR with a consumption tax is more robust with respect to uncertainties about leakage than OBR alone. The reason is that, because the consumption tax offsets the distortive effects of the output subsidy, the negative consequences of including too many sectors in an OBR-regime are reduced when the consumption tax is added.

Intuitively, the welfare gains of supplementing OBR with a consumption tax will tend to be higher the less exposed to leakage a sector is. Leakage exposure is not formally defined in our model framework, but one indicator of exposure is to what degree reduced domestic consumption leads to increased consumption abroad (as opposed to decreased global production). By making two simplifying assumptions, we can then show the following result:

Corollary 2. *Consider a region that has implemented a Pigouvian tax on emissions combined with 100% OBR (* $s^1 = t^1 e^{y1} / y^1$ *). Assume that the y and z goods are not substitutes in region 2, i.e.,* $d\bar{z}^2 / d\bar{y}^2 \geq 0$*, and that* $e^{y1} / y^1 = \partial e^{y2} / \partial y^2$ *. Then the* *global welfare gains of reducing consumption of good y in region 1 with one unit, by introducing a consumption tax v^1, is higher the less consumption of good y in region 2 increases.*

Proof. *See Appendix A.*

Thus, the more the consumption tax is able to reduce overall production rather than shifting consumption abroad, the more valuable is the consumption tax. However, the optimal level of the consumption tax may not necessarily be highest in this case. In the simulations in Section 3, where we vary the Armington elasticities as indicators of trade exposure, the optimal consumption tax is in the range 80-100% when global welfare is maximized.

In Corollary 2 we assumed 100% OBR, which is a policy-relevant case (see e.g. the discussion in section 2.1). As shown in Appendix A, the optimal consumption tax will then tend to be lower than the subsidy ($v^{1**} < s^1$) if the emissions intensities of good y are quite similar in the two regions. That is, contrary to the special case with no leakage, the regulator does not wish to completely offset the OBR subsidy, because the tax also stimulates consumption in region 2 (cf. Corollary 2). On the other hand, if the emissions intensity is highest in region 2, v^{1**} is not necessarily lower than s^1, and could in fact be higher if the emissions intensity in region 2 is significantly higher than in region 1 *and* the consumption tax affects global production more than consumption in region 2.

2.3 Equivalence between border carbon adjustment and OBR with consumption tax

In this subsection we show that the combination of OBR and consumption tax on good y is equivalent to a certain specification of border carbon adjustment (BCA) on good y (assuming that a given emission tax is in place). Let π^1 denote the carbon tariff on imports of good y to region 1, and let γ^1 denote the export rebate to exports of good y from region 1. We still assume no climate policy in region 2, so that $\gamma^2 = \pi^2 = t^2 = 0$.

A carbon tariff is an import tariff on the embodied carbon in the imported good, proportional to the emission price in the importing region. Ideally, the tariff should reflect the emission intensity of the exporting firm, giving this firm an incentive to reduce emissions. However, such a system may be difficult and costly to implement, and hence analysis of carbon tariffs usually assume that the tariff is determined based on some average emission intensity. This average can either be the average emission intensity in the exporting region (which could be differentiated across regions if there were more than one export region), or the average emission intensity in the importing region.[17] Ismer and Neuhoff (2007) and Monjon and Quirion (2011b) argue that uniform tariffs, i.e., tariffs that do not differentiate across exporting countries, are more likely to be compatible with the WTO rules, and this is what we consider here. Initially, we base the tariff on the emission intensity in the import region, i.e., $\pi^1 = t^1 e^{y1} / y^1$. Export rebates under BCA proposals are usually set equal to $\gamma^1 = t^1 e^{y1} / y^1$, so the export rebate and the carbon tariff are equal in this case. Moreover, we notice that $\gamma^1 = \pi^1 = s^1$ in the case of 100% OBR.

The maximization problems for producers of goods *x* and *z* under BCA are equal to the OBR case. Hence, their first-order conditions are as given in equation (2). Producers of good *y* in region *j* maximize profits:

$$\max_{y^{1j}, y^{2j}, e^j} \left[\left(p^{y1} - \pi^i \right) y^{1j} + \left(p^{y2} + \gamma^j \right) y^{2j} - c^{yj}(\mathrm{y}^j, \mathrm{e}^{yj}) - t^j e^{yj} \right] ,$$

where *i≠j*. This gives the following first-order conditions for an interior solution:

$$\text{(10)} \qquad \begin{aligned} & p^{y1} = p^{y2} + \gamma^1 = c_y^{y1} \quad ; \quad p^{y1} - \pi^1 = p^{y2} = c_y^{y2} \\ & -c_e^{y1} = t^1 \quad ; \quad c_e^{y2} = 0 \end{aligned} .$$

For producers in region 1, the net price at home and abroad are p^{y1} and $p^{y2} + \gamma^1$, respectively, while for producers in region 2, the net price at home and abroad are p^{y2} and $p^{y1} - \pi^1$, respectively. An interior solution requires equal net prices on exports and domestic sales, implying $p^{y1} = p^{y2} + \gamma^1$ and $p^{y2} = p^{y1} - \pi^1$. That is,

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[17] Both these variants are examined in the literature (see, e.g., Böhringer et al., 2012b; Kuik and Hofkes, 2010; and Mattoo et al., 2009).

the price in region 1 must exceed the price in region 2 by the amount $\gamma^{y1} = \pi^1$. Notice that if we had specified the carbon tariff differently, so that $\gamma^1 \neq \pi^1$, we would not have an interior solution in this model with homogenous goods.[18]

The consumer utility maximization problem is similar as under OBR and a consumption tax, but with $v^j = 0$ in (3). The budget constraint under BCA is still given by equation (4), where p^y denotes the international price of good *y* and also the price in region 2 ($p^y \equiv p^{y2}$). The first-order conditions for good *y* in (2), (3) and (10) may then be rewritten as in Table 1.

Table 1. First-order conditions for good *y* under unilateral regulation

	OBR+Consumption Tax	*BCA*
Production	$p^y + s^1 = c_y^{y1}$; $p^y = c_y^{y2}$	$p^y + \gamma^1 = c_y^{y1}$; $p^y = c_y^{y2}$
Abatement	$-c_e^{y1} = t^1$; $c_e^{y2} = 0$	$-c_e^{y1} = t^1$; $c_e^{y2} = 0$
Consumption	$u_y^1 = p^y + v^1$; $u_y^2 = p^y$	$u_y^1 = p^y + \pi^1$; $u_y^2 = p^y$

In addition, equilibrium requires the market equilibrium condition (1) and the budget constraint (4) to hold under both types of regulation. It is also straightforward to see that net government revenues are the same in the two cases. We then have:

Proposition 3. *The two types of regulation i) emission tax with OBR and consumption tax, and ii) emission tax with BCA as specified above, induce equal production, consumption and emissions in both regions if* $v^1 = s^1 = \pi^1 = \gamma^1$.

Proof. *According to Table 1, all first-order conditions for good y are equal. Moreover, first-order conditions (2) and (3) for the goods x and z are equal, too. Market equilibrium conditions and budget constraints for all goods are given by*

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[18] In a model with heterogeneous goods, interior solution is feasible also when the carbon tariff deviates from the export rebate. However, equivalence still requires that these are identical, see (the proof of) Corollary 4 and the numerical analysis in Section 3.

equations (1) and (4), respectively, in both cases. The second-order conditions put identical constraints on the cost and utility functions under both types of regulations. The proposition follows.

Proposition 3 implies that under certain conditions, combining output-based rebating with a consumption tax has the same effect as full border carbon adjustment. As BCA is regarded as more contentious, though more effective than OBR, combining OBR with a consumption tax can be a viable policy alternative to implementing BCA.

In the discussion leading up to Proposition 3, we assumed that the carbon tariff is determined based on the emission intensity in region 1. However, it is straightforward to see that the proposition also may hold for different levels of carbon tariffs, *given that the export rebate is equal to the tariff.* Then by adjusting the OBR rate and the consumption tax accordingly, the equivalence still holds. The only requirement is that $v^1 = s^1 = \gamma^1 = \pi^1$. Thus, if the regulator in region 1 would like to impose a higher carbon tariff (and export rebate), e.g., if emission intensities abroad are higher than at home, or a lower tariff if the foreign region has also implemented climate policy (but weaker than in region 1), the same result can be achieved by imposing a combination of OBR and consumption tax. We state this generalization as a separate corollary:

Corollary 3. *The two types of regulation i) emission tax with OBR and consumption tax, and ii) emission tax with BCA, are equivalent for any level of carbon tariff as long as* $v^1 = s^1 = \pi^1 = \gamma^1$.

Proof. *The proof follows from the proof of Proposition 3.*

With more than two regions, it is straightforward to show that the equivalence result still holds as long as only uniform carbon tariffs are considered. If region 1 would like to differentiate the tariff across exporting regions, e.g., if emissions intensities differ or if some but not all regions have imposed climate policies, the equivalence result no longer holds. As mentioned above, however, differentiated tariffs are less likely to be compatible with WTO rules (Monjon and Quirion, 2011b).

Whereas the motivation for OBR and BCA typically is to mitigate carbon leakage through the international product markets, the assumption that the good *y* is homogeneous and independent of region of origin is unrealistic for many emission-intensive and trade-exposed goods. Moreover, with several EITE goods exposed to leakage, these will typically have different carbon tariffs in a BCA system. It is straightforward to show that Propositions 1-3 above carry over to the case with several heterogeneous EITE-goods. For the equivalence result in Proposition 3, this requires that the output-based rebating is good specific, i.e., emission payments from the production of one specific good is rebated back to producers of this specific good. We state these findings in the following corollary:

Corollary 4. *Consider the case with* $m = \left\{1, 2, ..., M\right\}$ *EITE goods denoted* y_m*, where each good is produced in both regions, and goods produced in different regions are imperfect substitutes. Then we have the following:*

- *The optimal consumption tax on good* y_m *is unambiguously positive if the regulator in region 1 maximizes global welfare.*
- *The two types of regulations i) emission tax with OBR and consumption tax, and ii) emission tax with BCA as specified above, are equivalent if* $v_m^1 = s_m^1 = \pi_m^1 = \gamma_m^1$.[19]

Proof. *See Appendix A.*

In the numerical simulations below we will consider both homogenous and heterogeneous EITE-goods, but restrict ourselves to the case with one EITE-good in each region. Whereas the analytical results state that the optimal consumption tax is positive, the numerical analysis can provide more insight into the size of the optimal consumption tax, the magnitude of the welfare gains, and the importance of substitutability between domestic and foreign EITE goods.

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[19] v_m^1, s_m^1, π_m^1 and γ_m^1 denote the consumption tax, the output subsidy, the carbon tariff and the export rebate on good y_m in region 1, respectively.

3. Stylized Numerical Analysis

We transfer our theoretical analysis to numerical simulations with a stylized computable general equilibrium (CGE) model to accommodate more functional (real-word) complexity to gain insights into the magnitude of economic effects based on empirical data. First, we summarize the main characteristics of the numerical model in a non-technical manner (see Appendix B for an algebraic model summary). We then discuss the parameterization of the model based on empirical data. Finally, we describe the specification of policy scenarios and interpret the simulation results.

3.1 Non-technical model summary

We consider two regions (1 and 2) with four production sectors: carbon-free and tradable production (*NC_T*), carbon-intensive and tradable production (*C_T*), carbon-intensive and non-tradable production (*C_NT*), and fossil energy production (*FE*). Sectors *NC_T*, *C_T*, and *C_NT* correspond to the goods x, y and z, respectively, in our theoretical model of Section 2. In the numerical model, these goods can be used both as intermediate inputs into production and in final consumption. Emissions are modelled as proportional to energy use. To keep in line with the analytical model, energy can neither be used in final consumption nor can it be traded between regions. Thus, we implicitly suppress the fossil-fuel channel for carbon leakage, as we want to focus on the competitiveness channel examined in the theoretical analysis.

Primary factors of production include labor, capital, and specific energy resources. Labor and capital are intersectorally mobile within a region but immobile between regions. The energy resource is specific to the energy production sector.

Producers combine primary factors and intermediate inputs at minimum cost subject to technological constraints. Production of non-energy goods is captured by three-level constant-elasticity-of-substitution (CES) cost functions describing the price-responsive demand for capital, labor, energy and other intermediate inputs. At the top level, non-energy intermediate inputs trade off with a composite of energy, capital and labor, subject to a constant elasticity of substitution. At the second level, a CES function describes the substitution possibilities between energy and a value-added composite of labor and capital. At the third level, capital and labor enter the CES value-added composite. In the production of energy, all inputs except for the specific energy resource are combined in fixed proportions. This Leontief composite trades off with the energy resource at a constant elasticity of substitution.

Final consumption demand in each region is determined by the representative agent who maximizes welfare subject to a budget constraint. Total income of the representative household consists of factor income and net revenues from emission regulation. Consumption demand of the representative agent is given as a CES composite of final consumption goods. Figures B1-B3 in Appendix B sketch the nesting of functional forms in production and consumption together with the default elasticities underlying our central case simulations.

As emissions are linked in fixed proportions to the use of energy, emission reductions in response to emission pricing will take place by energy savings. The latter can take place either through substitution of energy through other non-energy inputs or through scale reduction of production and final demand activities.

Only the two goods *C_T* and *NC_T* can be traded bilaterally (with no transport cost). A balance of payment constraint incorporates the base-year trade deficit or surplus for each region. The stylized model can reflect two alternative trade paradigms – either trade in homogeneous goods or trade in heterogeneous goods. In case of heterogeneous goods, we follow Armington's differentiated goods approach, where domestic and foreign goods are distinguished by origin (Armington, 1969). All goods used on the domestic market in intermediate and final demand correspond to a CES composite that combines the domestically produced good and the imported good from the other region. The size of the (Armington) substitution elasticities determine how close substitutes goods produced in different regions are. In case of homogeneous trade, only net trade flows matter such that there is no crosshauling.

3.2 Data and parametrization

We adopt the standard calibration procedure in applied general equilibrium analysis in which a balanced base-year dataset determines the free parameters of the functional forms (i.e., cost and expenditure functions) such that the economic flows represented in the data are consistent with the optimizing behavior of the economic agents.

To have the stylized numerical analysis closely related with our theoretical exposition, we restructure an empirical dataset in line with the fundamental settings of the theoretical part. Our dataset is based on the most recent GTAP data for the world economy (base-year 2011) with 57 sectors and 140 regions. We first map all 57 GTAP sectors to the four composite sectors in our model (see Table C1 in Appendix C). Then we construct a social accounting matrix (SAM) for the global economy based on the GTAP data. Since the *NC_T* good is assumed to be carbon-free, we set (fossil) energy use in this sector equal to zero.[20]

Next, we divide the world into two identical regions to follow the symmetry assumption in the theoretical analysis.[21] Thus, each entry in the SAM for region *j* is half of the corresponding entry in the global SAM. As there is no trade in the global SAM, we have to make an assumption about initial trade volumes between the two regions. For each of the two goods *C_T* and *NC_T* we simply assume that 50% of the trade observed in 2011 (according to the GTAP data) takes place between regions 1 and 2. As mentioned before, we assume no trade for *C_NT* and *FE*. The derived SAM for each region is displayed in Table C2 in Appendix C.

3.3 Scenarios

Our reference scenario (*REF*) for unilateral climate policy is a situation where a single country (or country coalition) – here: region 1 – undertakes uniform emission pricing to achieve an exogenous domestic emission reduction target,[22] which we set at 20 percent of the base-year emissions. We use the stylized numerical model to quantify how the *REF* outcome changes if the region adopts in addition either full border carbon adjustment (*BCA*), or output-based rebating combined with a consumption tax (*OBR+Tax*). In both cases, the additional policies are directed only towards the emission-intensive and trade-exposed good *C_T*. In the *BCA* case, the carbon tariff and the export rebate are determined based on the domestic emission intensity (see Section 2). In the *OBR+Tax* case, we assume full rebating (100% OBR) and consider different levels of the consumption tax, which is applied to both final consumption

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[20] In the original GTAP dataset, this sector only accounts for 3-4% of total fossil energy use.

[21] This implies that there are no terms-of-trade effects at the margin (before any policy is implemented).

[22] Uniform emission pricing to achieve some emission reduction target can either be implemented through an emission tax which is set at a sufficiently high level or equivalently through an emissions cap-and-trade system.

and intermediate use of the *C_T* good. We indicate the different levels of the consumption tax as a fraction *v* of the OBR rate where we increase *v* subsequently in steps of 20 percentage points from 0% to 200%. Obviously, *OBR+Tax* includes output-based rebating stand-alone as a special case when we set the consumption tax to zero (*v*=0%). As demonstrated in our theoretical analysis (see Proposition 3 and Corollary 4), *OBR+Tax* is equivalent to *BCA* when the consumption tax is set equal to the implicit output subsidy under output-based rebating (*v*=100%).

Table 4. Policy scenarios for region 1

REF	Emission price only
OBR+Tax	Output-based rebating + consumption tax for the carbon-intensive and tradable good (*C_T*)
BCA	Border carbon adjustment

Considering that the climate is a global public good, a coherent cross-comparison of results requires that we keep global emissions constant unless we can value the damage from emissions. Here, we do not attempt to trade off the abatement cost with the benefit from avoided climate change but restrain ourselves to a cost-effectiveness analysis. Therefore, we require the abating region to adjust its unilateral emissions reduction effort such that a given global emission cap is maintained. The cap is taken as the global emission level which emerges from scenario *REF*. If additional policy measures such as *OBR+Tax* turn out to reduce leakage compared to *REF*, then the effective unilateral emission reduction requirement will be lower than the *REF* target.

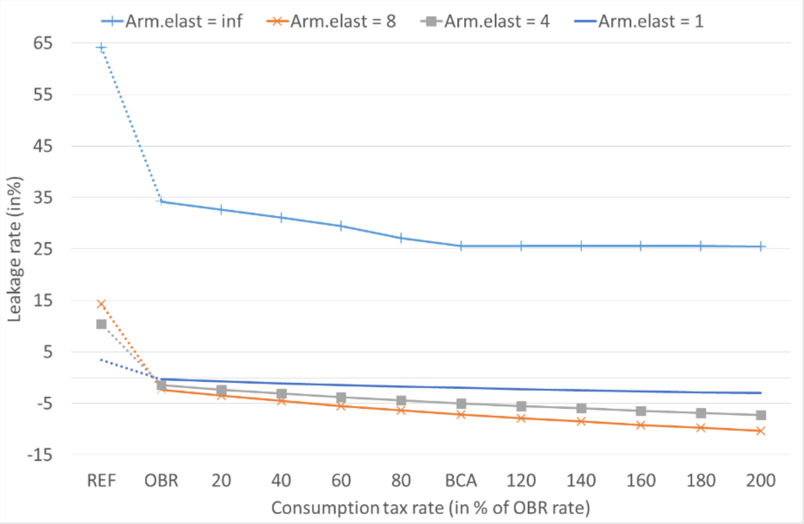
A key parameter regarding the magnitude of emission leakage through the competitiveness channel is the Armington elasticity, which determines the ease of substitution between the domestically produced good and its foreign counterpart. The higher this elasticity, the more pronounced leakage becomes. To investigate the robustness of our findings, we provide simulation results for alternative choices of the Armington elasticity ranging from a lower end value of 1, via the benchmark GTAP elasticity of 4, to an upper end value of 8. For an infinite Armington elasticity the heterogeneous goods setting transforms into the case of homogenous goods.

3.4 Results

In our results discussion, we first check if the equivalence result between *BCA* and *OBR+Tax* holds (when *v*=100%). We then investigate changes in leakage rates, welfare, and production output as the key indicators of policy interest. The leakage rate is defined as the ratio of the emission change in the non-abating region over the emission reduction in the abating region. Welfare effects are defined as Hicksian equivalent variation (HEV) in income as a percentage of the pre-policy equilibrium levels – the so-called business-as-usual (*BAU*).

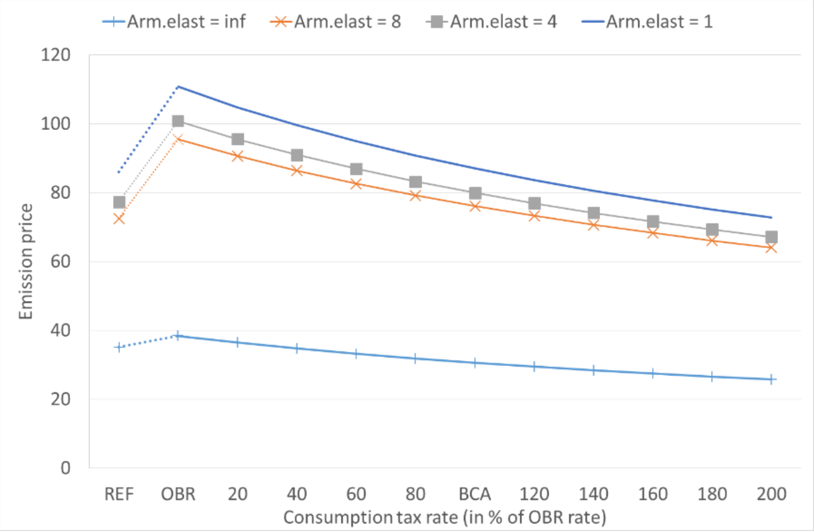
We find that the numerical results are in accordance with the equivalence results in Proposition 3 and Corollary 4. That is, given emissions pricing (tax or quotas), the combination of output-based rebating and a consumption tax equal to the OBR rate (*OBR+Tax* with *v*=100%) gives exactly the same outcome as border carbon adjustment (*BCA*). This equivalence result is robust independent of whether we assume homogenous or heterogeneous goods (with various Armington elasticities).

Figure 1. Leakage rates under different policy scenarios and Armington elasticities (in %)



Next we turn to leakage mitigation which is a central policy justification for supplementing unilateral emission pricing with *OBR* or *BCA*. Previous studies have suggested that *BCA* is more effective in leakage mitigation than *OBR*. Figure 1 shows how the combination of *OBR+Tax* affects leakage across alternative choices of the Armington elasticity as we increase the consumption tax from 0% to 200% of the OBR rate (note that *v*=0% and *v*=100% are replaced with respectively *OBR* and *BCA* in all figures). As expected, leakage rates go up with higher Armington elasticities, and becomes very high with homogenous goods. Further, Figure 1 clearly shows that introducing *OBR* reduces the leakage rate significantly, and more so the higher is the Armington elasticity. The leakage rates in fact become negative in all three cases with heterogeneous goods.[23] Next, we notice that the consumption tax decreases leakage further: When the consumption tax rate is set equivalent to the OBR rate (*BCA*) the leakage rate drops by another 2-9 percentage points compared to *OBR*. We also see that leakage is further reduced when the consumption tax is increased beyond 100%.

Figure 2. Emission price under different policy scenarios and Armington elasticities (in Euro per ton CO$_2$)



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[23] This is because we deliberately suppress the fossil-fuel channel in our analysis, which makes leakage rates rather low to start with in the *REF* scenario (relative to most numerical analysis featuring both the competitiveness and the fossil-fuel channel), and explains why anti-leakage measures have a strong potential to drive leakage negative. If we include the fossil fuel channel by allowing for trade in energy, none of our qualitative findings changes.

As mentioned before, a main difference between *OBR* and the consumption tax is that the former stimulates domestic supply while the latter dampens domestic demand. Hence, *OBR* tends to increase domestic emissions, while the consumption tax has the opposite effect. Figure 2 shows the endogenous emission prices needed to reach the same global emission target (across policy scenarios for a given choice of Armington elasticity). Although *OBR* leads to lower leakage (as shown in Figure 1), the first order effect of higher domestic output of the *C_T* good dominates with respect to global emissions, implying a higher necessary emission price under *OBR* than under *REF*. If the consumption tax is introduced, however, a lower emission price is needed.

In Figure 3 we show how the policies affect economic welfare in region 1. Since we assume that global emissions are the same across all policy scenarios, we do not have to value emission changes. We first notice that the welfare effects of *OBR* are positive in the case of homogenous goods. In this case, the implicit subsidy given by *OBR* reduces the inefficient relocation of production from region 1 to region 2. On the other hand, if the substitution possibilities between domestic and foreign goods are more limited, then the distortionary negative effect of subsidising this good becomes more important and dominates the former positive effect. In all the three cases with heterogeneous goods, the welfare cost for region 1 increases rather than decreases when shifting from emission pricing only (*REF*) to emission pricing combined with *OBR* (but only marginally with the Armington elasticity at a value of 8).

Figure 3. Welfare effects (HEV) for region 1 under different policy scenarios and Armington elasticities (% change from business-as-usual)

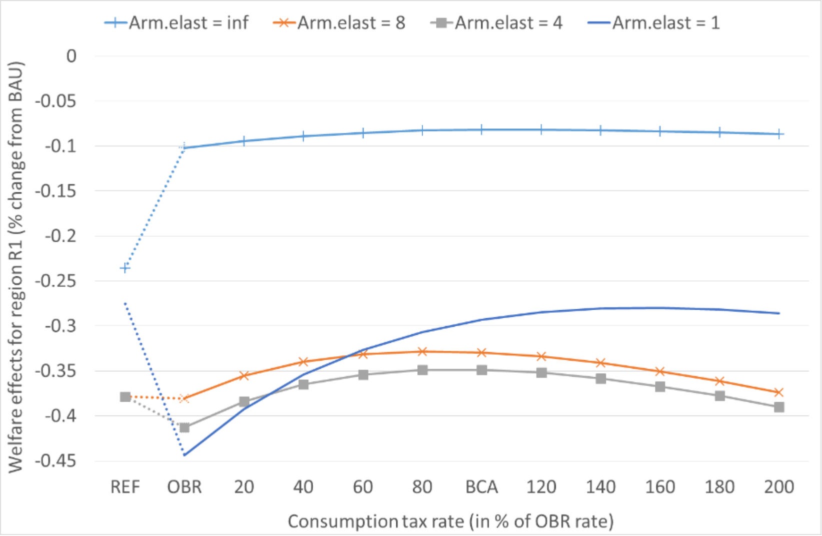

Figure 3 furthermore shows that it is welfare improving for region 1 to implement a consumption tax when output-based rebating is already in place, which is in line with Proposition 1 of our theoretical analysis. This holds irrespective of the choice of Armington elasticity. The optimal consumption tax level is in the range 80-160% of the OBR-rate in the simulated cases. With homogenous goods, the benefits of the consumption tax are rather modest. With heterogeneous goods, the benefits are more pronounced, and more so the lower is the Armington elasticity. In the case with Armington elasticity equal to 1, the welfare costs are reduced by one third when *OBR* is supplemented with a consumption tax of 100% of the OBR-rate (i.e., the *BCA* case). If the consumption tax is increased to 160%, the welfare costs are approximately the same as in the *REF* case, i.e., emission pricing only.

The numerical results provide evidence that *OBR* may serve as a decent second-best policy for goods that are much exposed to foreign competition, due to high substitutability between domestic and foreign goods, but not so for goods that are less exposed. Moreover, supplementing *OBR* with a consumption tax is beneficial whether or not the good is much exposed to foreign competition. Thus, when output-based rebating is applied to a certain group of goods, our policy-relevant conclusion is to also introduce a corresponding tax on all purchases of the same goods.

A relevant question to ask is whether the findings in Figure 3 are due to efficiency improvements, or whether it is due to terms-of-trade benefits for region 1 at the expense of region 2. Although we start from an initial *BAU* situation with no net trade in either of the tradable goods, the *REF* scenario is characterized by net export of the *C_T* good from region 2 to region 1 (and vice versa for the *NC_T* good). As both *OBR* and the consumption tax reduce the relative price of the *C_T* good (over the *NC_T* good), terms-of-trade effects for region 1 are positive as we move towards the right from *REF* in Figure 3. In order to examine this more closely, we first consider the case where region 1 must provide a transfer to region 2 so that welfare in the latter region does not decrease vis-à-vis the *REF* case. The qualitative findings are then very similar to the ones in Figure 3, i.e., the optimal consumption tax is in the range 80-140%, and the welfare gains increase notably as we lower the Armington elasticity.

Next, we consider the effects on global welfare.[24] According to Proposition 2, introducing such a tax should also be beneficial from a global perspective. Figure 4 shows the global welfare cost of the different policies. We notice that *OBR* increases global welfare cost across alternative values for Armington elasticities, except in the case with homogenous goods. This is similar to findings in Figure 3 for region 1. Next, we see that introducing a consumption tax in addition to *OBR* reduces global welfare cost in all four cases, which is in accordance with Proposition 2. The lowest welfare cost is obtained when the consumption tax is in the range 80-100% of the OBR rate, i.e., close to the *BCA*-equivalent rate. This holds irrespective of how close substitutes domestic and foreign goods are (including the homogenous goods case).

Figure 4. Global welfare effects (HEV) under different policy scenarios and Armington elasticities (% change from BAU)

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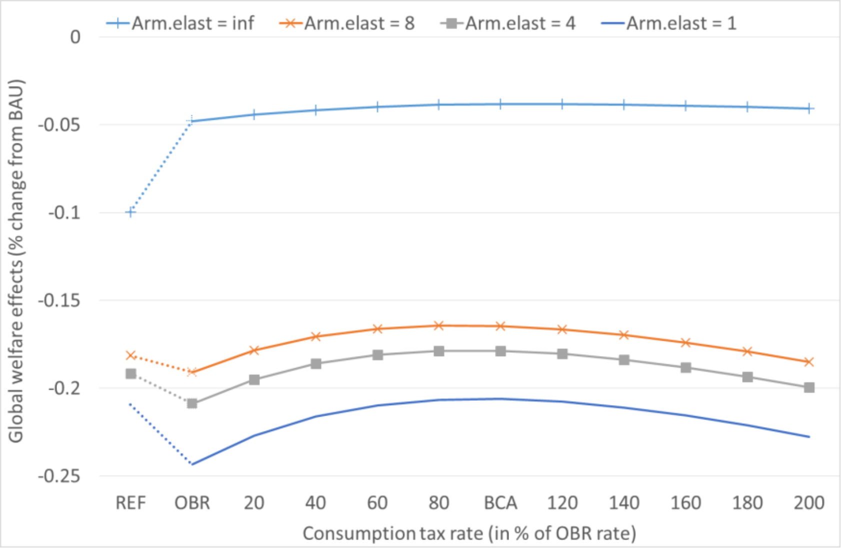
[24] Global welfare accounting is based on a utilitarian (Benthamite) perspective on efficiency where welfare changes of individual regions are treated as perfect substitutes.

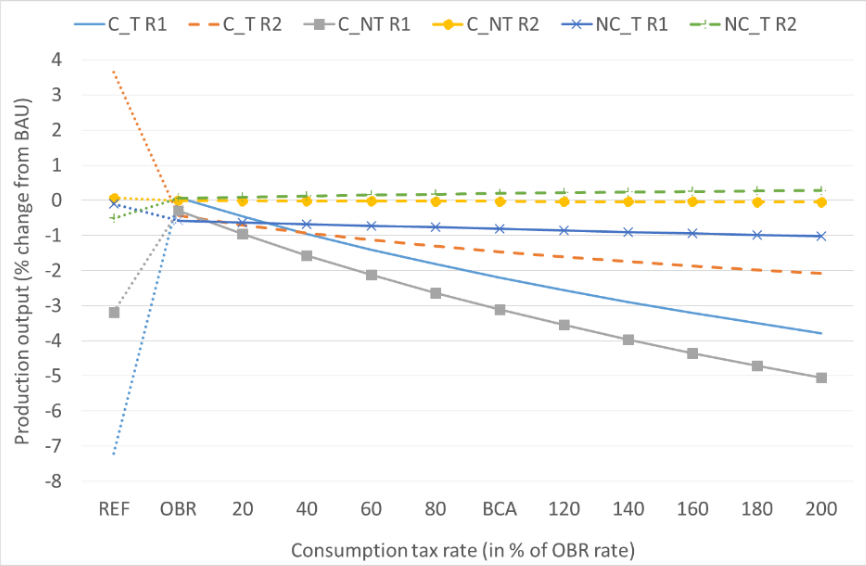


Whereas the consumption tax is advantageous for region 1 and also for the two regions jointly, region 2 is mostly worse off by the consumption tax. This is due to the disadvantageous terms-of-trade effects discussed above.

Finally, we consider how the policies affect production output in the two regions. Output effects are shown in Figure 5 for the case with an Armington elasticity equal to 4. As expected, the emission price (*REF*) reduces output of the two carbon-intensive goods *C_T* and *C_NT* in region 1, and increases output of the good *C_T* in the other region 2. When *OBR* is introduced, the effects on output of the good *C_T* are turned around, as region 1 (2) marginally *increases* (*decreases*) its output compared to the *BAU* level (see the negative leakage rates in Figure 1). When the consumption tax is introduced on the good *C_T* in region 1, we observe that output of this good is reduced in both regions.

We see from Figure 5 that also the *C_NT* output in region 1 increases when *OBR* is implemented for the good *C_T*, and then decreases when the consumption tax is implemented. The explanation is that the two emission-intensive goods are used quite a lot as intermediate inputs into each other's production (relative to the *NC_T* good), see Table C2 in Appendix C. Thus, when the *C_T* production is stimulated by the *OBR* policy, this indirectly stimulates *C_NT* production, too (and vice versa with the consumption tax). Output of the carbon-free good *NC_T* in region 1 declines with the implementation of the emission price, and with the introduction of *OBR* as well as the consumption tax. This is partly due to reduced real income in region 1, and partly because production of this good uses the two carbon-intensive goods as inputs.

Figure 5. Production output in regions 1 and 2 under different policy scenarios (% change from BAU)



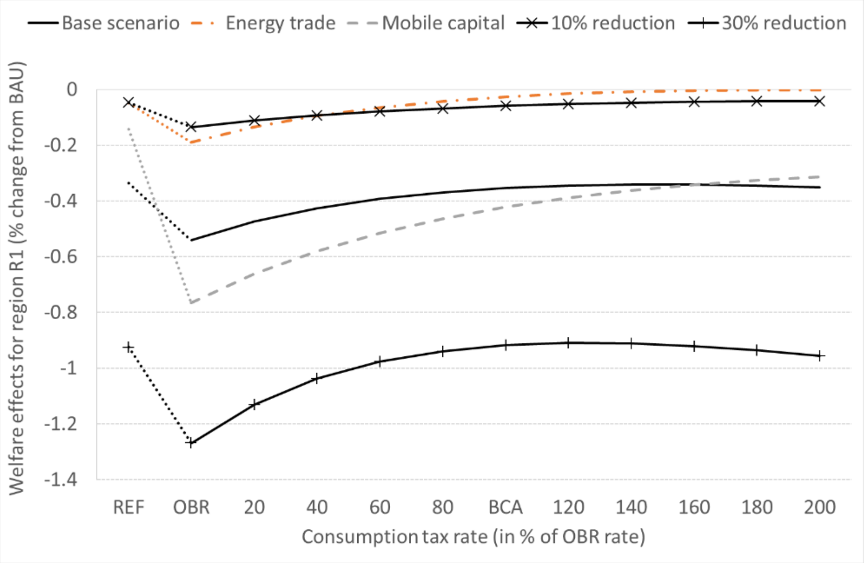
3.5 Sensitivity analysis

A relevant question to ask is to what degree our numerical results are robust with respect to changes in important modeling assumptions. Above we have considered four different Armington elasticities, reflecting uncertainty with respect to leakage exposure. On the one hand, the results show that implementing a consumption tax in addition to OBR increases welfare, irrespective of this elasticity, i.e., confirming our analytical results. On the other hand, the simulations illustrate that the welfare gains of such a tax is highest when OBR has been implemented for sectors that are little exposed to leakage, also consistent with the theory section.

We now want to examine the effects of changing the following assumptions: i) capital fully mobile across regions, ii) trade in energy between regions, and iii) emission reductions of respectively 10% and 30%. In the base scenarios, we have assumed immobile capital across regions, no energy trade between regions, and an emission reduction of 20%. We will focus on welfare effects in region 1, and the case with Armington elasticity equal to 1, but will briefly refer results for global welfare, leakage, and other Armington elasticities at the end of this section.

Figure 6 shows the results of the sensitivity analysis, where *Base scenario* is the same as in Figure 3 (for Armington elasticity = 1). We notice that region 1's welfare is consistently increasing when the consumption tax is introduced, and that the optimal level of the tax is 120% of the OBR rate or higher. In three of the four sensitivity cases, the optimal tax is higher than in the *Base scenario*, and in fact at least 200% of the OBR rate. The welfare gains are particularly high in the case with fully mobile capital (the optimal tax is then 280% in the simulations). In this case, the OBR stimulates domestic production of the *C_T* good much more than in the base scenario as it attracts capital also from the foreign region, and global output of *C_T* is in fact higher than in *BAU*. As shown in Figure 6, this has adverse welfare effects for region 1, and the consumption tax mitigates the negative effects of the OBR. Allowing for energy trade between regions reduces the welfare costs of climate policy in region 1, and with a consumption tax around 200% of the OBR rate the welfare costs for this region become close to zero.

Figure 6. Welfare effects (HEV) for region 1 under different policy scenarios and different modeling assumptions (% change from business-as-usual)



With different Armington elasticities, the qualitative welfare results are still the same, that is, welfare in region 1 as well as global welfare increase when the consumption tax is introduced. In all the performed sensitivity analysis, the optimal consumption tax is always at least 80%, both from region 1's perspective and from a global perspective. Carbon leakage is generally decreasing with the consumption tax, except in the case with mobile capital when leakage increases with the tax except when the Armington elasticity is equal to 1. The increased leakage is due to slightly higher output of both *C_T* and *C_NT* in region 2 when the consumption tax is implemented in region 1.

4. Concluding remarks

In the absence of world-wide cooperation to mitigate global warming, many countries consider or have introduced unilateral climate policies. This causes carbon leakage associated with the relocation of emission-intensive and trade-exposed (EITE) industries. Economic theory and numerical studies suggest that border carbon adjustment, in addition to emission pricing, can be used as a second-best instrument to improve cost-effectiveness of unilateral climate policy. However, as carbon tariffs and export rebates are politically contentious to implement, policy makers have typically chosen other instruments such as variants of output-based rebating to EITE industries.

A prime example for output-based rebating is the EU Emission Trading System (EU ETS) where emission allowances are allocated to EITE industries conditional on output. Martin et al. (2014) find that there has been substantial overallocation of allowances in the EU ETS for the given carbon leakage risk. As the optimal allocation scheme relies on data that are not publicly observable, they propose a more “feasible” allocation scheme based on easily observable characteristics of firms such as employment and historic CO_2 emissions.

Our paper suggests an alternative strategy, namely to combine output-based rebating to production of EITE goods with a consumption tax on all use of the same EITE goods. We have shown analytically that it is welfare improving for a region to introduce such a consumption tax if output-based rebating is already in place. The theoretical result is confirmed when using a stylized numerical general equilibrium model calibrated to data for the world economy, highlighting that the welfare gains from such consumption taxes can be substantial. The administrative cost of adding such a consumption tax is likely to be moderate as the tax level could be set in proportion to the benchmarks already set by the emission allocation mechanisms in place. It is also important to realize that the addition of consumption taxes makes output-based rebating more robust with respect to uncertainties and political economy risks about leakage exposure: The distortive effects of allowance overallocation – by including too many sectors with limited carbon leakage risk or warranting too high rebates – are moderated.

Regarding political feasibility of anti-leakage policies, we have shown that a certain combination of output-based rebating and a consumption tax is equivalent to full border carbon adjustment as long as the carbon tariffs (and the export rebate) are not differentiated across importers. Thus, whereas border carbon adjustment may be politically contentious to introduce under current WTO rules, the same outcome can in fact be achieved by supplementing output-based rebating with a consumption tax.

We thus conclude that supplementing output-based rebating with a consumption tax constitutes a robust policy to mitigate carbon leakage: Compared to output-based rebating stand-alone it improves cost-effectiveness of unilateral climate policy; compared to border carbon adjustment it limits the risks of detrimental trade disputes.

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Appendix A: Proofs and derivations – For Online Publication

Proof of Lemma 1:

Differentiating welfare (5) with respect to the consumption tax we get:

$$\begin{aligned}(11)\qquad &\frac{\partial W^1}{\partial v^1}=u_x^1(\cdot)\frac{\partial \overline{x}^1}{\partial v^1}+u_y^1(\cdot)\frac{\partial \overline{y}^1}{\partial v^1}+u_z^1(\cdot)\frac{\partial \overline{z}^1}{\partial v^1}-c_x^{x1}(\cdot)\frac{\partial x^1}{\partial v^1}-c_y^{y1}(\cdot)\frac{\partial y^1}{\partial v^1}-c_z^{z1}(\cdot)\frac{\partial z^1}{\partial v^1}\\ &-\left(c_e^{y1}(\cdot)+\tau\right)\frac{\partial e^{y1}}{\partial v^1}-\left(c_e^{z1}(\cdot)+\tau\right)\frac{\partial e^{z1}}{\partial v^1}-\tau\left(\frac{\partial e^{y2}}{\partial v^1}+\frac{\partial e^{z2}}{\partial v^1}\right)\end{aligned}$$

By using the first-order conditions (2) and (3) we can simplify this equation:

$$\begin{aligned}&\frac{\partial W^1}{\partial v^1}=p^x\left(\frac{\partial \overline{x}^1}{\partial v^1}-\frac{\partial x^1}{\partial v^1}\right)+\left(p^y+v^1\right)\frac{\partial \overline{y}^1}{\partial v^1}-\left(p^y+s^1\right)\frac{\partial y^1}{\partial v^1}+p^z\left(\frac{\partial \overline{z}^1}{\partial v^1}-\frac{\partial z^1}{\partial v^1}\right)\\ &-\left(\tau-t^1\right)\frac{\partial e^{y1}}{\partial v^1}-\left(\tau-t^1\right)\frac{\partial e^{z1}}{\partial v^1}-\tau\left(\frac{\partial e^{y2}}{\partial v^1}+\frac{\partial e^{z2}}{\partial v^1}\right)\end{aligned}$$

In addition, from (4), we must have:

$$(12)\qquad \frac{\partial p^y}{\partial v^1}\left(y^1-\overline{y}^1\right)+p^y\left(\frac{\partial y^1}{\partial v^1}-\frac{\partial \overline{y}^1}{\partial v^1}\right)+\frac{\partial p^x}{\partial v^1}\left(x^1-\overline{x}^1\right)+p^x\left(\frac{\partial x^1}{\partial v^1}-\frac{\partial \overline{x}^1}{\partial v^1}\right)=0\ \ ;\ \ \frac{\partial z^1}{\partial v^1}=\frac{\partial \overline{z}^1}{\partial v^1}$$

We assume that the emission tax is set equal to the Pigouvian tax, i.e., $t^1=\tau$. Using equation (12) we can then further simplify equation (11):

$$\begin{aligned}\frac{\partial W^1}{\partial v^1}&=p^y\left(\frac{\partial y^1}{\partial v^1}-\frac{\partial \overline{y}^1}{\partial v^1}\right)+\frac{\partial p^y}{\partial v^1}\left(y^1-\overline{y}^1\right)+\frac{\partial p^x}{\partial v^1}\left(x^1-\overline{x}^1\right)+\left(p^y+v^1\right)\frac{\partial \overline{y}^1}{\partial v^1}-\left(p^y+s^1\right)\frac{\partial y^1}{\partial v^1}-\tau\left(\frac{\partial e^{y2}}{\partial v^1}+\frac{\partial e^{z2}}{\partial v^1}\right)\\ &=v^1\frac{\partial \overline{y}^1}{\partial v^1}-s^1\frac{\partial y^1}{\partial v^1}-\tau\left(\frac{\partial e^{y2}}{\partial y^2}\frac{\partial y^2}{\partial v^1}+\frac{\partial e^{z2}}{\partial z^2}\frac{\partial z^2}{\partial v^1}\right)+\frac{\partial p^y}{\partial v^1}\left(y^1-\overline{y}^1\right)+\frac{\partial p^x}{\partial v^1}\left(x^1-\overline{x}^1\right)\end{aligned}$$

where we also used the fact that emissions in region 2 are only affected via production changes of good y and z in region 2. For a given s^1 (from the OBR regulation), we can solve for the optimal v^1 by setting $\partial W^1/\partial v^1=0$. This gives equation (6).

***Sign of first factor in equation (6)*:**

To see that the first factor of (6) is negative, note that equations (2) and (3) imply $u_y^1 - c_y^{y1} = v^1 - s^1$. Because the second order derivatives are non-zero and finite, an increase in v^1 entails that u_y^1 increases and c_y^{y1} decreases when s^1 is constant. This implies $\partial y^{1} / \partial v^1 < 0$ and $\partial y^1 / \partial v^1 < 0$, because $u_{yy}^1 < 0$ and $c_{yy}^1 > 0$.

Derivation of equation (9):

We differentiate equation (8) and follow the steps explained in the proof of Lemma 1:

$$\frac{\partial W^G}{\partial v^1} = \sum_{j=1,2}\left[u_x^j \frac{\partial \overline{x}^j}{\partial v^1} + u_y^j \frac{\partial \overline{y}^j}{\partial v^1} + u_z^j \frac{\partial \overline{z}^j}{\partial v^1} - c_x^{xj} \frac{\partial x^j}{\partial v^1} - c_y^{yj} \frac{\partial y^j}{\partial v^1} - c_z^{zj} \frac{\partial z^j}{\partial v^1} - \left(c_e^{yj} + \tau\right)\frac{\partial e^{yj}}{\partial v^1} - \left(c_e^{zj} + \tau\right)\frac{\partial e^{zj}}{\partial v^1} \right]$$

$$= \sum_{j=1,2}\left[p^x \left(\frac{\partial \overline{x}^j}{\partial v^1} - \frac{\partial x^j}{\partial v^1} \right) + \left(p^y + v^j\right)\frac{\partial \overline{y}^j}{\partial v^1} - \left(p^y + s^j\right)\frac{\partial y^j}{\partial v^1} \right] - \left(\tau - t^1\right)\frac{\partial e^{y1}}{\partial v^1} - \left(\tau - t^1\right)\frac{\partial e^{z1}}{\partial v^1} - \tau\left(\frac{\partial e^{y2}}{\partial v^1} + \frac{\partial e^{z2}}{\partial v^1} \right)$$

$$= \sum_{j=1,2}\left[p^y \left(\frac{\partial y^j}{\partial v^1} - \frac{\partial \overline{y}^j}{\partial v^1} \right) + \frac{\partial p^y}{\partial v^1}\left(y^j - \overline{y}^j\right) + \frac{\partial p^x}{\partial v^1}\left(x^j - \overline{x}^j\right) + \left(p^y + v^j\right)\frac{\partial \overline{y}^j}{\partial v^1} - \left(p^y + s^j\right)\frac{\partial y^j}{\partial v^1} \right] - \tau\left(\frac{\partial e^{y2}}{\partial v^1} + \frac{\partial e^{z2}}{\partial v^1} \right)$$

$$= \sum_{j=1,2}\left[v^j \frac{\partial \overline{y}^j}{\partial v^1} - s^j \frac{\partial y^j}{\partial v^1} + \frac{\partial p^y}{\partial v^1}\left(y^j - \overline{y}^j\right) + \frac{\partial p^x}{\partial v^1}\left(x^j - \overline{x}^j\right) \right] - \tau\left(\frac{\partial e^{y2}}{\partial v^1} + \frac{\partial e^{z2}}{\partial v^1} \right)$$

$$= \sum_{j=1,2}\left[v^j \frac{\partial \overline{y}^j}{\partial v^1} - s^j \frac{\partial y^j}{\partial v^1} \right] - \tau\left(\frac{\partial e^{y2}}{\partial v^1} + \frac{\partial e^{z2}}{\partial v^1} \right) = v^1 \frac{\partial \overline{y}^1}{\partial v^1} - s^1 \frac{\partial y^1}{\partial v^1} - \tau\left(\frac{\partial e^{y2}}{\partial y^2}\frac{\partial y^2}{\partial v^1} + \frac{\partial e^{z2}}{\partial z^2}\frac{\partial z^2}{\partial v^1} \right)$$

We also used $c_e^{y2} = c_e^{z2} = t^2 = s^2 = 0$. Setting $\partial W^G / v^{1,G} = 0$ gives equation (9).

Proof of Corollary 2:

With $s^1 = t^1 e^{y1} / y^1$, $e^{y1} / y^1 = \partial e^{y2} / \partial y^2$, and $v^1 = 0$ initially, we have the following from the derivation of equation (9) above:

$$\frac{\partial W^G}{\partial v^1} = -\tau \frac{e^{y1}}{y^1}\frac{\partial y^1}{\partial v^1} - \tau\left(\frac{\partial e^{y2}}{\partial y^2}\frac{\partial y^2}{\partial v^1} + \frac{\partial e^{z2}}{\partial z^2}\frac{\partial z^2}{\partial v^1} \right) = \tau\left(-\frac{e^{y1}}{y^1}\left(\frac{\partial \overline{y}^1}{\partial v^1} + \frac{\partial \overline{y}^2}{\partial v^1} \right) - \frac{\partial e^{z2}}{\partial z^2}\frac{\partial z^2}{\partial v^1} \right)$$

Assume that the consumption tax is scaled so as to reduce domestic consumption by one unit ($\partial \overline{y}^1 / \partial v^1 = 1$). We then see that the higher is $\partial \overline{y}^2 / \partial v^1$, the lower is the increase in global welfare (remember that we have assumed $d\bar{z}^2 / d\bar{y}^2 \geq 0$, and that $\bar{z}^2 = z^2$). Thus, the corollary follows.

Investigation of the special case 100% OBR:

In the special case with 100% OBR, $s^1 = t^1 e^{y1} / y^1$. Given a Pigouvian emission tax, this implies $\tau = s^1 y^{e1} / e^1$. Assume first that the average emissions intensity of good *y* in region 1 is equal to the marginal emissions intensity in region 2, i.e., $e^{y1} / y^1 = \partial e^{y2} / \partial y^2$. Equation (9) becomes (using the market equilibrium for *y*):

$$v^{1**} = \left[1 + \left(\frac{\partial \bar{y}^1}{\partial v^1} \right)^{-1} \frac{\partial \bar{y}^2}{\partial v^1} + \left(\frac{\partial \bar{y}^1}{\partial v^1} \right)^{-1} \frac{y^1}{e^{y1}} \frac{\partial e^{z2}}{\partial z^2} \frac{\partial z^2}{\partial v^1} \right] s^1 \ .$$

We know that consumption in region 1 decreases and consumption in region 2 increases in the consumption tax in region 1. Hence, the sum of the two first terms inside the square bracket is less than one. Thus, if $\partial z^2 / \partial v^1$ is positive or sufficiently small in absolute value, we have $v^{1**} < s^1$.

On the other hand, if $e^{y1} / y^1 < \partial e^{y2} / \partial y^2$, there will be another positive term inside the square bracket, in which case v^{1**} is not necessarily lower than s^1.

Proof of Corollary 4:

We now extend the model to several heterogeneous *EITE* goods y_m, with $m = \{1, 2, ..., M\}$. The y_m-goods produced in different regions are imperfect substitutes. The representative consumer's utility from consumption in region *j* is given by $u^j \left(\bar{x}^j, \bar{y}_1^{j1}, \bar{y}_2^{j1}, ..., \bar{y}_M^{j1}, \bar{y}_1^{j2}, \bar{y}_2^{j2}, ..., \bar{y}_M^{j2}, \bar{z}^j \right)$. We assume that the Hessian matrix associated with the consumers' utility maximization problem is negative definite and that $u^j_{x^j} \equiv \partial u^j / \partial \bar{x}^j, u^j_{y_m^{j1}}, u^j_{y_m^{j2}}, u^j_{z^j} > 0$ for all $m \in M$. The market equilibrium conditions and the first-order conditions w.r.t. goods *x* and *z* are not affected by the extension to several heterogeneous y goods (i.e., they remain as in equations (1), (2), (3) and (10)).

We therefore omit good *x* and *z* from the analysis below (except in budget constraints).

Let y_m^{ij} ($\overline{y}_m^{ij}$) denote good y_m produced in region *j* and sold (consumed) in region *i*. The market equilibrium condition for each y_m good is:

(13)
$$y_m^{ij} = \overline{y}_m^{ij} \quad i, j \in \{1,2\}, \forall m \in M ,$$

and we have $y_m^j = y_m^{1j} + y_m^{2j}$. We now show that the first-order conditions w.r.t. y_m^j are equal across the regimes. The profit maximization problem for the producer of y_m^j under OBR is:

$$\max_{y_m^{1j}, y_m^{2j}, \mathrm{e}^{y_m j}} \left[\left(p^{y_m 1j} + s_m^j \right) y_m^{1j} + \left(p^{y_m 2j} + s_m^j \right) y_m^{2j} - c^{y_m j}(\mathrm{y}_m^j, \mathrm{e}^{y_m j}) - t^j e^{y_m j} \right].$$

for all $m \in M$. Here $p^{y_m ij}$ refers to the price of good y_m sold in region *i* and produced in region *j*. Further, s_m^j, $e^{y_m j}$ and $c^{y_m j}(\cdot)$ refer to the output subsidy, emissions, and production costs related to y_m, respectively.

The associated first-order conditions imply:

(14)
$$\begin{array}{l} p^{y_m 11} + s_m^1 = p^{y_m 21} + s_m^1 = c_y^{y_m 1} \\ p^{y_m 12} = p^{y_m 22} = c_y^{y_m 2} \\ -c_e^{y_m 1} = t^1 \;\; ; \;\; c_e^{y_m 2} = 0 \end{array} .$$

for all $m \in M$. In the BCA case, competitive producers of *y* in region *j* maximize profits:

$$\begin{array}{c} \max_{y_m^{1j}, y_m^{2j}, \mathrm{e}^{y_m j}} \left[\left(p^{y_m 1j} - \pi_m^i \right) y_m^{1j} + \left(p^{y_m 2j} + \gamma_m^j \right) y_m^{2j} - c^{y_m j}(\mathrm{y}_m^j, \mathrm{e}^{y_m j}) - t^j e^{y_m j} \right] \\ i, j \in \{1,2\} \left(i \neq j \right), \forall m \in M \end{array} .$$

Here π_m^i and γ_m^j denote the carbon tariff and export rebate on good y_m in region *j*, respectively. This gives the following first-order conditions for interior solution:

(15)
$$\begin{array}{l} p^{y_m 11} = p^{y_m 21} + \gamma_m^1 = c_y^{y_m 1} \\ p^{y_m 12} - \pi_m^1 = p^{y_m 22} = c_y^{y_m 2} \\ -c_e^{y_m 1} = t^1 \;\; ; \;\; -c_e^{y_m 2} = 0 \end{array} .$$

for all $m \in M$. Finally, the representative consumer in region *j* maximizes welfare:

$$\max_{\omega}\left[u^{j}(\omega)-\left(p^{xj}\overline{x}^{j}+\left[\sum_{m\in M}\left(\left(p^{y_m j1}+v_m^{j}\right)\overline{y}_m^{j1}+\left(p^{y_m j2}+v_m^{j}\right)\overline{y}_m^{j2}\right)\right]+p^{zj}\overline{z}^{j}\right)\right].$$

where $\omega=\overline{x}^{j},\overline{y}_1^{j1},\overline{y}_2^{j1},\ldots,\overline{y}_M^{j1},\overline{y}_1^{j2},\overline{y}_2^{j2},\ldots,\overline{y}_M^{j2},\overline{z}^{j}$. The associated first-order conditions for the *y* goods are:

$$u^{j}_{y_m^{ji}}=p^{y_m ji}+v_m^{j}\quad i=\{1,2\},\ \forall m\in M\,, \tag{16}$$

which is valid under OBR and BCA ($v^1=0$ under BCA).

The budget constraint required for import expenditures to equal export revenue in region *j* is (under OBR and BCA):

$$\sum_{m\in M}\left(p^{y_m ij}y_m^{ij}-p^{y_m ji}\overline{y}_m^{ji}\right)+p^{x}\left(x^{j}-\overline{x}^{j}\right)=0\quad i,j\in\{1,2\}\left(i\neq j\right), \tag{17}$$

Following the steps in the derivation of equation (6), we find the optimal consumer tax with *M* heterogeneous *y* goods:

$$v_m^{1*'}=\left(\frac{\partial\overline{y}_m^{11}}{\partial v_m^{1}}+\frac{\partial\overline{y}_m^{12}}{\partial v_m^{1}}\right)^{-1}\left(\sum_{m\in M}\left[s_m^{1}\frac{\partial y_m^{1}}{\partial v_m^{1}}+\tau\left(\frac{\partial e^{y_m 2}}{\partial y_m^{2}}\frac{\partial y_m^{2}}{\partial v_m^{1}}\right)-\frac{\partial p^{y_m 21}}{\partial v_m^{1}}y_m^{21}+\frac{\partial p^{y_m 12}}{\partial v_m^{1}}\overline{y}_m^{12}\right]+\tau\frac{\partial e^{z2}}{\partial z^{2}}\frac{\partial z^{2}}{\partial v^{1}}+\frac{\partial p^{x}}{\partial v^{1}}\left(\overline{x}^{1}-x^{1}\right)\right)$$

The interpretation is similar to that of equation (6), with condition (7) replaced with:

$$\sum_{m\in M}\left(\frac{\partial e^{y_m 2}}{\partial y_m^{2}}\frac{\partial y_m^{2}}{\partial v_m^{1}}\right)+\frac{\partial e^{z2}}{\partial z^{2}}\frac{\partial z^{2}}{\partial v^{1}}<0$$

The first part of Corollary 4 follows.

We now turn to the second part of Corollary 4. Table A1 summarizes and compares the first-order conditions for the *y* goods:

Table A1. First-order conditions under the two regimes with *M* heterogeneous y goods.

	OBR + tax	*BCA*
Production y_m^1	$p^{y_m 11} + s_m^1 = p^{y_m 21} + s_m^1 = c_y^{y_m 1}$	$p^{y_m 11} = p^{y_m 21} + \gamma_m^1 = c_y^{y_m 1}$
Production y_m^2	$p^{y_m 12} = p^{y_m 22} = c_y^{y_m 2}$	$p^{y_m 12} - \pi_m^1 = p^{y_m 22} = c_y^{y_m 2}$
Abatement	$-c_e^{y_m 1} = t^1 \quad ; \quad c_e^{y_m 2} = 0$	$-c_e^{y_m 1} = t^1 \quad ; \quad c_e^{y_m 2} = 0$
Consumption $\tilde{y}_m^{11}$	$u_{y_m^{11}} = p^{y_m 11} + v_m^1 = p^{y_m 21} + v_m^1$	$u_{y_m^{11}} = p^{y_m 11} = p^{y_m 21} + \gamma_m^1$
Consumption $\tilde{y}_m^{12}$	$u_{y_m^{12}} = p^{y_m 12} + v_m^1 = p^{y_m 22} + v_m^1$	$u_{y_m^{12}} = p^{y_m 12} = p^{y_m 22} + \pi_m^1$

Note that equal consumption across regimes in region 1 implies equal consumption in region 2, given equal production levels and the market equilibrium condition (13). Table A1 shows that the first-order conditions are equal across the regimes if $v_m^1 = s_m^1 = \gamma_m^1 = \pi_m^1$. This proves the last part of Corollary 4.

Appendix B: Algebraic summary of the numerical CGE model – For Online Publication

Our stylized multi-sector multi-region computable general equilibrium model is formulated as a system of nonlinear inequalities. The inequalities correspond to the two classes of conditions associated with a general equilibrium: (i) exhaustion of product (zero profit) conditions for producers with constant returns to scale; and (ii) market clearance for all goods and factors. The former class determines activity levels, and the latter determines price levels. In equilibrium, each variable is linked to one inequality condition: an activity level to an exhaustion of product constraint and a commodity price to a market clearance condition. In our algebraic exposition, the notation is Π_{gr}^{z} used to denote the unit profit function (calculated as the difference between unit revenue and unit cost) for production with constant returns to scale of sector g in region r, where z is the name assigned to the associated production activity. Differentiating the unit profit function with respect to input and output prices provides compensated demand and supply coefficients (Hotelling's lemma), which appear subsequently in the market clearance conditions. We use g as an index for all sectors/commodities except primary fossil energy and index r (aliased with s) to denote region. Furthermore, we indicate complementarity between equilibrium conditions and variables with the operator $\perp$.

Tables B1–B6 explain the notations for variables and parameters employed within our algebraic exposition. Figures B1-B3 sketch the nesting of functional forms in production and consumption together with the default elasticities underlying our central case simulations. Numerically, the model is implemented in GAMS (Brooke et al., 1996)[25] and solved using PATH (Dirkse and Ferris, 1995).[26]

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[25] Brooke, A., D. Kendrick, and Meeraus, A. (1996). GAMS: A User's Guide. GAMS Development Corporation: Washington DC.

[26] Dirkse, S., and M. Ferris (1995). The PATH Solver: A Non-monotone Stabilization Scheme for Mixed Complementarity Problems. *Optimization Methods & Software* 5: 123–56.

Table B.1. Indices and sets

G	Set of all commodities $\{NC\_T, C\_T, C\_NT, FE\}$
EG	Subset of primary energy goods $\{FE\}$
R	Set of regions $\{1, 2\}$
g (*alias* i)	Index for sectors and commodities
r (*alias* s)	Index for regions

Table B.2. Activity variables

Y_{gr}	Production of commodity g in region r
M_{gr}	Material composite for commodity g in region r
KL_{gr}	Value-added composite for commodity g in region r
A_{gr}	Armington aggregate of commodity g in region r
IM_{gr}	Import aggregate of commodity g in region r
C_r	Consumption composite in region r

Table B.3. Price variables

p_{gr}	Price of commodity g in region r
p_{gr}^{M}	Price of material composite for commodity g in region r
p_{gr}^{KL}	Price of value-added composite for commodity g in region r
p_{gr}^{A}	Price of Armington aggregate of commodity g in region r
p_{gr}^{IM}	Price of aggregate imports of commodity g in region r
p_r^{C}	Price of consumption composite in region r
w_r	Price of labor (wage rate) in region r
v_r	Price of capital services (rental rate) in region r
q_r	Rent for primary energy resource in region r
p_r^{CO2}	Price of carbon emissions in region r

Table B.4. Cost shares

θ_{gr}^{M}	Cost share of material composite in production of commodity g in region r
θ_{gr}^{FE}	Cost share of primary energy in capital-labor-energy composite input to production of commodity g in region r
θ_{igr}^{MN}	Cost share of input i in material composite of commodity g in region r
θ_{gr}^{K}	Cost share of capital within the value-added of commodity g in region r
θ_{r}^{Q}	Cost share of primary energy resource in primary energy production in region r
$\theta_{FE,r}^{LN}$	Cost share of labor in non-resource composite of primary energy production in region r
$\theta_{FE,r}^{KN}$	Cost share of capital in non-resource input to primary energy production in region r
$\theta_{g,FE,r}^{N}$	Cost share of good g in non-resource input to primary energy production in region r
θ_{gr}^{A}	Cost share of domestic input g in the Armington composite of commodity g in region r
θ_{gsr}^{IM}	Cost share of commodity g from region s in import composite of region r
θ_{gr}^{C}	Cost share of commodity g in consumption composite of region r

Table B.5. Elasticities of substitution

σ_{gr}^{KLEM}	Substitution between the material composite and the energy-value-added aggregate in production of commodity g in region r
σ_{gr}^{KLE}	Substitution between primary fossil energy and the value-added nest in production of commodity g in region r
σ_{gr}^{M}	Substitution between material inputs within the material composite in production of commodity g in region r
σ_{gr}^{KL}	Substitution between the capital and labor within the value-added composite in production of commodity g in region r
σ_{gr}^{Q}	Substitution between natural resource input and the composite of other inputs in primary energy production in region r
σ_{gr}^{A}	Substitution between import composite and domestic input to Armington production of commodity g in region r
σ_{gr}^{IM}	Substitution between imports from different regions within the import composite of commodity g in region r
σ_{r}^{C}	Substitution between commodity inputs to composite consumption in region r

Table B.6. Endowments

$\bar{L}_r$	Aggregate labor endowment in region r
$\overline{K}_r$	Capital endowment in region r
$\overline{Q}_r$	Resource endowment of primary fossil energy in region r
$\overline{CO2}_r$	Endowment with CO_2 emission allowances in region r
$a_{FE,r}^{CO_2}$	CO_2 emissions coefficient for primary fossil energy in region r

Zero profit conditions

- Production of goods except fossil primary energy ($g \notin EG$):

$$\Pi_{gr}^{y} = p_{gr} - \left[\theta_{gr}^{M} p_{gr}^{M\left(1-\sigma_{gr}^{KLEM}\right)} + \left(1-\theta_{gr}^{M}\right) \left[\theta_{gr}^{FE} \left(p_{FE,r} + a_{FE,r}^{CO_2} p_{r}^{CO_2} \right)^{\left(1-\sigma_{gr}^{KLE}\right)} + \left(1-\theta_{gr}^{FE}\right) p_{gr}^{KL\left(1-\sigma_{gr}^{KLE}\right)} \right]^{\frac{\left(1-\sigma_{gr}^{KLEM}\right)}{\left(1-\sigma_{gr}^{KLE}\right)}} \right]^{\frac{1}{\left(1-\sigma_{gr}^{KLEM}\right)}} \leq 0 \qquad \perp \; Y_{gr}$$

- Sector-specific material composite ($g \notin EG$):

$$\Pi_{gr}^{M} = p_{gr}^{M} - \left[\sum_{i \notin EG} \theta_{igr}^{MN} p_{ir}^{A\left(1-\sigma_{gr}^{M}\right)} \right]^{\frac{1}{\left(1-\sigma_{gr}^{M}\right)}} \leq 0 \qquad \perp \; M_{gr}$$

- Sector-specific value-added aggregate ($g \notin EG$):

$$\Pi_{gr}^{KL} = p_{gr}^{KL} - \left[\theta_{gr}^{K} v_{r}^{\left(1-\sigma_{gr}^{KL}\right)} + \left(1-\theta_{gr}^{K}\right) w_{r}^{\left(1-\sigma_{gr}^{KL}\right)} \right]^{\frac{1}{\left(1-\sigma_{gr}^{KL}\right)}} \leq 0 \qquad \perp \; KL_{gr}$$

- Production of primary fossil fuel:

$$\Pi_{FE,r}^{Y} = p_{FE,r} - \left[\theta_{r}^{Q} q_{r}^{\left(1-\sigma_{r}^{Q}\right)} + \left(1-\theta_{r}^{Q}\right) \left[\theta_{FE,r}^{LN} w_{r} + \theta_{FE,r}^{KN} v_{r} + \sum_{g \notin EG} \theta_{g,FE,r}^{N} p_{gr}^{A} \right]^{\left(1-\sigma_{r}^{Q}\right)} \right]^{\frac{1}{\left(1-\sigma_{r}^{Q}\right)}} \leq 0 \qquad \perp \; Y_{FE,r}$$

- Armington aggregate ($g \notin EG$):

$$\Pi_{gr}^{A} = p_{gr}^{A} - \left[\theta_{gr}^{A} p_{gr}^{\left(1-\sigma_{gr}^{A}\right)} + \left(1-\theta_{gr}^{A}\right) p_{gr}^{IM\left(1-\sigma_{gr}^{A}\right)} \right]^{\frac{1}{\left(1-\sigma_{gr}^{A}\right)}} \leq 0 \qquad \perp \; A_{gr}$$

- Import composite ($g \notin EG$):

$$\Pi_{gr}^{IM} = p_{gr}^{IM} - \left[\sum_{s \neq r} \theta_{gsr}^{IM} p_{gs}^{\left(1-\sigma_{gr}^{IM}\right)} \right]^{\frac{1}{\left(1-\sigma_{gr}^{IM}\right)}} \leq 0 \qquad \perp \; IM_{gr}$$

- Consumption composite:

$$\Pi_r^C = p_r^C - \left[\sum_{g \notin EG} \theta_{gr}^C p_{gr}^{A\left(1-\sigma_{gr}^C\right)} \right]^{\frac{1}{\left(1-\sigma_{gr}^C\right)}} \leq 0 \qquad \perp \;\; C_r$$

Market clearance conditions

- Labor:

$$\bar{L}_r \geq Y_{FE,r} \frac{\partial \Pi_{FE,r}^Y}{\partial w_r} + \sum_{g \notin EG} KL_{gr} \frac{\partial \Pi_{gr}^{KL}}{\partial w_r} \qquad \perp \;\; w_r$$

- Capital:

$$\bar{K}_r \geq Y_{FE,r} \frac{\partial \Pi_{FE,r}^Y}{\partial v_r} + \sum_{g \notin EG} KL_{gr} \frac{\partial \Pi_{gr}^{KL}}{\partial v_r} \qquad \perp \;\; v_r$$

- Primary fossil energy resource:

$$\bar{Q}_r \geq Y_{FE,r}^Y \frac{\partial \Pi_{FE,r}^Y}{\partial q_r} \qquad \perp \;\; q_r$$

- Material composite ($g \notin EG$):

$$M_{gr} \geq Y_{gr} \frac{\partial \Pi_{gr}^Y}{\partial p_{gr}^M} \qquad \perp \;\; p_{gr}^M$$

- Value-added ($g \notin EG$):

$$KL_{gr} \geq Y_{gr} \frac{\partial \Pi_{gr}^Y}{\partial p_{gr}^{KL}} \qquad \perp \;\; p_{gr}^{KL}$$

- Armington aggregate ($g \notin EG$):

$$A_{gr} \geq C_r \frac{\partial \Pi_r^C}{\partial p_{gr}^A} + Y_{FE,r} \frac{\partial \Pi_{FE,r}^Y}{\partial p_{gr}^A} + \sum_{i \notin EG} M_{ir} \frac{\partial \Pi_{ir}^M}{\partial p_{gr}^A} \qquad \perp \;\; p_{gr}^A$$

- Import composite ($g \notin EG$):

$$IM_{gr} \geq A_{gr} \frac{\partial \Pi_{gr}^A}{\partial p_{gr}^{IM}} \qquad \perp \;\; p_{gr}^{IM}$$

- Goods except primary energy ($g \notin EG$):

$$Y_{gr} \geq A_{gr} \frac{\partial \Pi_{gr}^{A}}{\partial p_{gr}} + \sum_{s \neq r} IM_{gs} \frac{\partial \Pi_{gs}^{IM}}{\partial p_{gs}} \qquad \perp \quad p_{gr}$$

- Primary energy:

$$Y_{FE,r} \geq \sum_{g \notin EG} Y_{gr} \frac{\partial \Pi_{gr}^{Y}}{\partial \left(p_{FE,r} + a_{FE,r}^{CO_2} p_r^{CO_2} \right)} \qquad \perp \quad p_{FE,r}$$

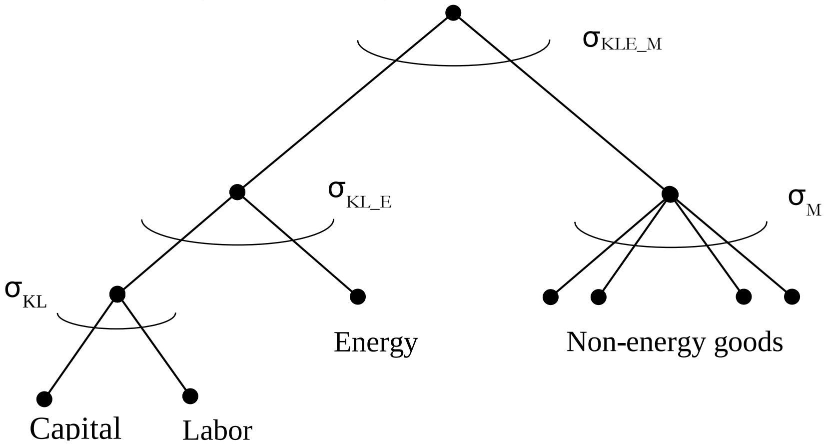
- Private consumption (g = C):

$$p_r^C C_r \geq w_r \bar{L}_r + v_r \bar{K}_r + q_r \bar{Q}_r + p_r^{CO_2} \overline{CO2}_r \qquad \perp \quad p_r^C$$

- Carbon emissions:

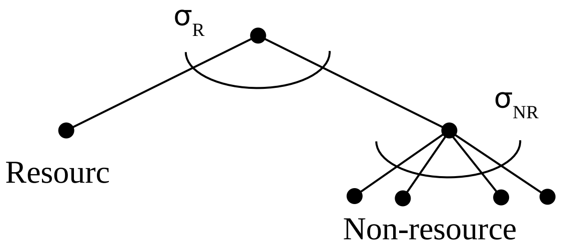
$$\overline{CO2}_r \geq a_{FE,r}^{CO_2} Y_{FE,r} \qquad \perp \quad p_r^{CO_2}$$

Figure B1. Nesting in non-energy production



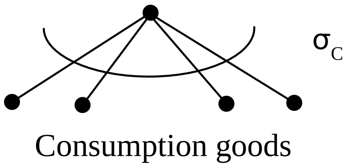
Elasticities: $\sigma_{KLE\_M} = 0.25$; $\sigma_{KLE} = 0.5$; $\sigma_M = 0$; $\sigma_{KL} = 1$

Figure B2. Nesting in energy production



Elasticities: σ_R =0.9; σ_{NR}=0

Figure B3. Nesting in final consumption



Elasticities: σ_C =0.5

Appendix C: Mapping of GTAP sectors and base-year data – For Online Publication

Table C1 shows the mapping of the 57 GTAP sectors to the four composite sectors in our model.

Table C1. Mapping of GTAP sectors to composite model sectors

Model sectors	GTAP sectors
FE: fossil energy composite	Coal; Crude oil; Gas (extraction and distribution)
C_T: carbon-intensive and tradable goods	Refined oil; Ferrous metals; Non-ferrous metals; Non-metallic minerals; Chemical rubber products; Other machinery and equipment; Paper and paper products
C_NT: carbon-intensive and non-tradable goods	Electricity; All transport sectors (air, water, rail, road)
NC_T: carbon-free and tradable goods	All remaining goods and services

Table C2 shows the derived SAM for each region. The entries constitute value flows with negative values being inputs (demands) and positive values being output or endowments (supplies). Since the base-year data is given in value terms, we have to choose units for goods and factors to separate price and quantity observations. A commonly used convenient convention is to choose units for both goods and factors to have a price of unity in the base-year such that values readily transfer into quantities.[27] In general, data consistency of a social accounting matrix requires that the sums of each of the rows and columns equal zero. Whereas market equilibrium conditions (including trade balance) are associated with the rows, the columns capture the zero-profit condition for production sectors as well as the income balance for the aggregate household sector.

Table C2. Base-year data for stylized model simulations. Social accounting matrix (in bn USD) for each region based on GTAP9 data*

	C_T	*C_NT*	*NC_T*	*FE*	*X*	*M*	*FD*	*C*
C_T	4521	-659.5	-3281	-40.5	-565	565	-540	
C_NT	-486	3136.5	-1495.5	-51			-1104	
NC_T	-1189	-816.5	26189	-221	-1440	1440	-23962.5	
FE	-994.5	-203.5		1198				
LAB	-957	-733.5	-13001.5	-127				14819
CAP	-894.5	-723.5	-8411	-462				10491
RES				-296.5				296.5
INC_EXP							25606.5	-25606.5
BOP					2005	-2005		

* *C_T* denotes carbon-intensive and tradable goods, *C_NT* carbon-intensive and non-tradable goods, *NC_T* carbon-free and tradable goods, *FE* fossil energy composite, *X* exports, *M* imports, *FD* final demand, *C* consumption, *LAB* labor, *CAP* capital, *RES* energy resource, *INC-EXP* income-expenditure constraint, *BOP* balance-of-payment constraint

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[27] We abstract from explicit tax wedges and use gross-of-tax values throughout to suppress initial tax distortions which are also absent in our theoretical analysis.