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Smart hedging against carbon leakage

Abstract:

Policy makers in the EU and elsewhere are concerned that unilateral pricing of the carbon externality induces carbon leakage through relocation of emission-intensive and trade-exposed production to other regions. A common measure to mitigate such leakage is to combine an emission trading system with output-based allocation (OBA) of allowances where the latter works as an implicit production subsidy to regulated industries. We show analytically that it is optimal to impose in addition a consumption tax on the OBA goods (i.e., goods that are entitled to OBA) at a rate which is equivalent in value to the OBA subsidy rate. The explanation is that the consumption tax alleviates excessive consumption of the OBA goods, which is a distortionary effect of introducing output-based allocation. Using a multi-region multi-sector computable general equilibrium model calibrated to empirical data, we quantify the welfare gains for the EU of imposing such a consumption tax on top of its existing emission trading system with OBA. We run Monte Carlo simulations to account for uncertain leakage exposure of goods entitled to OBA. The consumption tax increases welfare whether the goods are highly exposed to leakage or not, and hence can be regarded as smart hedging against carbon leakage.

Keywords: Carbon leakage; output-based allocation; consumption tax

JEL classification: D61, F18, H23, Q54

1. Introduction

The Paris Agreement entails that all signatory countries should mitigate greenhouse gas emissions. The stringency of climate policies varies substantially across countries, however, partly due to the UNFCCC principle of "common but differentiated responsibilities" (UN, 1992). The European Union has been a frontrunner in greenhouse gas emissions pricing, initiating its EU Emission Trading Scheme (ETS) in 2005.[1] The EU ETS regulates about half of the greenhouse gas emissions in the EU, mainly CO_2 emissions from large energy-intensive installations in the electricity and manufacturing sectors. From the very start of the EU ETS, policy makers in the EU have been concerned about carbon leakage associated with the relocation of emission-intensive and trade-exposed (EITE) production to countries with less stringent climate policies. Hence, large amounts of free emission allowances have been granted to EITE industries considered at (significant) risk of carbon leakage (EU, 2019). Allocation of allowances is approximately proportional to the individual installation's production output, so-called output-based allocation (OBA).[2] Similar allocation schemes are also applied in other emission trading schemes (Meunier et al., 2017).

There is a large literature showing that implementing OBA tends to reduce leakage and improve competitiveness compared to carbon pricing alone (for an overview see e.g., Zhang, 2012). However, this comes with a negative side effect, as OBA simultaneously leads to excessive domestic consumption of EITE goods. The explanation is that OBA works as an implicit production subsidy, which is especially distortive for sectors that after all turn out to have only little leakage exposure. Hence, border carbon adjustments, in particular carbon tariffs on imports of EITE goods, have been regarded in the literature as a more targeted and hence more cost-effective instrument to mitigate carbon leakage through international trade (Böhringer et al., 2014): Whereas OBA stimulates overall domestic production, carbon tariffs only constrain foreign supply (exports).

[1] Emission trading involves that the regulator sets a cap on total emissions from the sectors included in the ETS, and that the entities that are covered can trade emissions allowances.
[2] For example, a steel producer receives *x* amount of gratis emission allowances per ton of steel the plant produces. There is a time lag between production output and allocation in the EU ETS. In Section 3.3, we return to this and compare our modeling of OBA with the allocation rules in the EU ETS.

In the policy realm, border carbon adjustments have gotten more traction in the EU just recently.[3] In its “European Green Deal”, the European Commission (2019) states: “Should differences in levels of ambition worldwide persist, …, the Commission will propose a border carbon adjustment mechanism, for selected sectors, to reduce the risk of carbon leakage.” Despite the Commission’s assertion that “this measure will be designed to comply with World Trade Organization rules”, China has immediately reacted to the proposal saying that it would “seriously undermine” international efforts to fight global warming.[4] In a nutshell: Border carbon adjustments remain very contentious as they directly interfere with trade legislations, which explains why they have so far not been implemented anywhere. Hence, it is important to consider alternatives to border carbon adjustments that are similarly appealing for reducing carbon leakage without increasing the likelihood of a trade war.

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 1985, p.356). Building on this fundamental idea, Böhringer et al. (2017) analyze the effects of imposing a tax on intermediate and final consumption of EITE goods in a situation where carbon pricing and OBA have already been implemented. They show that under certain conditions such an instrument mix will in fact be equivalent to carbon pricing combined with border carbon adjustments. They also show, both analytically and with stylized numerical simulations, that such a consumption tax is likely to be welfare enhancing. The intuitive reasoning behind is that the domestic consumption tax alleviates the distortionary effects of OBA, that is, the excessive domestic consumption of EITE goods.

Apparently, the negative effects of OBA are in particular large if the leakage exposure is limited, i.e., the second-best argument for the implicit production subsidy is lacking substance (Böhringer et al., 2017). On empirical grounds, the actual leakage exposure

[3] BCA have been discussed in the EU for more than ten years (Mehling, 2019), e.g. as a possible future alternative to free allowance allocation. BCA have also been discussed outside the EU, and were included in the American Clean Energy and Security Act of 2009 that passed the U.S. Congress but not the Senate (Fischer and Fox, 2011).

of industries may be difficult to assess, while trade-exposed industries have incentives to exaggerate the exposure in order to increase the number of allowances they receive for free. Hence, the extent of free allocation may become higher than optimal. Martin et al. (2014) conclude that the current allocation in the EU ETS results in "substantial overcompensation for given carbon leakage risk". Whereas a majority of industry sectors receives a high share of free allowances, Sato et al. (2015) find that "vulnerable sectors account for small shares of emission".

In this paper we show that supplementing OBA with a consumption tax alleviates the downside risk of over-subsidization by OBA stand-alone while maintaining the desirable effect of leakage reduction. Our theoretical analysis concludes that it is optimal from a regional and global welfare perspective to implement a consumption tax at a rate that is equivalent in value to the OBA subsidy rate: The distortionary impacts of OBA on domestic consumption are exactly offset by the consumption tax.

For our numerical analysis based on empirical data, we use a multi-sector multi-region computable general equilibrium (CGE) model of the global economy. In international trade, goods are distinguished by country of origin (Armington, 1969): Imported and domestically produced goods of the same variety are treated as incomplete substitutes reflecting that they differ in kind and quality. The values of the (Armington) substitution elasticities determine how close substitutes goods produced in different regions are, and hence to what degree the domestic industry is exposed to competition from abroad and to carbon leakage. Whereas the Armington elasticities are key for determining which sectors should receive free emission permits to offset carbon leakage, the exact values for these elasticities are difficult to pin down. Indeed, the previously cited literature on free allowance allocation (Martin et al., 2014; Sato et al., 2015) suggests that the policy makers in the EU ETS tend to overestimate the leakage exposure of carbon-intensive and trade-exposed industries, which in our model translates into overestimating the Armington elasticities. To reflect the uncertain empirical estimates for Armington elasticities, we use a Monte Carlo approach based on a probability distribution for the Armington elasticities. Our simulations for EU climate policy design suggest that imposing a consumption tax as a supplement to OBA is unambiguously welfare-improving for the EU. The magnitude of the welfare gains is negatively correlated with the Armington elasticities: If leakage exposure is lower than assumed, the welfare gains are quite substantial, whereas if leakage exposure is as high as assumed by many policy makers (or even higher), the advantage of the consumption tax is lower, but it does no harm either. Therefore, we conclude that implementing a consumption tax in addition to output-based allocation is smart hedging against carbon leakage when precise estimates of the Armington elasticities are difficult to obtain.

The literature on carbon leakage is extensive, going back to seminal theoretical studies by Markusen (1975) and Hoel (1996). Most numerical studies use multi-region and multi-sector CGE models of the global economy (as we do), see e.g. Zhang (2012) for a review. Of particular interest for our analysis of anti-leakage climate policy design are the relatively few studies that examine supplemental consumption taxes. In particular, our paper builds on Böhringer et al. (2017). Compared to that paper, our contribution is twofold. First, Böhringer et al. (2017) show analytically that it is welfare improving to *marginally* increase the consumption tax from zero. However, the paper says nothing (in analytical terms) about the *optimal level* of the consumption tax. This is exactly what the current paper does – it shows analytically that the optimal consumption tax level should be equal in size to the implicit OBA subsidy. Second, Böhringer et al. (2017) apply a stylized small-scale CGE model for two symmetric regions and four sectors, undertaking only piece-meal sensitivity analysis for four alternative Armington elasticities. The current paper uses a large-scale CGE model based on empirical data which reflects real-world heterogeneity across regions and sectors. We use this model to assess EU climate policy design under uncertainty about leakage exposure, where the uncertainty is captured in a systematic manner through Monte Carlo simulations based on probability distributions for the Armington elasticities.

Regarding other related studies, Holland (2012) shows analytically, using a one-good model, that a consumption tax can be a supplement to an emission intensity standard, for much the same reasons as pointed out in our paper. Eichner and Pethig (2015a,b) analyze consumption-based taxes, either as an alternative or as a supplement to production-based (emission) taxes, and conclude similarly. An important limitation in their analytical model is that emissions can only be reduced by cutting output. In our more general analytical framework, emissions can also be curbed by reducing the emission intensity, which is particularly relevant from a leakage and competitiveness perspective. Pauliuk et al. (2016) discuss the possibility of including charges for the consumption of carbon-intensive materials in the EU ETS, while Kaushal and Rosendahl (2020) studies whether a single country should go alone in implementing a consumption tax if the country has a joint ETS with other countries.

The remainder of this paper is organized as follows. In Section 2, we lay out the theoretical model and analyze the optimal consumption tax in a situation where an ETS combined with OBA is already in place. In Section 3, we present our numerical CGE analysis where we quantify the effects of implementing a consumption tax in the context of the EU ETS. Section 4 concludes.

2. Analytical model

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. We interpret *y* as emission-intensive and trade-exposed (EITE) sectors where output-based allocation is considered (e.g., chemicals, metals, and other mineral production), and *z* as sectors where leakage is of less concern (e.g., electricity production and transport). Consumption of *x* in Region *j* is denoted $\bar{x}^j$, and similarly for the other goods.

The representative consumer in Region *j* has a constant-elasticity-of-substitution (CES) utility function given by:

$$u^j\left(\bar{x}^j, \bar{y}^j, \bar{z}^j\right) = \left(\alpha^{xj}\left(\bar{x}^j\right)^\rho + \alpha^{yj}\left(\bar{y}^j\right)^\rho + \alpha^{zj}\left(\bar{z}^j\right)^\rho\right)^{\frac{1}{\rho}}, \quad j = 1, 2, \qquad (1)$$

in which the positive α's represent initial consumption shares, and the substitution elasticity is $1/(1-\rho)$. Assume that *y* is a composite good, consisting of goods *d* and *f* such that:

$$\bar{y}^j = \left(\beta^j \left(\bar{d}^j \right)^\theta + \left(1-\beta^j\right)\left(\bar{f}^j \right)^\theta \right)^{\frac{1}{\theta}}. \tag{2}$$

Here *d* and *f* refer to EITE goods produced in regions 1 and 2, respectively. The parameter β^j represents the initial consumption share in region *j* of the EITE good *d* produced in Region 1. This formulation allows to differentiate between EITE goods produced in the two regions. Thus, we have essentially four goods in our model: $g = \{x, z, d, f\}$.

The Armington elasticity, given by $\sigma = 1/(1-\theta)$, determines how close substitutes in consumption *d* and *f* are. The goods become perfect substitutes as $\theta \to 1$ ($\sigma \to \infty$), perfect complements as $\theta \to -\infty$ ($\sigma \to 0$), and Cobb-Douglas as $\theta \to 0$ ($\sigma \to 1$). A high Armington elasticity (θ close to 1) implies a strong potential for carbon leakage. Conversely, the potential for carbon leakage becomes negligible as $\theta \to -\infty$.[5] We assume $\rho, \theta \neq 0$ and $\rho, \theta < 1$.

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 goods *z*, *d* and *f*, but omit the redundant region of origin superscript *j* for *d* and *f* to reduce notational clutter (except when useful in summation signs). Utility does not depend on the country of origin for the emission-free and tradable good *x*. The market equilibrium conditions are:

$$\begin{aligned} x^1 + x^2 &= \bar{x}^1 + \bar{x}^2, \\ z^j &= \bar{z}^j, \\ d &= \bar{d}^1 + \bar{d}^2, \\ f &= \bar{f}^1 + \bar{f}^2, \end{aligned} \tag{3}$$

with $j = \{1, 2\}$.

Let e^{gj} denote emissions from production of good *g* in Region *j*. For our analysis, we assume that Region 1 undertakes unilateral emission regulation and disposes of three policy instruments: an emission trading regime regulating emissions $e^{z1} + e^d$ with

[5] In the numerical analysis in Section 3, we run Monte Carlo simulations to account for uncertainty w.r.t the actual carbon leakage exposure of EITE producers by letting the parameters corresponding to θ be stochastic.

permit price t^1, an output subsidy s^1 to production of the domestically produced EITE good *d*, and a domestic consumption tax v^1 on buying EITE goods *d* and *f*. Output-based allocation (OBA) functions similarly to an output subsidy, where the implicit subsidy is linked to the price of emission permits. The EITE good producer in Region 1 pays $t^1 e^d$ for emission permits; i.e., the permit price t^1 multiplied with emissions e^d. With 100% OBA, the permit sale revenues from EITE producers are fully redistributed back (not at the firm level but at the aggregate EITE level). The value of the implicit production subsidy to the domestic EITE producers in Region 1 is given by $s^1 d$, which equals $t^1 e^d$ if $s^1 = t^1 e^d / d$. We will henceforth refer to this specific subsidy level as 100% OBA. The main analysis focuses on the case with no climate policy in Region 2, i.e., $t^2 = s^2 = v^2 = 0$, but we consider global emission trading ($t^1 = t^2 > 0$) for comparative statics.

In order to avoid valuing the damages from climate change, we impose that the global emissions are constant across alternative climate policy scenarios. Hence, we assume the abating region to adjust its unilateral emissions reduction effort such that a given global emission cap $\overline{E}$ is maintained. Hence, if leakage varies across different policy regimes, the effective unilateral emission reduction requirement will be adjusted such that global emissions equal the target $\overline{E}$. Thus, the emission constraint is:

$$\overline{E} = \sum_{j=1,2} \sum_{g \in G} e^{gj}, \qquad (4)$$

The paper examines cost-effective emission reductions for a given emission target. Whereas this precludes analysis of optimal emission levels, the results remain valid for the particular emission level associated with optimal policy, in which case the permit price would equal the Pigou tax (as in Böhringer et al, 2017). An important difference between our approach and that of a Pigou tax is that changes in emissions in Region 2 must be exactly offset by emission in the Region 1, such that aggregate emissions are constant. We assume that similar production technologies are available in the two regions, such that the cost functions are identical for the same types of goods (*x*, *y*, and *z*).[6] Production cost is specified as follows:

[6] In the numerical analysis, the model is calibrated to real world data, which implies that the cost functions and emissions intensities vary across regions.

$$c^{gj}\left(g^j, e^{gj}\right) = c^g g^j + \frac{\phi^g}{2}\left(\xi^g g^j - e^{gj}\right)^2, \quad j = 1, 2, \tag{5}$$

where c^g, ϕ^g, and ξ^g are constants and $\xi^g g^j$ is business-as-usual (BaU) emissions in the absence of restrictive climate policies. Hence, $a^{gj} = \xi^g g^j - e^{gj}$ is the abatement level (emission reduction) for a given production level. We make the standard assumptions that $c^x, c^z > 0$, $c^d = c^f \equiv c^y > 0$, $\xi^x = \phi^x = 0$, $\xi^z, \phi^z > 0$, $\xi^d = \xi^f \equiv \xi^y > 0$ and $\phi^d = \phi^f \equiv \phi^y > 0$. Note that abatement costs are increasing and strictly convex if $\phi^g > 0$, and that $c^g + \xi^g \phi^g a^{gj}$ represents the marginal production cost. Thus, without any emission regulations, we notice that production exhibits constant returns to scale.

We assume that competitive producers maximize profits and that the representative consumer maximize utility subject to a budget constraint; see Appendix A for details. The profits of firms located in Region *j* accrue to the representative consumer in that region, and the regulator redistributes the net tax revenue as a lump-sum transfer to the representative consumer. The specification of the regulatory regimes is given in Table 1. We henceforth let superscript $* = \{REF, OBA, CTAX, FB\}$ indicate competitive equilibrium values under the regulatory regimes specified in Table 1.[7]

Table 1. Specification of regulatory regimes ($t^j > 0$ indicates emission trading in Region *j*)

	Region 1	Region 2
REF (reference, unilateral emission trading)	$t^1 > 0, s^1 = v^1 = 0$	$t^2 = s^2 = v^2 = 0$
OBA (*REF* with output subsidy)	$t^1 > 0, s^1 > 0, v^1 = 0$	$t^2 = s^2 = v^2 = 0$
CTAX (*OBA* with consumption tax)	$t^1 > 0, s^1 > 0, v^1 > 0$	$t^2 = s^2 = v^2 = 0$
FB ('first-best', global emission trading)	$t^1 = t > 0, s^1 = v^1 = 0$	$t^2 = t > 0, s^2 = v^2 = 0$

[7] Whereas it is reasonable to assume that the global emission cap $\overline{E}$ in equation (4) is equal across the unilateral climate policies (*REF*, *OBA* and *CTAX*), international policies (*FB*) may have more stringent emission caps. Whether or not the global emission cap is more stringent under international agreements does not affect our results, and we keep $\overline{E}$ fixed for simplicity.

We are now ready to compare the different regulatory regimes, and to derive Proposition 1, which is our main analytical result. An important step towards this result is Lemma 1, which is stated and proved in Appendix A. It characterizes the market equilibrium under the different regimes through a number of equations. Here we will highlight some insights we get from this lemma before turning to the proposition, and refer the technically interested reader to the appendix. We will focus our discussion on the special cases of *OBA* and *CTAX* where $s^1 = t^1 e^d / d$ (100% *OBA*) and $v^1 = s^1$.

Assume first that there is unilateral emission trading (*REF*) in Region 1. Then there will be too large a share of the composite EITE good *y* being produced in Region 2, relative to the first-best (*FB*) allocation, with associated carbon leakage from Region 1 (cf. Lemma 1). This observation is the motivation for implementing output-based allocation, that is, a shift from *REF* to *OBA* regulation as defined in Table 1. *OBA* is a two-edged sword, however. That is, whereas *OBA* reduces carbon leakage, it also induces excessive consumption of the EITE good produced in Region 1, *d*, because of the *OBA* subsidy to production of *d*.[8]

Interestingly, this can be counteracted in the domestic market by introducing a consumption tax v^1 on domestic consumption of the EITE goods. This consumption tax does not increase carbon leakage through the competitiveness channel, because the consumption tax is levied on both domestic and foreign EITE goods (cf. (14) in Appendix A). Moreover, the consumption tax counteracts the negative externality caused by unregulated emissions from EITE goods that are produced in Region 2 and consumed in Region 1 ($\overline{f}^1$). Indeed, assume, for the sake of our argument, that the permit price under *CTAX* is equal to the permit price under global emission trading ($t^{1,CTAX} = t^{FB} = t$).[9] Then it can be shown that a *CTAX* regime with $v^1 = s^1$ replicates the relative prices in the home region under global emission trading (cf. equation (21) in Appendix A). Note, however, that Region 1's *production* of the EITE good *d* under

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[8] It is well-known that OBA distorts relative prices and may cause excessive production of the EITE goods; see, e.g., Böhringer and Lange (2005).

[9] It is straightforward to show that the equilibrium price on emission permits is higher under *REF*, *OBA* or *CTAX* than under *FB* if the global emissions cap ($\overline{E}$) is equal across the regulatory regimes. Hence, equal permit prices in *CTAX* and *FB* imply lower global emissions in the latter regime.

CTAX is still too high, because the domestic consumption tax is not applied to exports of *d*. It follows that *CTAX* approximates the global emission trading allocation for *consumption* in the home region if the emission price in the home region is the same in the two regimes.[10]

Before turning to Proposition 1, it is useful to also consider some impacts on consumption in the foreign region. In the *OBA* regime, the implicit output subsidy creates a wedge between the price on *d* and marginal production cost. For example, in the case of 100% *OBA*, it is straightforward to show that marginal production cost is $c^d + \xi^y t^1$, whereas the export price is $p^{d2} = c^d$. Hence, the representative consumer in Region 1, who owns the firms and collects net tax revenues in Region 1, indirectly sells the EITE good *d* with negative profits. That is, the *OBA* subsidy does not only distort the relative prices, it also involves subsidizing foreign consumption of the EITE good which is produced in region 1 and exported for consumption in region 2 ($\bar{d}^2$). This implies that net income from trade for Region 1 is reduced by $s^1\bar{d}^2$.[11]

When it comes to *CTAX* versus *OBA*, relative prices and hence relative consumption levels in Region 2 are equal, because the consumption tax v^1 only affects prices in the domestic Region 1 (cf. Lemma 1).[12]

We can now state the following result:

Proposition 1. *Consider a competitive equilibrium with unilateral emission trading and 100% OBA; i.e.,* $s^1 = \xi^y t^1 > 0$ *and* $t^2 = s^2 = v^2 = 0$ *(as characterized by Lemma 1 in Appendix A). Assume that a consumption tax* $v^1 \geq 0$ *is feasible. Then, setting* $v^1 = s^1$ *maximizes both global welfare and welfare in Region 1 (given no other changes to the regulatory regimes in regions 1 and 2).*

Proof. See Appendix A

Proposition 1 implies that welfare can be increased by coupling an existing *OBA* regime with a consumption tax equal to the implicit *OBA* subsidy. In fact, the optimal

[10] This implies that output-based *rebating* (where the emission price is fixed but global emissions are endogenous) coupled with a consumption tax can replicate the relative prices under a global emissions tax in Region 1. The assumption of constant returns to scale in production is important for this result.
[11] This monetary transfer from Region 1 to Region 2 is also shown in the budget constraints (10), see Appendix A.

[12] This result relies on the constant-returns-to-scale cost function.

level of the consumption tax is identical to the *OBA* subsidy, given the model assumptions outlined above.[13]

Note that terms-of-trade effects do not appear in the analytical model, given 100% *OBA* at home and no climate policy abroad. The reason is that constant returns to scale (in the case of no abatement) makes export and import prices exogenous. In our CGE analysis below, we will see that terms-of-trade effects may be quite important when considering regional welfare. That is, whereas the numerical results are in accordance with Proposition 1 with respect to global welfare, it turns out that the terms of trade effects dwarf the mechanisms driving Proposition 1 when considering welfare for Region 1 (the European Union). The consumption tax that maximizes regional welfare is well above the implicit OBA subsidy in the numerical simulations. For global welfare, terms-of-trade effects are of minor importance.

The model does not allow for active policies in the foreign region, for example retaliation in the form of consumption taxes on EITE goods in the foreign Region 2 is not considered. Related to this, it may be difficult to implement an optimal EITE good consumption tax that is uniform and independent of origin in the case of more than two regions and active foreign climate policy. For example, consider the case with two foreign regions 2 and 3, where Region 2 implements emission pricing and Region 3 does not. In this case, a uniform consumption tax on EITE goods would imply that EITE good producers in Region 2 pay twice for their emissions (emission pricing in region 2 and EITE good consumption tax in region 1). In this case, regions 1 and 2 may benefit from coordination of their climate policies (e.g., a CTAX regime in both regions).

The carbon leakage targeted by the *OBA* policy depends crucially on the Armington elasticity $\sigma = 1/(1-\theta)$. Specifically, we show in Appendix A that the EITE good consumption ratio $\overline{f}^j / \overline{d}^j$ approaches $\beta^j / (1-\beta^j)$ if the Armington elasticity approaches perfect complements (i.e., as $\theta \to -\infty$). Remember that β^j denotes the

[13] Böhringer et al. (2017) show that Region 1 welfare can be improved by *marginally* increasing v^1 (from $v^1 = 0$) if $s^1 > 0$ and $t^1 > t^2$, but does not investigate analytically the optimal level of v^1, nor the effects of $v^1 = s^1$.

initial consumption share of the EITE good *d* produced in Region 1 (over the Region 2 EITE good *f*). Carbon leakage is clearly a moot point in this case, as less use of *d* will reduce the use of *f* (since the share $\bar{f}^j / \bar{d}^j$ is fixed). Thus, *OBA* would *increase* production of *f* if the Armington elasticity is sufficiently low, as increased output and hence consumption of *d* will lead to increased consumption and hence production of *f*, increasing emissions in Region 2. Combining *OBA* with a consumption tax would both offset the negative effects of *OBA* and ameliorate the environmental damage caused by EITE goods produced in Region 2 and sold in Region 1 ($\bar{f}^1$, cf., Lemma 1). If, on the other hand, the Armington elasticity is high, such that *OBA* reduces carbon leakage and hence may have positive effect on utility in Region 1, we still know from Proposition 1 that a well-specified consumption tax will increase domestic utility.

In practice, the Armington elasticity may be difficult to pin down (see the discussion in Section 1). In this case, a policy that combines *OBA* with a domestic consumption tax on EITE goods may provide a sort of insurance policy. The rationale is simply that one (potentially large) downside with *OBA*, i.e., the excessive domestic consumption of EITE goods, is attenuated by the consumption tax.

In the next section, we explore the properties of standalone *OBA* and *OBA* coupled with a consumption tax numerically. We focus on the case where the regulating region is the European Union (EU). This example is of interest, because the EU currently implements emission pricing with approximately output-based allocation of free emission quotas to producers of EITE goods.

3. Numerical Analysis

3.1 Non-technical model summary

For our quantitative impact assessment of alternative unilateral climate policy designs, we adopt a standard multi-region multi-sector static computable general equilibrium (CGE) model of global trade and energy use (see e.g. Böhringer et al. 2015, 2018). The strength of CGE models is their rigorous microeconomic foundation in Walrasian equilibrium theory, which accommodates the comprehensive welfare analysis of market supply and demand responses to policy shocks. For the sake of brevity, we confine ourselves to a brief non-technical summary of key model characteristics. A detailed algebraic description of the generic model is provided in Appendix B.

Our model features a representative agent in each region who receives income from three primary factors: labor, capital, and specific fossil fuel resources for coal, natural gas, and crude oil. Labor and capital are inter-sectorally mobile within a region but immobile between regions. Fossil resources are specific to fossil fuel production sectors in each region.

All commodities except for fossil fuels are produced according to a four-level nested CES cost function combining inputs of capital (K), labor (L), energy (E), and material (M) – see Figure 1.

At the top level, a material composite trades off with an aggregate of capital, labor, and energy. At the second level, the material composite splits into non-energy intermediate goods whereas the aggregate of capital, labor and energy splits into a value-added component and the energy component. At the third level, capital and labor inputs enter the value-added composite subject to a constant elasticity of substitution; likewise, within the energy aggregate, electricity trades off with the composite of fossil fuels (coal, natural gas, and refined oil). At the fourth level, a CES function describes the substitution possibilities between coal, refined oil, and natural gas.

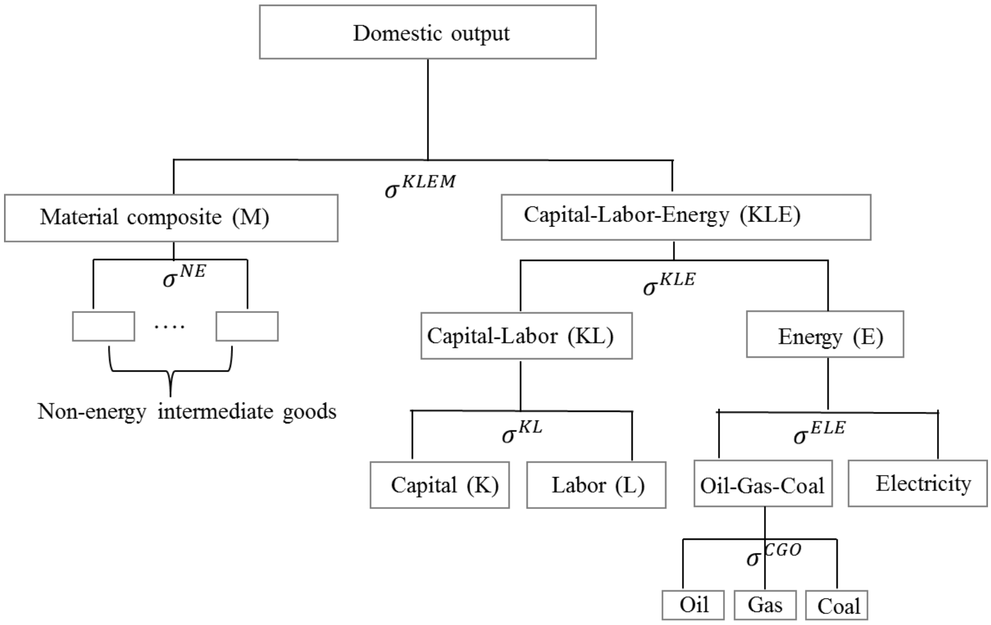

Figure 1. Production structure (see Appendix B for notations)

Fossil fuel production is represented by a constant-elasticity-of-substitution (CES) cost function, where the demand for the specific resource trades off with a Leontief composite of all other inputs.

Final consumption demand in each region is determined by the representative agent who maximizes welfare subject to a budget constraint with fixed investment and exogenous government provision of public goods and services. Consumption demand of the representative agent is given as a CES composite that combines consumption of composite energy and a CES aggregate of other consumption good. Substitution possibilities across different energy inputs in consumption are depicted in a similar nested CES structure as with production.

Bilateral trade is modeled following Armington's differentiated goods approach, where domestic and foreign goods are distinguished by origin (Armington, 1969). A balance of payment constraint incorporates the base-year trade deficit or surplus for each region.

CO_2 emissions are linked in fixed proportions to the use of coal, refined oil and natural gas, with CO_2 coefficients differentiated by fuels and sector of use. Restrictions to the use of CO_2 emissions in production and consumption are implemented through explicit emission pricing of the carbon associated with fuel combustion either via CO_2 taxes or the auctioning of CO_2 emission allowances. CO_2 emissions abatement takes place by fuel switching (interfuel substitution) or energy savings (either by fuel-non-fuel substitution or by a scale reduction of production and final consumption activities).

3.2 Data and parametrization

For model parameterization, we use the most recent data from the Global Trade, Assistance and Production Project (GTAP –version 9) which includes detailed balanced accounts of production, consumption, bilateral trade flows as well as data on physical energy consumption and CO_2 emissions for the base-year 2011 in 140 regions and 57 sectors (Aguiar et al., 2016). As is customary in applied general equilibrium analysis, base-year data together with exogenous elasticities determine the free parameters of the functional forms. Elasticities in international trade (Armington elasticities) as well as factor substitution elasticities are directly provided by the GTAP database. The elasticities of substitution in fossil fuel sectors are calibrated to match exogenous estimates of fossil-fuel supply elasticities (Graham et al. 1999, Krichene 2002, Ringlund et al. 2008).

The GTAP dataset can be flexibly aggregated across sectors and regions to reflect specific requirements of the policy issue under investigation. As to sectoral disaggregation our aggregate dataset explicitly includes different primary and secondary energy carriers: Coal, Crude Oil, Natural Gas, Refined Oil, and Electricity. This disaggregation is essential in order to distinguish energy goods by CO_2 intensity and the degree of substitutability. In addition, we keep those GTAP sectors explicit in the aggregate dataset which are considered as emission-intensive and trade-exposed (EITE) industries such as Chemical Products, Non-Metallic Minerals, Iron & Steel, Non-Ferrous Metals, and Refined Oil, as well as the three transport sectors (Air Transport, Water Transport, and Other Transport). Following the EU ETS, all sectors except Electricity, Water Transport, Other Transport and Other Goods and Services are potentially entitled to free allocation (see Section 3.3).

Regarding regional coverage, we single out the EU and its eight most important trading partners as individual regions. The remaining countries are divided into three composite regions. Table 2 summarizes the sectors (commodities) and regions present in our model simulations.

A key parameter regarding the extent of leakage is the Armington elasticity, which determines the ease of substitution between domestically produced goods and goods produced abroad. The higher this elasticity, the more pronounced leakage becomes, as higher costs of domestic production to a larger degree will cause relocation of production. The size of the Armington elasticity will likely vary across sectors and regions. The elasticities are of course not possible to observe, and also hard to assess although some attempts have been done (e.g., Saito, 2004; Welsch, 2008). The GTAP database provides sector-specific estimates of the Armington elasticities (which are equal across regions). These estimates are however quite uncertain, and hence leakage exposure of different sectors is also uncertain. This is probably a main reason why a large group of sectors is deemed "highly exposed to leakage" in the EU ETS, leading to "substantial overcompensation" according to Martin et al. (2014).

To reflect this uncertainty, we construct probability distributions for the Armington elasticities (see Appendix C for details), and then perform Monte Carlo simulations. For each simulation (1000 in total), we make a draw from the probability distribution for all the OBA sectors. Then we run all policy scenarios (see next subsection) given this set of Armington elasticities.

A relevant question is whether the Armington elasticities in different sectors are correlated or not. In the main simulations, we consider that the Armington elasticities in different sectors are stochastically independent. In the sensitivity analysis, we also consider the opposite case, that is, the Armington elasticities in different sectors are perfectly correlated. In both variants, the Armington elasticities are equal across regions.

Table 2. Sectors and regions in the CGE model (acronyms provided in brackets)

Sectors and commodities	*Countries and regions*
Primary Energy	Europe – EU-28 plus EFTA (EUR)

Coal (COA)	United States of America (USA)
Crude Oil (CRU)	Japan (JPN)
Natural Gas (GAS)	Russia (RUS)
*Emission-intensive and trade-exposed sectors**	China (CHN)
Chemical Products (CRP)	India (IND)
Non-Metallic Minerals (NMM)	Brazil (BRA)
Iron and Steel (I_S)	Turkey (TUR)
Non-Ferrous Metals (NFM)	South Korea (KOR)
Refined Oil (OIL)	Other OECD (OEC)
Paper Products, Publishing (PPP)	OPEC (OPC)
Machinery and Equipment (OME)	Rest of the World (ROW)
Food Products (OFD)	
Beverages and Tobacco Products (B_T)	
Air Transport (ATP)	
Other ETS sectors (RES)	
Other sectors	
Electricity (ELE)	
Water Transport (WTP)	
Other Transport (OTP)	
Other Goods and Services (ROI)	

* Sectors that are entitled to output-based allocation in the main simulations – referred to as "OBA goods" in Table 3.

3.3 Scenarios

We consider the same policy scenarios as in the theoretical analysis (cf. Table 1 in Section 2), but now in the context of the EU. Our starting point is a business-as-usual (*BaU*) scenario corresponding to the base-year outcome in 2011, i.e., the calibrated equilibrium as explained in the previous subsection. Then we consider a reference scenario (*REF*) where the EU implements economy-wide uniform emission pricing to reduce its emission by 20% of the base-year emissions.[14] We then quantify how the *REF* outcome changes if the region adopts in addition either output-based allocation

[14] 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.

(*OBA*), or *OBA* combined with a consumption tax (*CTAX*), cf. Table 3. In both cases, the additional policies are directed towards goods that are more or less emission-intensive and trade-exposed (referred to as “OBA goods”). In the main simulations, we follow the current situation in the EU ETS where a large group of sectors receive free allowances in proportion to output. In the sensitivity analysis, we consider the case where only the most emission-intensive and trade-exposed (EITE) goods are given free allowances. In the *OBA* and *CTAX* cases, we assume 100% allocation.[15]

It should be mentioned here that allocation of allowances in the EU ETS is not identical to our modeling of OBA, mainly because our model is static. First of all, if an EU firm increases its output, it does not receive more allowances the same year – instead it receives more allowances in future years. For instance, allocation of allowances in the years 2026-30 is proportional to the firm’s activity level in 2019-2023. Still, the implication of this is that producers of OBA goods receive valuable assets in proportion to their output, i.e., an implicit output subsidy. Furthermore, if the expected emissions price follows Hotelling’s rule (increasing with the interest rate), the implicit (expected) subsidy is equal to the current emissions price times the product benchmark. For the highly exposed industries in the EU ETS, this translates into an allocation close to what we refer to as 100% allocation.[16]

In the *CTAX* case we first consider a variety of tax rates to check whether the analytical result carries over. That is, according to Proposition 1, the optimal consumption tax is equal to the implicit output subsidy of the *OBA* (referred to as “*100% CTAX*”), both from a regional and global welfare perspective. Subsequently, we focus on the *100% CTAX* case. The consumption tax is applied to both final consumption and intermediate use of OBA goods.

Table 3. Policy scenarios for the EU*

REF	Economy-wide emission price

[15] By 100% allocation, we mean that in a given scenario the number of free allowances given to the OBA sectors is equal to the (endogenous) emissions in these sectors. The implicit output subsidy of *OBA* is equal to the value of the free allowances per unit of production

[16] There is also an updating rule stating that if a firm’s average activity level the last two years deviates from its historic activity level by more than 15%, the allocation is adjusted up- or downwards accordingly. This may imply a stronger OBA effect for firms that are close to the threshold. We thank one of the referees for pointing out this.

OBA	*REF* + Output-based allocation to "OBA goods" 100% allocation (cf. footnote15)
CTAX	*OBA* + consumption tax for "OBA goods" The consumption tax level is expressed in terms of percentage share of the value of the OBA-rate

* See Table 2 and the text for definition of "OBA goods"

As mentioned before, in order to avoid explicit damage valuation from greenhouse gas emissions, we keep the global emissions constant across the three policy scenarios. This means that the EU adjusts its unilateral emission constraint so that the same global emission cap is reached. The cap is set equal to the global emissions in the *REF* scenario. As the two alternative policy scenarios turn out to reduce leakage compared to *REF* (see next subsection), the emission constraint in the EU will be slightly less stringent in *OBA* and *CTAX* than in *REF*.

3.4 Results

We start by looking at welfare effects (measured in terms of Hicksian equivalent variation of income), and compare with our main analytical results in Proposition 1. The *REF* scenario involves an economy-wide CO_2 price in the EU of 106 USD per ton (on average). When implementing output-based allocation (*OBA*), and adjusting the EU cap to keep global emissions unchanged, welfare in the EU decreases slightly vis-à-vis *REF*, whereas global welfare increases marginally.

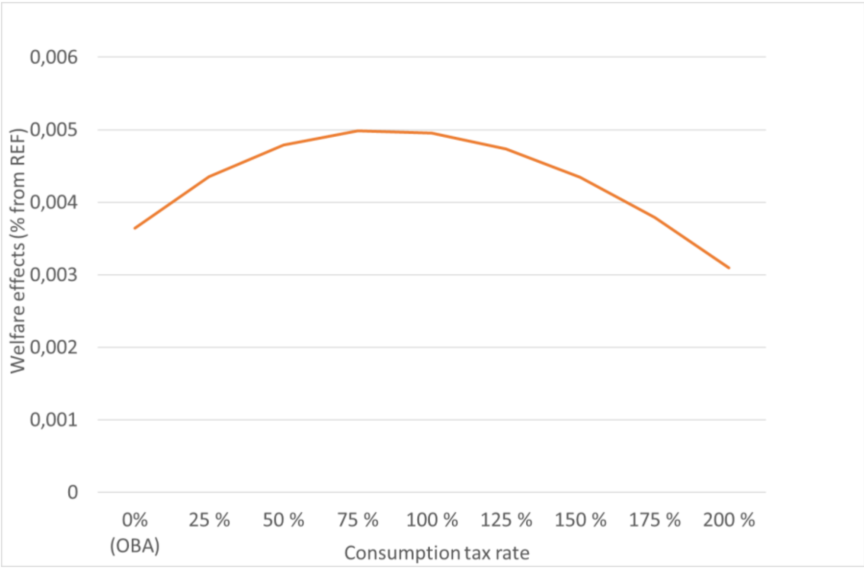

Figure 2. Welfare effects in the world vis-à-vis *REF*, for different consumption tax rates in the EU (in %). Average results based on 1000 runs. Percentages on the x-axis refer to the consumption tax level in percent of the OBA-rate

Remember that *OBA* has four important welfare effects: First, it reduces leakage, which is welfare-improving as it relaxes EU's own emission cap and increases global cost-effectiveness. Second, it involves subsidizing foreign consumption of the OBA goods, which is a negative side effect. Both these effects are bigger the more leakage exposed the sectors are. Third, *OBA* stimulates too much use of the OBA goods domestically, which has a negative welfare effect. The less leakage exposed the sectors are, the more important this third effect is. Fourth, *OBA* has terms-of-trade effects, which in general can be either positive or negative for the individual region depending on the trade pattern. As the EU is a net exporter of OBA goods, and output-based allocation tends to reduce the price of these goods, the terms-of-trade effects are likely negative for the EU.[17] Thus, there is one positive and three negative effects of *OBA* for the EU, and the simulations suggest that the net effect is negative. For global welfare, terms-of-trade effects are negligible since terms-of-trade benefits for one region are terms-of-trade losses for another region. Hence, we are left with the three first effects, which according to the simulations are net positive.

[17] Other regions are on aggregate better off when the EU implements *OBA*, which confirms the terms-of-trade deterioration for the EU.

When also implementing the consumption tax (*CTAX*) in the EU, we see from Figure 2 that the optimal consumption tax rate from a global welfare perspective is on average 80-85% of the OBA-rate. This is quite consistent with Proposition 1, which suggests that the optimal tax rate would be 100%. When looking more closely at the results, we find that the optimal consumption tax (from a global perspective) tends to decrease with the Armington elasticity. For low elasticities, the optimal tax rate is slightly above 100% of the OBA-rate.

According to Proposition 1, the optimal consumption tax rate is 100% also when considering regional welfare, in this case for the EU. This is not the case in the simulations, however. The optimal consumption tax rate for the EU is far above 100%. The explanation for this is the terms-of-trade effects, which were absent in the theoretical analysis.[18] Other regions are on average worse off when the consumption tax is imposed in the EU. Thus, increasing the consumption tax beyond 100% would involve a trade-off between EU welfare and global welfare. Furthermore, implementing a very high consumption tax could be seen as exploiting terms-of-trade effects rather than improving environmental quality, and might therefore be regarded as in conflict with the WTO. On the other hand, if the EU were to choose a consumption tax that is beneficial both for the EU and for the world in aggregate, a tax of about the same order as the OBA-rate would be appropriate.

At first glance, it may seem surprising that the consumption tax gives terms-of-trade benefits for the EU, as the EU is a net exporter of EITE goods (see above). Implementing a consumption tax normally depresses the market price. However, the tax is imposed on all purchase of EITE goods, including the use of EITE goods as intermediates in production of (other) EITE goods. Thus, the tax increases production costs for EITE producers in the EU, which we return to below in relation to leakage and competitiveness (cf. Figure 6). The net effect of the consumption tax is therefore

[18] The optimal consumption tax rate for the EU is in the range 850-900% of the *OBA*-rate. This may sound like a very high tax rate, but note that a 100% consumption tax amounts to less than 2.5% increase in the price of the different OBA goods (except Air Transport, for which the price increase is 8%). If we search for the optimal consumption tax rate *in the absence of OBA*, it is in the range 600-650%. Thus, from a regional point of view, a quite substantial consumption tax is beneficial, mostly due to terms-of-trade effects. Further, we observe that when *OBA* is implemented, the optimal consumption tax rate increases by around 250%-points (from 600-650% to 850-900%).

to reduce both supply and demand of EITE goods in the EU, and in most runs and for most EITE sectors, total output in non-EU regions slightly increase, reflecting higher international prices of these goods. Thus, in aggregate the negative supply effect is stronger than the negative demand effect. Although this may be considered a disadvantage from a competitiveness perspective (see below), it is an advantage from a terms-of-trade perspective as the EU is a net exporter of these goods.

Next, we want to focus on the *100% CTAX* variant, and compare it with *OBA*, which is similar to the current policy in the EU. We are interested in whether *100% CTAX* is always an improvement vis-à-vis *OBA*, i.e., irrespective of whether the leakage exposure (Armington elasticities) is high or low. The results are shown in Figures 3 (global welfare) and 4 (EU welfare).

The figures show that the consumption tax (*100% CTAX*) improves global welfare vis-à-vis *OBA* in almost all simulations (966 of 1000 runs), and improves EU welfare in all simulations.[19] Thus, the results suggest that implementing a consumption tax in addition to output-based allocation is smart hedging against carbon leakage, both from a regional (EU) and global perspective. The consumption tax mitigates the third effect of *OBA* mentioned above, i.e., too much use of the OBA goods domestically. For the EU, the beneficial terms-of-trade effects come in addition.

[19] The average welfare gain for the EU amounts to 0.07% of *REF* welfare, or around 30 billion USD per year.

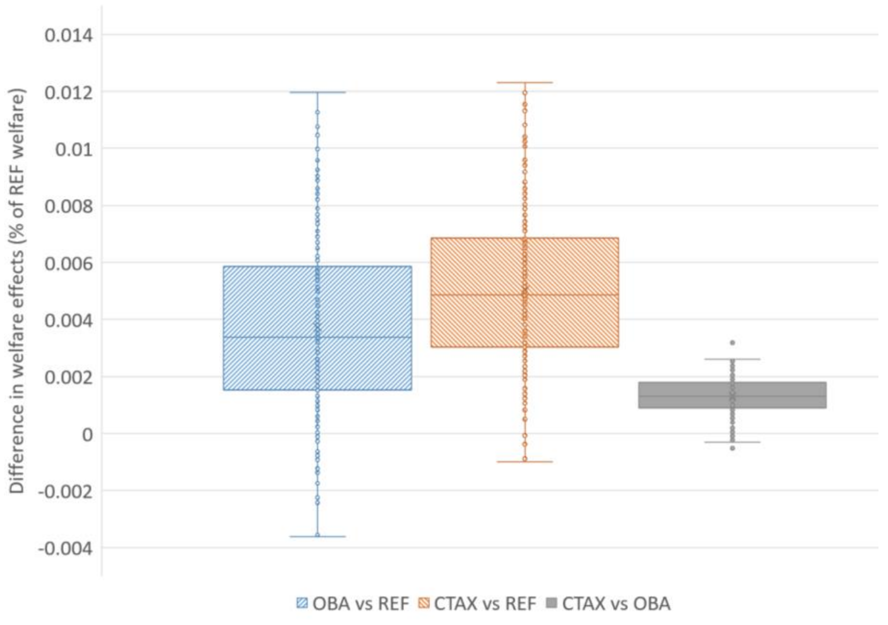

Figure 3. Differences in global welfare effects between scenarios (in % of REF welfare). Box-and-Whisker plot based on 1000 runs[20]

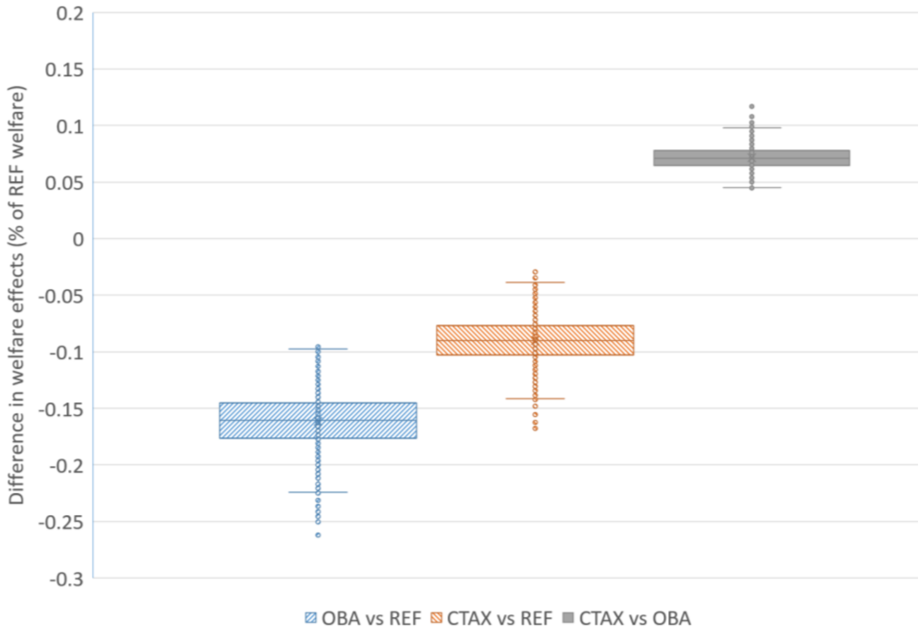

Figure 4. Differences in welfare effects in the EU between scenarios (in % of *REF* welfare). Box-and-Whisker plot based on 1000 runs

[20] The Box-and-Whisker plot shows minimum, first quartile, median, third quartile, and maximum.

As pointed out before, the less leakage exposed OBA goods are, the more likely it is that the effects of *OBA* are negative. Further, the more beneficial it would be to supplement *OBA* with a consumption tax. This is confirmed in our simulations, see Figure 5. The figure shows how EU and global welfare gains from the consumption tax (i.e., *100% CTAX* vs. *OBA*) vary with the weighted average Armington elasticity of the OBA goods.[21] We notice that the consumption tax has bigger welfare gains when the Armington elasticity is low. As Armington elasticities can be seen as a proxy for leakage exposure, we conclude that the less leakage exposed the sectors are, the more important it is to correct the undesired effects of output-based allocation, both from a regional and global perspective.

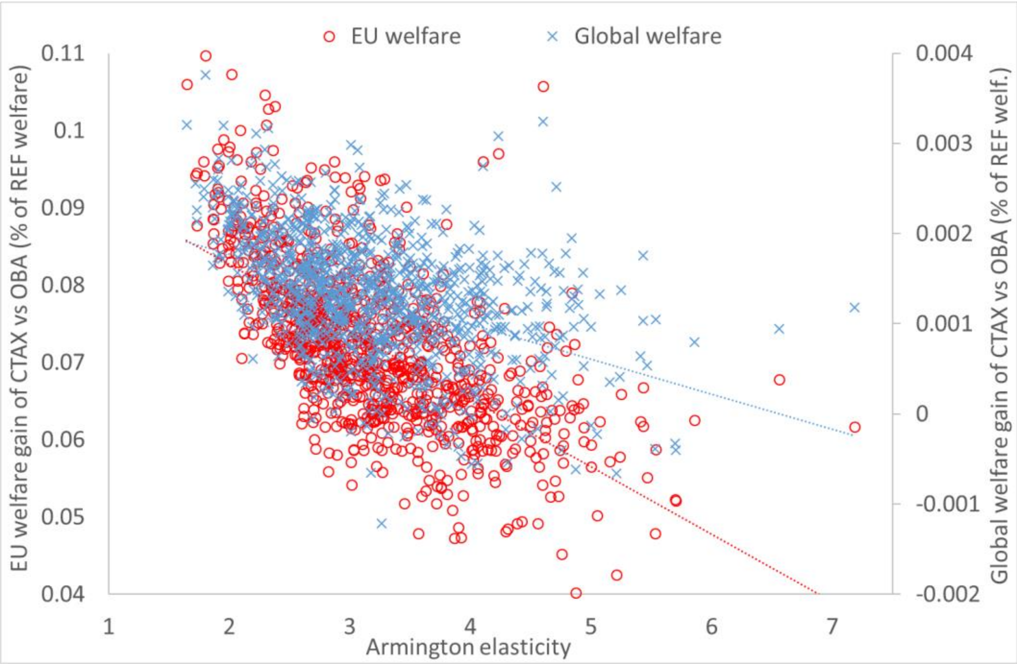

Figure 5. Relationship between weighted average Armington elasticity and EU welfare gain (left axis) and global welfare gain (right axis) from *100% CTAX* versus *OBA* (in % of *REF* welfare). Scatter plot based on 1000 runs

Although the consumption tax may be regarded as smart hedging against leakage, it doesn't mean that leakage is reduced. In fact, the leakage rate is 1 percentage point *higher* in *100% CTAX* than in *OBA*. This may seem surprising at first – after all the

[21] The weights used are the production value of the sectors.

consumption tax reduces demand for OBA goods, which are typically emission-intensive and trade-exposed. The explanation is that the consumption tax not only reduces consumption of OBA goods in the EU – it also shifts to some degree market shares from the EU to non-EU regions. In fact, overall output of OBA goods outside the EU increases slightly. The reason is that the consumption tax not only applies to end-use of OBA goods, but also to intermediate use of these goods. As many OBA sectors use various OBA goods as inputs in their production, their costs of production increase when this tax is introduced. This makes domestic production of OBA goods slightly less competitive, and shifts production to some degree out of the EU. As one motivation for allocating allowances, in addition to mitigating leakage, is to prevent losses in competitiveness, this may be regarded as an undesirable implication of the consumption tax.

We can further investigate the competitiveness implications, by examining the effects on net exports in the three scenarios across three important manufacturing industries, that is, Iron & Steel (I_S), Non-Metallic Minerals (NMM), and Chemical Products (CRP), see Figure 6. We see that carbon pricing alone reduces net export as production is relocated outside Europe – as expected. The biggest effects, measured in monetary values, are seen for Chemical Products. *OBA* mitigates the loss in competitiveness, but net export is still negative (vis-à-vis *BaU*) for all three sectors. On average, the reduction in net export is about halved when *OBA* is implemented. With the consumption tax, net export drops again, but is slightly closer to the *OBA* outcome than the *REF* outcome. Note however that the reduced net export from the consumption tax amounts to less than 0.5% of EU production of these goods.

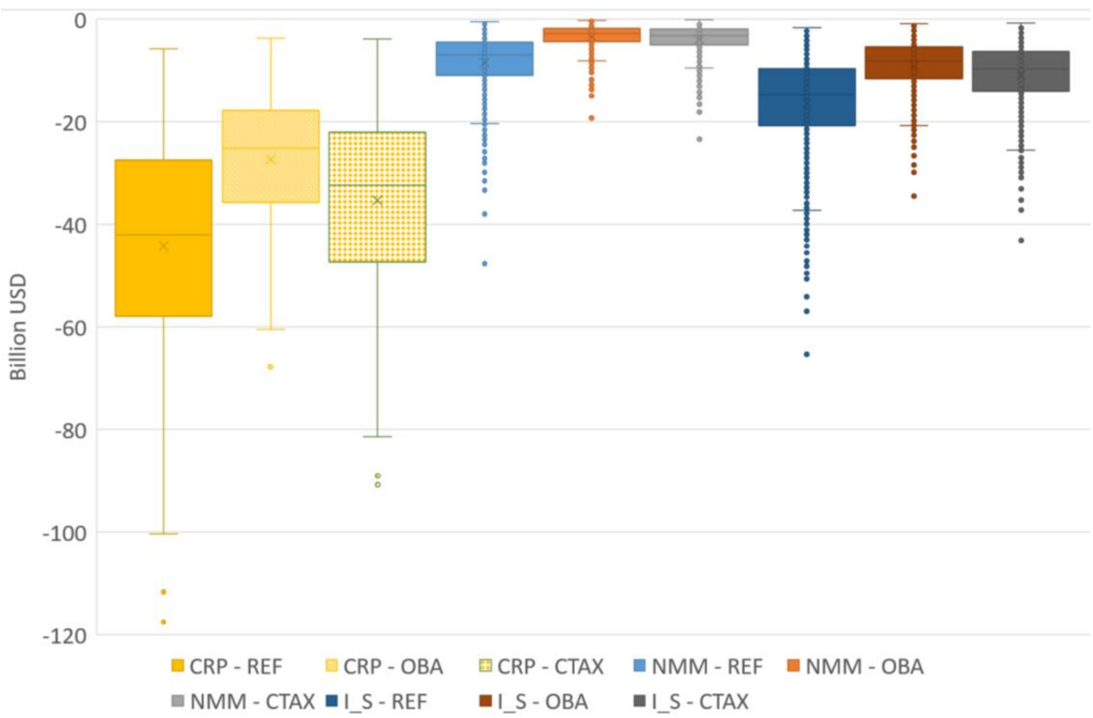

Figure 6. Effects on net trade (export minus import) in the EU of three EITE products (CRP, NMM, I_S) in three policy scenarios (*REF*, *OBA*, *CTAX*). Changes vis-à-vis BaU (billion USD). Box-and-Whisker plot based on 1000 runs

3.5 Sensitivity analysis

We examine the sensitivity of our results along different dimensions, where we focus on the welfare effects of imposing a consumption tax in a situation where an ETS is already in place together with output-based allocation to the same sectors as before (i.e., *100% CTAX* vs *OBA*). Figures 7-8 show regional welfare effects, but we also discuss global welfare effects in the text.

Figure 7 considers the case where the policy region differs.[22] We notice that if China or the US is the policy region, implementing a consumption tax is (almost) always

[22] When we change the policy region, we first construct a new reference scenario (*REF*) where the policy region reduces its emissions by 20%. Then we keep global emissions at the same level as in this new *REF* scenario. In the case with several regions acting together, we assume uniform CO_2 price across these regions. It could be argued that it is more likely with higher CO_2 prices in the EU than in the two other regions considered (USA and China), but our choice makes it easier to compare the effects of the policies in the different regions. An interesting next step could be to model a game in climate policies, focusing on anti-leakage measures, and e.g. examine whether there exists a unique Nash equilibrium and the characteristics of such an equilibrium (see e.g. Kaushal, 2020).

beneficial (both for the policy region and for the world in aggregate), but the benefits are smaller than in the EU case. If all three regions have implemented ETS with *OBA* (but with different CO_2 prices), imposing a consumption tax in all regions is again beneficial and the aggregate effects for the three regions are slightly higher than the weighted average of the single region benefits (this is also the case from a global welfare perspective). Thus, the more regions are implementing carbon pricing jointly with *OBA*, the more beneficial it is to also impose the consumption tax.

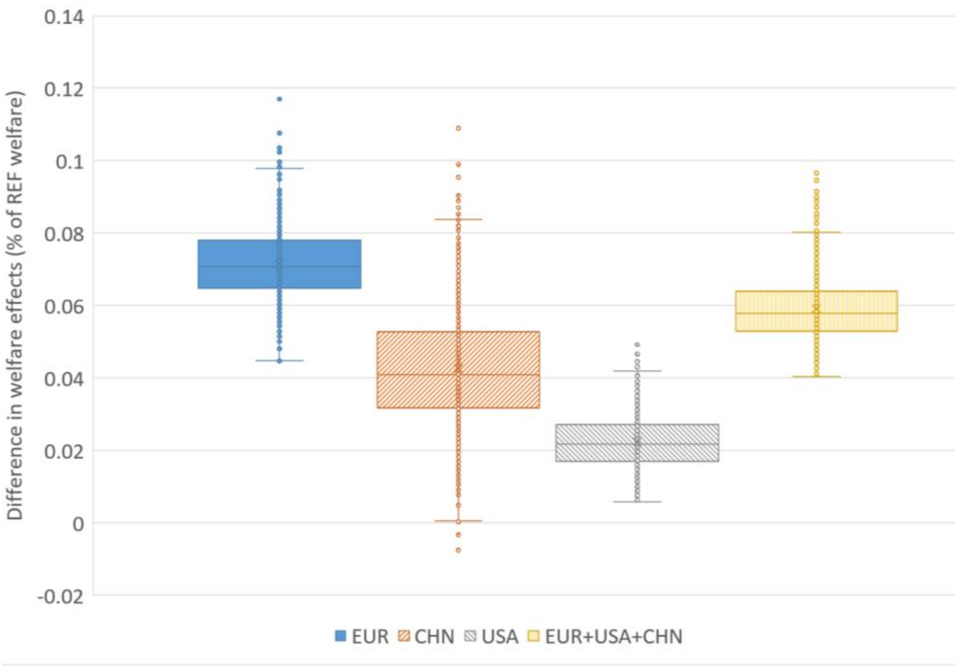

Figure 7. Regional welfare effects of *100% CTAX* vis-à-vis *OBA* (in % of *REF* welfare). Box-and-Whisker plot based on 1000 runs

Next, we consider alternative assumptions about the size of the emission reduction in the EU. If the EU reduces emissions by 30% instead of 20%, on average the benefits of the consumption tax for the EU increase by about 50%, cf. Figure 8, while the global welfare gains double. Furthermore, if a very ambitious climate policy is introduced in the EU, reducing emissions by 50%, the welfare gains from the consumption tax triple for the EU (compared to the base case of 20% reduction), while global welfare benefits increase more than tenfold. In both cases, the consumption tax enhances welfare in all the runs.

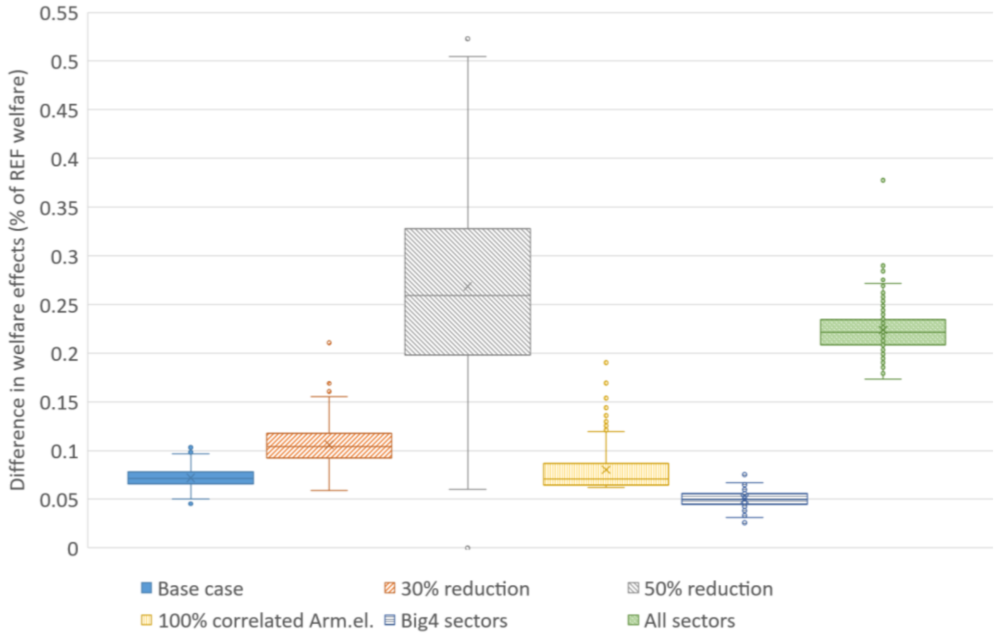

Figure 8. Welfare effects in the EU of *100% CTAX* vis-à-vis *OBA* (in % of *REF* welfare). Box-and-Whisker plot based on 1000 runs

If output-based allocation is only provided to the four big EITE sectors Iron & Steel, Non-Metallic Minerals, Chemical Products, and Refined Oil, the consumption tax is still increasing welfare for the EU, but the benefits are somewhat reduced. Moreover, the global welfare gains of the consumption tax disappear. On the other hand, if *OBA* were provided to all sectors of the ETS, including the electricity sector, the consumption tax would become quite desirable as it reduces the too high consumption of electricity. The global welfare gains would then increase almost tenfold compared to the base case simulations.

Finally, we notice that to what degree the Armington elasticities are correlated across sectors has fairly limited importance for the welfare effect of the consumption tax. The average welfare benefit (across the Monte Carlo simulations) is almost the same in the two extreme cases (i.e., no correlation and 100% correlation).[23]

[23] We have also tested the effects of different fossil fuel elasticities. The results are fairly similar to the base case results and are thus not shown in the figure.

4. Concluding remarks

The Paris Agreement calls for global action to mitigate climate change. Yet, the stringency of climate policies differs quite substantially between countries, and will likely continue to do so in the future reflecting differences in historical responsibilities and economic capacity to pay for mitigation measures. Cross-country differences in the explicit or implicit price tags on greenhouse gas emissions will result in carbon leakage associated with the relocation of emission-intensive and trade-exposed (EITE) production from countries with more stringent climate policies to countries with laxer regulations. To reduce the extent of counterproductive leakage, a common regulatory approach is to supplement an emission trading system with free allocation of allowances proportional to the output of industries at risk of carbon leakage, so-called output-based allocation (OBA). In the EU ETS, OBA has been in place since 2013, and will continue also after 2020.

A disadvantage of granting OBA to EITE goods is that it tends to stimulate too much domestic consumption of these goods, because output-based allocation works as an implicit output subsidy which in turn restrains substitution towards less emission-intensive goods. In this paper we have analyzed the impacts of adding a consumption tax on all (intermediate as well as final) use of the EITE goods. Our theoretical analysis shows that it is optimal from both a regional and global welfare perspective to impose a consumption tax that is equivalent in value to the OBA subsidy rate.

We provide a reality check of our theoretical finding in the context of the EU ETS. Using a multi-region multi-sector computable general equilibrium model based on empirical data we show that the addition of sector-specific consumption taxes increases EU welfare, irrespective of how leakage exposed the sectors actually are. Martin et al. (2014) have identified that there has been substantial overallocation of allowances in the EU ETS for the given carbon leakage risk. Our results suggest that climate policy becomes more cost-effective with respect to uncertainties about leakage exposure when adding consumption taxes. The distortive effects of allowance overallocation – by including too many sectors with limited carbon leakage risk or warranting too generous allocation – are attenuated. Additional administrative costs of implementing such consumption taxes in practice are likely to be negligible, as the consumption tax rates should be set at the level of the OBA subsidy rates, i.e., based on information that is already available. Supplementing OBA with consumption taxes is also less contentious than implementing border carbon adjustments, as the EU is currently considering. We thus conclude that supplementing output-based allocation with consumption taxes constitutes smart hedging against carbon leakage.

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Appendix A: Analytical proofs and derivations

Analytical model solution:

Let p^{xj}, p^{zj}, p^{dj} and p^{fj} denote the market prices (excluding taxes) of goods *x*, *z*, *d* and *f* in Region *j*. Further, let capital letters indicate consumer prices (including taxes), such that P^{x}, P^{zj}, P^{dj} and P^{fj} denote the consumer prices of goods *x*, *z*, *d* and *f* in Region *j* ($P^{x1} = P^{x2} = P^{x}$).

Competitive producers maximize profits:

$$\begin{aligned}
\pi^{xj} &= \max_{x^{1j},x^{2j}} \left(p^{x1}x^{1j} + p^{x2}x^{2j} - c^{x}\left(x^{j}\right)\right), \quad j=1,2,\\
\pi^{zj} &= \max_{z^{j},e^{zj}} \left(p^{zj}z^{j} - c^{z}\left(z^{j},e^{zj}\right) - t^{j}e^{zj}\right), \quad j=1,2,\\
\pi^{d} &= \max_{\bar{d}^{1},\bar{d}^{2},e^{d}} \left(\left(p^{d1}+s^{1}\right)\bar{d}^{1} + \left(p^{d2}+s^{1}\right)\bar{d}^{2} - c^{d}\left(d,e^{d}\right) - t^{1}e^{d}\right),\\
\pi^{f} &= \max_{\bar{f}^{1},\bar{f}^{2},e^{f}} \left(p^{f1}\bar{f}^{1} + p^{f2}\bar{f}^{2} - c^{f}\left(f,e^{f}\right) - t^{2}e^{f}\right),
\end{aligned} \tag{6}$$

where we use the market-clearing constraint for the EITE goods in the two last expressions (sales equal consumption). The firms' first order conditions for profit maximization are:

$$\begin{aligned}
&p^{x1} = p^{x2} = p^{x} = c^{x},\\
&p^{zj} = c^{z} + \xi^{z}\phi^{z}a^{zj}, \quad j=1,2,\\
&p^{d1} + s^{1} = p^{d2} + s^{1} = c^{d} + \xi^{y}\phi^{y}a^{d},\\
&p^{f1} = p^{f2} = c^{f} + \xi^{y}\phi^{y}a^{f},\\
&\phi^{z}a^{zj} = t^{j},\ \phi^{y}a^{d} = t^{1}, \phi^{y}a^{f} = t^{2}, \quad j=1,2.
\end{aligned} \tag{7}$$

Here $a^{gj} = \xi^{g}g^{j} - e^{gj}$, i.e., the emission reductions for good *g* in Region *j* caused by lower emission intensity induced by the climate policy regulation, so the equation in the bottom row states that the emission price equals the cost of marginal emission reductions. We have $a^{z1} = \xi^{z}z^{1} + e^{f} + e^{d} + e^{z2} - \bar{E}$, and similarly for the other goods. Note that the market equilibrium for the x^j good requires that $x^{j} = \bar{x}^{1j} + \bar{x}^{2j}$; i.e., the volume of *x* produced in Region *j* must equal the sum of consumption of good x originating from Region *j* in both regions. We also observe that the firms' profits π^{xj} in (6) are concave in production in equilibrium, given the demand functions associated with the consumer utility maximization problem (8). The model does not uniquely determine production of *x*, however, only that we must have $x^{1} + x^{2} = \bar{x}^{1} + \bar{x}^{2}$. This does not matter for the results, because there are no emissions or profits associated with production of x.

The representative consumer in Region j solves:

$$\max_{\bar{x}^j,\bar{y}^j,\bar{z}^j} u\left(\bar{x}^j,\bar{y}^j,\bar{z}^j\right), \quad j=1,2, \tag{8}$$

subject to equations (1), (2) and the budget constraint:

$$m^j + A^j \geq p^{xj}\bar{x}^j + p^{zj}\bar{z}^j + \left(p^{dj}+v^j\right)\bar{d}^j + \left(p^{fj}+v^j\right)\bar{f}^j, \quad j=1,2, \tag{9}$$

where m^j denotes an exogenous monetary endowment and A^j is a term that includes firm profits and government income from sale of emission permits and net taxes (see below). We follow the usual assumption that the representative consumers and firms do not consider the redistribution of taxes and profits when choosing consumption and production levels. We observe that the budget constraints must hold with equality in equilibrium (for finite m^j), because utility can always be increased by more consumption of one or more goods (cf., the utility function (1)).

We have:

$$\begin{aligned}
A^1 &= \sum_g t^1 e^{g1} + v^1\left(\bar{d}^1+\bar{f}^1\right) - s^1 d + \sum_g \pi^{g1} \\
&= t^1\left(e^{z1}+e^d\right) + v^1\left(\bar{d}^1+\bar{f}^1\right) - s^1\left(\bar{d}^1+\bar{d}^2\right) + p^{z1}\bar{z}^1 - c^z\left(z^1,e^{z1}\right) - t^1 e^{z1} + \left(p^{d1}+s^1\right)\bar{d}^1 + \left(p^{d2}+s^1\right)\bar{d}^2 - c^d\left(d^1,e^d\right) - t^1 e^d \\
&= v^1\left(\bar{d}^1+\bar{f}^1\right) + \left(p^{z1}\bar{z}^1 - c^z\left(z^1,e^{z1}\right)\right) + \left(p^{d1}\bar{d}^1 + p^{d2}\bar{d}^2 - c^d\left(d^1,e^d\right)\right),
\end{aligned}$$

for Region 1. Inserting in the budget constraint of Region 1, we have:

$$\begin{aligned}
& m^1 + v^1\left(\bar{d}^1+\bar{f}^1\right) + p^{z1}\bar{z}^1 - c^z\left(z^1,e^{z1}\right) + p^{d1}\bar{d}^1 + p^{d2}\bar{d}^2 - c^d\left(d^1,e^d\right) \geq p^{x1}\bar{x}^1 + p^{z1}\bar{z}^1 + \left(p^{d1}+v^1\right)\bar{d}^1 + \left(p^{f1}+v^1\right)\bar{f}^1 \\
&\Leftrightarrow m^1 + p^{d2}\bar{d}^2 - p^{f1}\bar{f}^1 - c^x\bar{x}^1 - c^d\left(d^1,e^d\right) - c^z\left(z^1,e^{z1}\right) \geq 0 \\
&\Leftrightarrow m^1 + \left(c^d + \xi^y t^1 - s^1\right)\bar{d}^2 - c^f\bar{f}^1 - c^x\bar{x}^1 - c^d\left(d^1,e^d\right) - c^z\left(z^1,e^{z1}\right) \geq 0,
\end{aligned} \tag{10}$$

where we used (7) in the equivalences. The budget constraint for Region 2 can be rewritten similarly.

The consumer's Lagrangian is:

$$L^j = u^j\left(\bar{x}^j,\bar{y}^j,\bar{z}^j\right) + \lambda^j\left(m^j + A^j - p^{xj}\bar{x}^j - p^{zj}\bar{z}^j - \left(p^{dj}+v^j\right)\bar{d}^j - \left(p^{fj}+v^j\right)\bar{f}^j\right), \quad j=1,2. \tag{11}$$

The CES utility function is strictly concave in the decision variables under our assumptions that $\beta^j, \alpha^{xj}, \alpha^{yj}, \alpha^{zj} > 0$ and $\rho, \theta < 1$. Hence, the Lagrangian (11) is strictly concave, being a sum of strictly concave and weakly concave functions. The first order conditions associated with (11) simplify to:

$$\begin{aligned}
&\frac{p^{xj}}{p^{zj}} = \frac{\alpha^{xj}}{\alpha^{zj}} \left(\frac{\bar{z}^j}{\bar{x}^j} \right)^{1-\rho}, \quad j = 1, 2, \\
&\frac{p^{dj} + v^j}{p^{fj} + v^j} = \frac{\beta^j}{1-\beta^j} \left(\frac{\bar{f}^j}{\bar{d}^j} \right)^{1-\rho}, \quad j = 1, 2, \\
&\frac{p^{xj}}{p^{dj} + v^j} = \frac{1}{\beta^j} \frac{\alpha^{xj}}{\alpha^{yj}} \frac{\left(\bar{d}^j\right)^{1-\theta}}{\left(\bar{x}^j\right)^{1-\rho}} \left(\beta \left(\bar{d}^j\right)^{\theta} + (1-\beta) \left(\bar{f}^j\right)^{\theta} \right)^{1-\frac{\rho}{\theta}}, \quad j = 1, 2.
\end{aligned} \tag{12}$$

Together with the budget constraint (9), (12) constitutes a system of four equations with four unknowns (for each *j*).

We have the following result, which is useful in comparing the outcomes of the different regulatory regimes.[24]

Lemma 1. *The interior solution competitive equilibrium is characterized by:*

$$\frac{c^x}{c^z + \xi^z t^{j*}} = \frac{P^{x*}}{P^{zj*}} = \frac{\alpha^{xj}}{\alpha^{zj}} \left(\frac{\bar{z}^{j*}}{\bar{x}^{j*}} \right)^{1-\rho}, \tag{13}$$

$$\frac{c^d + \xi^y t^{1*} - s^1 + v^j}{c^f + \xi^y t^{2*} + v^j} = \frac{P^{dj*}}{P^{fj*}} = \frac{\beta^j}{1-\beta^j} \left(\frac{\bar{f}^{j*}}{\bar{d}^{j*}} \right)^{1-\rho}, \tag{14}$$

$$\frac{c^x}{c^d + \xi^y t^{1*} - s^1 + v^j} = \frac{P^{x*}}{P^{dj*}} = \frac{\alpha^{xj}}{\alpha^{yj}} \frac{1}{\beta^j} \left(\beta^j \left(\bar{d}^{j*}\right)^{\theta} + (1-\beta^j) \left(\bar{f}^{j*}\right)^{\theta} \right)^{1-\frac{\rho}{\theta}} \frac{\left(\bar{d}^{j*}\right)^{1-\theta}}{\left(\bar{x}^{j*}\right)^{1-\rho}}, \tag{15}$$

$$t^{j*} = \phi^z a^{zj*}, t^{1*} = \phi^y a^{d*}, t^2 = \phi^y a^{f*}, \tag{16}$$

with $j \in \{1, 2\}$ *, the global emissions cap (4) and the budget constraints:*

$$\begin{aligned} m^1 + \left(\left(c^d + \xi^y t^{1*} - s^1 \right) \overline{d}^{2*} - c^f \overline{f}^{1*} \right) &= c^x \overline{x}^{1*} + c^z \left(z^{1*}, e^{z1*} \right) + c^d \left(d^*, e^{d*} \right) \quad (j=1), \\ m^2 + \left(c^f \overline{f}^{1*} - \left(c^d + \xi^y t^{1*} - s^1 \right) \overline{d}^{2*} \right) &= c^x \overline{x}^{2*} + c^z \left(z^{2*}, e^{z2*} \right) + c^f \left(f^*, e^{f*} \right) \quad (j=2), \end{aligned} \tag{17}$$

Here equations (13) to (16) follows from (7) and (12), and equation (17) is equivalent with (10) (the derivation of the budget constraint for Region 2 is similar and not repeated here). These are the necessary conditions for solving the analytical model in Section 2. Note that the necessary conditions (13) to (17) are also sufficient, because the second order conditions are fulfilled for firms (profits are concave in production) and the representative consumer (the Lagrangian is concave in consumption of the four goods).

In equations (13) to (15) the first equalities follow from the producers' first order conditions, whereas the second equalities follow from the consumers' first order conditions. Note that $c^g + \xi^g t^j = c^g + \xi^g \phi^g a^{gj}$ represents the marginal production cost for commodity *g* in Region *j* at the emission intensity that follows from the region's emission cap (4). Equation (16) states the familiar result that the emission price t^j equals marginal abatement costs $\phi^g a^{gj}$. Further, the left-hand sides of the budget constraints (17) are monetary endowments m^j plus net income from trade (c^f and $c^d + \xi^y t^1 - s^1$ are the equilibrium prices on imported EITE goods in regions 1 and 2, respectively), whereas the right-hand sides are production cost.

When it comes to consumption in the non-regulating Region 2, we observe from Lemma 1 that relative prices and hence relative consumption levels are equal under *OBA* and *CTAX*, because the consumption tax v^1 only affects prices in the domestic Region 1 ($v^2 = 0$ in equations (14) and (15)). This result relies on the constant-returns-to-scale cost function.

Assume first that there is unilateral emission trading (REF) in Region 1. Then we get from equation (14) when comparing with the first-best (FB):

$$\frac{P^{dj,REF}}{P^{fj,REF}} = \frac{c^d + \xi^y t^{1,REF}}{c^f} > \frac{c^d + \xi^y t^{FB}}{c^f + \xi^y t^{FB}} = \frac{P^{dj,FB}}{P^{fj,FB}}, \quad j = 1,2. \tag{18}$$

We see that unilateral emission trading causes too large a share of the composite EITE good *y* originating from abroad, relative to the first-best (*FB*) allocation, with associated carbon leakage.

Equation (15) gives:

$$\frac{P^{x,OBA}}{P^{dj,OBA}} = \frac{c^x}{c^d} > \frac{c^x}{c^d + \xi^y t^{FB}} = \frac{P^{x,FB}}{P^{dj,FB}}, \quad j = 1, 2, \tag{19}$$

implying that *OBA* causes too much consumption of the emission-intensive *d* good, relative to the clean good *x*, as compared to the first-best case. Moreover, dividing equation (15) by equation (13), we get:

$$\frac{P^{zj,OBA}}{P^{dj,OBA}} = \frac{c^z + \xi^z t^{OBA}}{c^d} > \frac{c^z + \xi^z t^{FB}}{c^d + \xi^y t^{FB}} = \frac{P^{zj,FB}}{P^{dj,FB}}, \quad j = 1, 2, \tag{20}$$

which implies too much consumption of *d* relative to the non-tradable emission-intensive good *z*, as compared to the first-best case.

Let the permit price under *CTAX* be equal to the permit price under global emission trading ($t^{1,CTAX} = t^{FB} = t$). Then we have:

$$\frac{P^{x,CTAX}}{P^{z1,CTAX}} = \frac{c^x}{c^z + \xi^z t} = \frac{P^{x,FB}}{P^{z1,FB}}, \frac{P^{d1,CTAX}}{P^{f1,CTAX}} = \frac{c^d + \xi^y t}{c^f + \xi^y t} = \frac{P^{d1,FB}}{P^{f1,FB}}, \frac{P^{x,CTAX}}{P^{d1,CTAX}} = \frac{c^x}{c^d + \xi^y t} = \frac{P^{x,FB}}{P^{d1,FB}}, \tag{21}$$

which shows that a *CTAX* regime with $v^1 = s^1$ replicates the relative prices in the home region under global emission trading when $t^{1,CTAX} = t^{FB} = t$.

We last observe the presence of the subsidy s^1 in the budget constraint (17). Net income from trade for Region 1 is reduced by $s^1 \overline{d}^{2*}$, i.e., the subsidy times the consumption of *d* in Region 2. The explanation is that the output subsidy creates a wedge between the price on *d* and marginal production cost. With 100% *OBA* ($s^1 = \xi^y t^1$), marginal production cost is $c^d + \xi^y t^1$, whereas the export price is $p^{d2} = c^d$. Thus *OBA* involves subsidizing foreign consumption of the domestically produced EITE good *d*. The cost of this subsidy, $s^1 \overline{d}^2$, is captured as a monetary transfer from Region 1 to Region 2 in the budget constraints (17). Note that $s^1 \overline{d}^1$ cancels out in the budget constraint (17) for Region 1, because the representative consumer in this case subsidizes domestic consumption $\overline{d}^1$, as opposed to foreign consumption $\overline{d}^2$.

Lemma 1 in the limit cases of perfect EITE good compliments and substitutes:

With perfect compliments, $\theta \to -\infty$, equation (2) becomes $y = \min\left(\beta^j \overline{d}^j, \left(1-\beta^j\right)\overline{f}^j\right)$,

which is maximized if $\beta^j \overline{d}^j = \left(1-\beta^j\right)\overline{f}^j$. Utility from the EITE good is $\beta^j \overline{d}^j$ (or,

equivalently, $\left(1-\beta^j\right)\overline{f}^j$). Hence, we must have $\beta^j \overline{d}^j / \left(1-\beta^j\right) = \overline{f}^j$ in optimum. The

representative consumer's Lagrangian is:

$$L^{PC,j} = \left(\alpha^{xj}\left(\overline{x}^j\right)^{\rho} + \alpha^{yj}\left(\beta^j \overline{d}^j\right)^{\rho} + \alpha^{zj}\left(\overline{z}^j\right)^{\rho}\right)^{\frac{1}{\rho}} + \lambda^j\left(m^j + A^j - p^{xj}\overline{x}^j - p^{zj}\overline{z}^j - \left(\left(p^{dj} + v^j\right) - \left(p^{fj} + v^j\right)\frac{\beta^j}{1-\beta^j}\right)\overline{d}^j\right).$$

and the competitive equilibrium is characterized by Lemma 1 with equations (14) and (15) replaced by:

$$\overline{f}^j = \frac{\beta^j}{1-\beta^j}\overline{d}^j,$$

$$\frac{c^x}{c^d + \xi^y t^1 - s^1 + v^j} = \frac{\alpha^{xj}}{\alpha^{yj}} \frac{1}{\left(\beta^j\right)^{\rho}} \left(\frac{\overline{d}^j}{\overline{x}^j}\right)^{1-\rho}.$$

With perfect substitutes, $\theta \to 1$, equation (2) becomes $\beta^j \overline{d}^j + \left(1-\beta^j\right)\overline{f}^j$. Demand for *d*

(*f*) is zero if $\left(1-\beta^j\right)/\beta^j < (>) P^{dj} / \mathrm{P}^{fj}$. Hence, a corner solution is likely to occur in

competitive equilibrium with constant returns to scale in production. There also exists

a continuum of interior solutions if $\left(1-\beta^j\right)/\beta^j = P^{dj} / \mathrm{P}^{fj}$. We do not solve the model in

the limiting case with perfect substitutes here; see Böhringer et al. (2017) for an analysis of output-based rebating and EITE good consumption taxes under the assumption of perfect substitute EITE goods (with convex production costs).

Proof of Proposition 1: We first observe that all equations in Lemma 1 are equal under *OBA* and *CTAX* for Region 2, and that consumption in Region 2 is unaffected by v^1 (this relies on constant returns to scale in production). We therefore let exports x^{21} and d^2 be treated as constants (determined by Lemma 1 with *CTAX/OBA*) in this proof.[25] Further, regarding *x*, the cost of consuming *x* in Region 1 is $c^x x^{11} + p^{x1}x^{21} = c^x \overline{x}^1$,

[25] Whereas restricting x^{21} to be constant does not matter for the zero emission and zero profit good *x* (profits from exports of *x* is $p^{x2}x^{12} - c^x x^{12} = 0$), the social planner solution would have the exports of domestic EITE good d^2 satisfy $p^{d2} = c^d + \varsigma\xi^y$ if given the opportunity (*OBA* and *CTAX* both feature $p^{d2} = c^d$, implying too much foreign consumption of the domestic EITE good).

(cf., (7) and (3)). Hence, $c^x \overline{x}^1$ is the cost of consuming x in the social planner's Lagrangian L^{SP} below.

Assume that a social planner maximizes Region 1 welfare, given the utility function (1), the exogenous global emissions cap (4), the production cost (5) and the budget constraint. We constrain the social planner from exploiting market power and foreign firms are price takers. Further, the regulator knows that foreign emissions are unregulated and internalizes the increased abatement demanded to uphold the global emissions cap to compensate for foreign emissions associated with imports of $\overline{f}^1$. The social planner's Lagrangian is:

$$L^{SP} = u^1\left(\overline{x}^1, \overline{y}^1, \overline{z}^1\right) + \lambda\left(m^1 - c^x \overline{x}^1 - c^z\left(z, e^{z1}\right) - c^d\left(d, e^d\right) + p^{d2} d^2 - c^f \overline{f}^1\right) + \mu\left(\overline{E} - e^{z1} - \zeta^z z^2 - e^d - \zeta^y f\right),$$

where λ and μ are the Lagrange multipliers associated with the budget constraint and the global emissions cap (4), respectively. The Lagrangian is maximized w.r.t $\overline{x}^1$, $\overline{z}^1$, $\overline{d}^1$, $\overline{f}^1$, e^{z1} and e^d. The first order conditions imply:

$$\begin{aligned}
&\frac{c^x}{c^z + \varsigma\xi^z} = \frac{\alpha^{x1}}{\alpha^{z1}}\left(\frac{\overline{z}^1}{\overline{x}^1}\right)^{1-\rho}, \\
&\frac{c^d + \varsigma\xi^y}{c^f + \varsigma\xi^y} = \frac{\beta^1}{1-\beta^1}\left(\frac{\overline{f}^1}{\overline{d}^1}\right)^{1-\rho}, \\
&\frac{c^x}{c^d + \varsigma\xi^y} = \frac{\alpha^{x1}}{\alpha^{y1}}\frac{1}{\beta^1}\left(\beta^1\left(\overline{d}^1\right)^{\theta} + \left(1-\beta^1\right)\left(\overline{f}^1\right)^{\theta}\right)^{1-\frac{\rho}{\theta}}\frac{\left(\overline{d}^1\right)^{1-\theta}}{\left(\overline{x}^1\right)^{1-\rho}}, \\
&\varsigma \equiv \frac{\mu}{\lambda} = \phi^z a^{z1} = \phi^y a^d.
\end{aligned} \tag{22}$$

The necessary conditions (22) are, together with (4) and (17), also sufficient, because the Lagrangian L^{SP} is concave in the decision variables. Together with the budget constraint (17) (for $j=1$) and the global emission cap (4), (22) constitutes a system of 7 equations with 7 unknowns which solves social planners' problem.

The admissibility conditions (4) and (17) enter both in the social planners solution and the competitive equilibrium in Lemma 1. Further, the remaining equations (13) to (16) in Lemma 1 for $j=1$ are equal to (22) under *CTAX* regulation with $v^1 = s^1 = \zeta^y t^1$ (here we use that $\varsigma = t^{1,CTAX}$, because the endogenous ς and $t^{1,CTAX}$ enter identical fully determined systems of equations (except for production of *x*)). It follows that the *CTAX* regime described in Proposition 1 solves the social planner's problem (and hence maximizes welfare in Region 1). That the *CTAX* regime described in Proposition 1 also maximizes global welfare follows immediately, because the allocation in Region 2 is unaffected by the consumption tax v^1. This proves Proposition 1.

Appendix B: Algebraic summary of computable general equilibrium (CGE) model

We provide a compact algebraic description for the generic multi-region multi-sector CGE model underlying our quantitative simulation analysis. Tables B.1 – B.5 explain the notations for variables and parameters employed within our algebraic exposition. The algebraic summary is organized in three sections that state the three classes of economic equilibrium conditions constituting a competitive market outcome: zero-profit conditions for constant-returns-to-scale producers, market-clearance conditions for commodities and factors, and income balances for consumers. In equilibrium, these conditions determine the variables of the economic system: zero-profit conditions determine activity levels of production, market-clearance conditions determine the prices of goods and factors, and income-balance conditions determine the income levels of consumers. We use the notation Π_{ir}^{X} to denote the unit-profit function of production activity *i* in Region *r* where *X* is the name assigned to the associated production activity.[26] For a condensed representation of market equilibrium conditions, we can differentiate the unit-profit functions with respect to input and output prices in order to obtain compensated demand and supply coefficients (Hotelling's lemma) which then enter the market equilibrium conditions. Numerically, the model is implemented in GAMS.[27]

Table B.1: Indices and sets

i (alias j)	Index for sectors and goods - including the composite private consumption good (i=C), the composite public consumption good (i=G), and the composite investment good (i=I)
r (alias s)	Index for regions
NE	Set of non-energy goods
FF	Set of primary fossil fuels: Coal, crude oil, gas
CGO	Set of fuels with CO_2 emissions: Coal, gas, refined oil

[26] Note that we can decompose production in multiple stages (nests) and refer to each nest as a separate sub-production activity. In our exposition below, we specify for example the choice of capital-labor inputs as a price-responsive sub-production: Π_{ir}^{KL} (X=KL) then denotes the zero-profit condition of value-added production in sector *i* and Region *r*.

[27] The model code and data to replicate simulation results are readily available upon request.

Table B.2: Variables

	Activity levels
KL_{ir}	Value-added composite in sector *i* and region *r*
E_{ir}	Energy composite in sector *i* and region *r*
Y_{ir}	Production in sector *i* and region *r*
M_{ir}	Import composite for good *i* and region *r*
A_{ir}	Armington composite for good *i* in region *r*
	Price levels
p_{ir}^{KL}	Price of aggregate value-added in sector *i* and region *r*
p_{ir}^{E}	Price of aggregate energy in sector *i* and region *r*
p_{ir}^{Y}	Output price of good *i* produced in region *r*
p_{ir}^{M}	Import price aggregate for good *i* imported to region *r*
p_{ir}^{A}	Price of Armington good *i* in region *r*
w_r	Wage rate in region *r*
v_r	Price of capital services in region *r*
q_{ir}	Rent to natural resources in region *r* ($i \in FF$)
$p_r^{CO_2}$	CO_2 emission price in region *r*
	Income levels
INC_r	Income level of representative household in region r

Table B.3: Cost shares

θ_{ir}^{K}	Cost share of capital in value-added composite of sector *i* and region *r* ($i \notin FF$)
θ_{ir}^{ELE}	Cost share of electricity in energy composite in sector *i* in region *r* ($i \notin FF$)
θ_{jir}^{CGO}	Cost share of fuel *j* in the fuel composite of sector *i* in region *r*($i \notin FF$), ($j \in CGO$)
θ_{ir}^{KLE}	Cost share of value-added and energy in the KLEM aggregate in sector *i* and region *r* ($i \notin FF$)
θ_{ir}^{KL}	Cost share of value-added in the KLE aggregate in sector *i* and region *r* ($i \notin FF$)
θ_{jir}^{NE}	Cost share of non-energy input *j* in the non-energy aggregate in sector *i* and region *r* ($i \notin FF$)
θ_{ir}^{Q}	Cost share of natural resources in sector *i* and region *r* ($i \notin FF$)
θ_{Tir}^{FF}	Cost share of good *j* (*T*=*j*) or labor (*T*=*L*) or capital (*T*=*K*) in sector *i* and region *r* ($i \in FF$)
θ_{isr}^{M}	Cost share of imports of good *i* from region *s* to region *r*
θ_{ir}^{A}	Cost share of domestic variety in Armington good *i* of region *r*

Key: KLEM – value-added, energy and non-energy; KLE – value-added and energy

Table B.4: Elasticities

σ_{ir}^{KL}	Substitution between labor and capital in value-added composite
σ_{ir}^{ELE}	Substitution between electricity and the fuel composite
σ_{ir}^{CGO}	Substitution between coal, gas and refined oil in the fuel composite
σ_{ir}^{KLE}	Substitution between energy and value-added in production
σ_{ir}^{KLEM}	Substitution between material and the KLE composite in production
σ_{jir}^{NE}	Substitution between material inputs into material composite
σ_{ir}^{Q}	Substitution between natural resources and other inputs in fossil fuel production
σ_{ir}^{M}	Substitution between imports from different regions
σ_{ir}^{A}	Substitution between the import aggregate and the domestic input

Table B.5: Endowments and emissions coefficients

$\overline{L}_r$	Base-year aggregate labor endowment in region *r*
$\overline{K}_r$	Base-year aggregate capital endowment in region *r*
$\overline{Q}_{ir}$	Base-year endowment of natural resource *i* in region *r* ($i \in FF$)
$\overline{G}_r$	Base-year public good provision in region *r*
$\overline{I}_r$	Base-year investment demand in region *r*
$\overline{B}_r$	Base-year balance of payment deficit or surplus in region *r*
$\overline{CO2}_r$	CO_2 emission endowment for region *r*
$a_{jir}^{CO_2}$	CO_2 emissions coefficient for fuel *j* (coal, gas, refined oil) in sector *i* and region *r*

Zero-profit conditions

Production of goods except fossil fuels

Production of commodities other than primary fossil fuels ($i \notin FF$) is captured by four-level constant elasticity of substitution (CES) cost functions describing the price-dependent use of capital, labor, energy, and material in production. At the top level, a CES composite of intermediate material demands trades off with an aggregate of energy, capital, and labor subject to a CES. At the second level, a CES function describes the substitution possibilities between intermediate demand for the energy aggregate and a value-added composite of labor and capital. At the third level, a CES function captures capital and labor substitution possibilities within the value-added composite, and likewise the energy composite is a CES function of electricity and a fuel aggregate. At the fourth level, coal, gas, and (refined) oil enter the fuel aggregate at a CES.

The unit-profit function for the value-added composite is:

$$\Pi_{ir}^{KL} = p_{ir}^{KL} - \left[\theta_{ir}^{K} v_r^{1-\sigma_{ir}^{KL}} + \left(1-\theta_{ir}^{K}\right) w_r^{1-\sigma_{ir}^{KL}}\right]^{\frac{1}{1-\sigma_{ir}^{KL}}} \leq 0 \tag{23}$$

The unit-profit function for the energy composite is:

$$\Pi_{ir}^{E} = p_{ir}^{E} - \left[\theta_{ir}^{ELE} {p_{ELE,r}^{A}}^{1-\sigma_{ir}^{ELE}} + \left(1-\theta_{ir}^{ELE}\right)\left(\sum_{j \in CGO} \theta_{jir}^{CGO} \left(p_{jr}^{A} + p_r^{CO_2} a_{jir}^{CO_2}\right)^{1-\sigma_{ir}^{CGO}}\right)^{\frac{1-\sigma_{ir}^{ELE}}{1-\sigma_{ir}^{CGO}}}\right]^{\frac{1}{1-\sigma_{ir}^{ELE}}} \leq 0 \tag{24}$$

The value-added composite and the energy composite enter the unit-profit function at the top level together with a CES composite of non-energy (material) intermediate input:[28]

[28] Note that the specification of the unit-profit function also includes the production of final demand components for private consumption (i=C), public consumption (i=G), and composite investment (i=I). In these cases, entries in the value-added nest are zero.

$$\Pi_{ir}^{Y} = p_{ir}^{Y} - \left[\theta_{ir}^{KLE} \left[\theta_{ir}^{KL} p_{ir}^{KL^{1-\sigma_{ir}^{KLE}}} + \left(1-\theta_{ir}^{KL}\right) p_{ir}^{E^{1-\sigma_{ir}^{KLE}}} \right]^{\frac{1-\sigma_{ir}^{KLEM}}{1-\sigma_{ir}^{KLE}}} + \left(1-\theta_{ir}^{KLE}\right) \left(\sum_{j \notin NE} \theta_{jir}^{NE} p_{jr}^{A^{1-\sigma_{ir}^{NE}}} \right)^{\frac{1-\sigma_{ir}^{KLEM}}{1-\sigma_{ir}^{NE}}} \right]^{\frac{1}{1-\sigma_{ir}^{KLEM}}} \leq 0$$

(25)

Production of fossil fuels

In the production of primary fossil fuels ($i \in FF$) all inputs except for the sector-specific fossil-fuel resource are aggregated in fixed proportions. This aggregate trades off with the sector-specific fossil-fuel resource at a CES. The unit-profit function for primary fossil fuel production is:

$$\Pi_{ir}^{Y} = p_{ir}^{Y} - \left[\theta_{ir}^{Q} q_{ir}^{1-\sigma_{ir}^{Q}} + \left(1-\theta_{ir}^{Q}\right) \left(\theta_{Lir}^{FF} w_r + \theta_{Kir}^{FF} v_r + \sum_{j} \theta_{jir}^{FF} \left(p_{ir}^{A} + p_r^{CO_2} a_{jir}^{CO_2} \right) \right)^{1-\sigma_{ir}^{Q}} \right]^{\frac{1}{1-\sigma_{ir}^{Q}}} \leq 0 \qquad (26)$$

Imports aggregate across regions

Imports of the same variety from different regions enter the import composite subject to a CES. The unit-profit function for the import composite is:

$$\Pi_{ir}^{M} = p_{ir}^{M} - \left[\sum_{s} \theta_{isr}^{M} p_{is}^{Y^{1-\sigma_{ir}^{M}}} \right]^{\frac{1}{1-\sigma_{ir}^{M}}} \leq 0 \qquad (27)$$

Armington aggregate

All goods used on the domestic market in intermediate and final demand correspond to a (Armington) CES composite that combines the domestically produced good and a composite of imported goods of the same variety. The unit-profit function for the Armington aggregate is:

$$\Pi_{ir}^{A} = p_{ir}^{A} - \left[\theta_{ir}^{A} p_{ir}^{Y^{1-\sigma_{ir}^{A}}} + \left(1-\theta_{ir}^{A}\right) p_{ir}^{M^{1-\sigma_{ir}^{A}}} \right]^{\frac{1}{1-\sigma_{ir}^{A}}} \leq 0 \qquad (28)$$

Market-clearance conditions

Labor

Labor is in fixed supply. The market-clearance condition for labor is:

$$\bar{L}_r \geq \sum_i Y_{ir} \frac{\partial \Pi_{ir}^Y}{\partial w_r} \tag{29}$$

Capital

Capital is in fixed supply. The market-clearance condition for capital is:

$$\bar{K}_r \geq \sum_i Y_{ir} \frac{\partial \Pi_{ir}^Y}{\partial v_r} \tag{30}$$

Natural resources

Natural resources for the production of primary fossil fuels ($i_{\in} FF$) are in fixed supply. The market-clearance condition for the natural resource is:

$$\bar{Q}_{ir} \geq Y_{ir} \frac{\partial \Pi_{ir}^Y}{\partial q_{ir}} \tag{31}$$

Energy composite

The market-clearance condition for the energy composite is:

$$E_{ir} \geq Y_{ir} \frac{\partial \Pi_{ir}^Y}{\partial p_{ir}^E} \tag{32}$$

Value-added composite

The market-clearance condition for the value-added composite is:

$$KL_{ir} \geq Y_{ir} \frac{\partial \Pi_{ir}^Y}{\partial p_{ir}^{KL}} \tag{33}$$

Output

Domestic output enters Armington demand and import demand by other regions. The market-clearance condition for domestic output is:

$$Y_{ir} \geq \sum_j A_{jr} \frac{\partial \Pi^Y_{jr}}{\partial p^Y_{ir}} + \sum_s M_{is} \frac{\partial \Pi^Y_{js}}{\partial p^Y_{ir}} \tag{34}$$

Armington aggregate

Armington supply enters all intermediate and final demands. The market-clearance condition for domestic output is:

$$A_{ir} \geq \sum_j Y_{jr} \frac{\partial \Pi^Y_{jr}}{\partial p^A_{ir}} \tag{35}$$

Import aggregate

Import supply enters Armington demand. The market-clearance condition for the import composite is:

$$M_{ir} \geq A_{ir} \frac{\partial \Pi^A_{ir}}{\partial p^M_{ir}} \tag{36}$$

Public consumption

Production of the public good composite (i=G) covers fixed government demand. The market-clearance condition for the public good composite is:

$$Y_{Gr} \geq \overline{G}_r \tag{37}$$

Investment

Production of the investment good composite (i=I) covers fixed investment demand. The market-clearance condition for composite investment is:

$$Y_{Ir} \geq \overline{I}_r \tag{38}$$

Private consumption

Production of the composite private consumption good ($i = C$) covers private consumption demand. The market-clearance condition for composite private consumption is:

$$Y_{Cr} \geq \frac{INC_r}{p_{Cr}^Y} \tag{39}$$

Carbon emissions

A fixed supply of CO_2 emissions limits demand for CO_2 emissions. The market-clearance condition for CO_2 emissions is:

$$\overline{CO2}_r \geq \sum_j \sum_i Y_{ir} \frac{\partial \Pi_{ir}^Y}{\partial (p_{jr}^A + a_{jir}^{CO_2} p_r^{CO_2})} a_{jir}^{CO_2} \tag{40}$$

Income-balance conditions

Income balance

Net income of the representative agent consists of factor income and revenues from CO_2 emission regulation adjusted for expenditure to finance fixed government and investment demand and the base-year balance of payment. The income-balance condition for the representative agent is:

$$INC_r = w_r \overline{L}_r + v_r \overline{K}_r + \sum_{i \in FF} q_{ir} \overline{Q}_{ir} + p_r^{CO_2} \overline{CO2}_r - p_{Ir}^Y \overline{Y}_{Ir} - p_{Gr}^Y \overline{Y}_{Gr} + \overline{B}_r \tag{41}$$

Appendix C: Generation of pseudo random Armington elasticities for Monte Carlo simulations

Monte Carlo simulations allow us to get a numerical estimate for the variables of interest (e.g., welfare and carbon leakage) in the presence of uncertain Armington elasticities. We still need to characterize the distribution, however. A key challenge when using estimates from micro studies for calibration of Armington elasticities in CGE models is that the CGE model, and hence interpretation and value of the relevant elasticity, differs from the econometric models used in the micro study. Further, the estimates on the Armington elasticities vary significantly and no consensus exist in the literature (Bajzik et al, 2020, p. 1. See also Saito, 2004; Welsch, 2008). Below we specify a gamma distribution with expected value of 4 (median is 3.6), which equals the benchmark value in the GTAP data set that we use in our numerical model. In comparison, Böhringer et al. (2017) use an Armington elasticity of 4 in their main simulations and do sensitivities for low and high elasticities with values equal to 1 and 8, respectively. For further comparison, Bajzik et al. (2020, p. 2) find that the elasticity is likely to range from 2.5 to 5.1, with a median of 3.8.

We first generate $i \in I = \{1, 2, ..., n\}$ sector specific gamma distributed variables, $\gamma_{s,i}$, and one common economy wide gamma distributed variable, γ_c. Let u_i be $i \in I$ draws from the standard uniform probability distribution. These pseudo-random numbers are generated using GAMS (numerical software). We transform the u_i 's to draws from the two-parameter gamma distribution, $G(\alpha_s, \beta_s)$, by solving:

$$\frac{1}{\Gamma(\beta_s)} \int_0^{\gamma_{s,i}/\alpha_s} t^{\beta_s - 1} e^{-\tau} d\tau = u_i, \quad \forall i \in I, \tag{42}$$

for $\gamma_{s,i}$; i.e., $\gamma_{s,i}$ is a random draw from $G[\alpha_s, \beta_s]$. Here, the denominator $\Gamma(\beta_s) = \int_0^{\infty} \tau^{\beta_s - 1} e^{-\tau} d\tau$ is the gamma function.[29] Note that the gamma variables have expectations $E\left[G(\alpha_s, \beta_s)\right] = \alpha_s \beta_s$ and variances $\mathrm{var}\left[G(\alpha_s, \beta_s)\right] = \alpha_s^2 \beta_s \equiv \sigma_s^2$. We generate draws from a second gamma distribution $G(\alpha_c, \beta_c)$, γ_c, by the same procedure.

[29] We restrict $1.0 \times 10^{-8} \le u_i \le 1 - 1.0 \times 10^{-8}$ to avoid $u_i = 0$ or $u_i = 1$ when solving equation (42).

Let the stochastic Armington elasticity of sector $i \in I$ be given by:

$$A_i = \overline{A}_i + \theta(\gamma_c - \alpha_c\beta_c) + (1-\theta)(\gamma_{s,i} - \alpha_s\beta_s). \tag{43}$$

Here, $\theta \in [0,1]$ is a constant and $\overline{A}_i$ is the benchmark Armington elasticity for sector $i \in I$. Note that the realized Armington elasticity, A_i is the constant $\overline{A}_i$ plus a linear combination of a 'shock' that hits all sectors, $\gamma_c - \alpha_c\beta_c$, and a sector specific shock $\gamma_{s,i} - \alpha_s\beta_s$.

Equations (42) and (43) implicitly define a random variable A_i for the Armington elasticity of sector $i \in I$, with expectation $E[A_i] = \overline{A}_i$. Further, the variance is given by $\text{var}[A_i] = \theta^2\sigma_c^2 + (1-\theta)^2\sigma_s^2 + 2\theta(1-\theta)\text{cov}[\gamma_c, \gamma_{s,i}] = \theta^2\sigma_c^2 + (1-\theta)^2\sigma_s^2$, whereas the covariance between the Armington elasticities of two sectors *i* and *j* is $\text{cov}[A_i, A_j] = E[A_iA_j] - E[A_j]E[A_i] = E[\theta^2\gamma_c^2 + \overline{A}_i\overline{A}_j] - \overline{A}_i\overline{A}_j = \theta^2\sigma_c^2$ ($j \in I \setminus \{i\}$). It follows that the correlation coefficient can be expressed as:

$$corr(A_i, A_j) = \frac{\theta^2\sigma_c^2}{\theta^2\sigma_c^2 + (\theta-1)^2\sigma_s^2}, \tag{44}$$

which satisfies $corr(A_i, A_j) = 1$ if $\theta = 1$ and $corr(A_i, A_j) = 0$ if $\theta = 0$.

We want to generate a probability distribution for the Armington elasticities with a specific correlation coefficient $corr(A_i, A_j) = \rho$ for use in the numerical simulations. Then, for any given triple $(\rho, \sigma_c^2, \sigma_s^2)$, equation (44) implies that the constant θ_o must solve:

$$\theta = \frac{\rho\sigma_s^2 - \sigma_c^2\sqrt{\rho(1-\rho)\sigma_s^2/\sigma_c^2}}{\rho(\sigma_s^2 + \sigma_c^2) - \sigma_c^2}, \tag{45}$$

with $\theta = 1/2$ if $\rho(\sigma_s^2 + \sigma_c^2) = \sigma_c^2$.

A histogram of the Armington elasticities generated using equations (42) and (43) with scale parameters $\alpha_c = \alpha_s = 5/4$, shape parameters $\beta_c = \beta_s = 3$, correlation $corr(A_i, A_j) = 0$ and expectation $\overline{A}_i = 4$ is given in Figure A1. A 95% prediction interval for A_i is given by $[1.0, 9.3]$ with these parameters. The median of the sample with $n = 5000$ simulation runs graphed in Figure A1 is 3.6. Equations (42) and (43) do not guarantee a non-negative Armington elasticity. This is not a problem given the selected parameter values (all draws turn out to be positive; see figure C1).

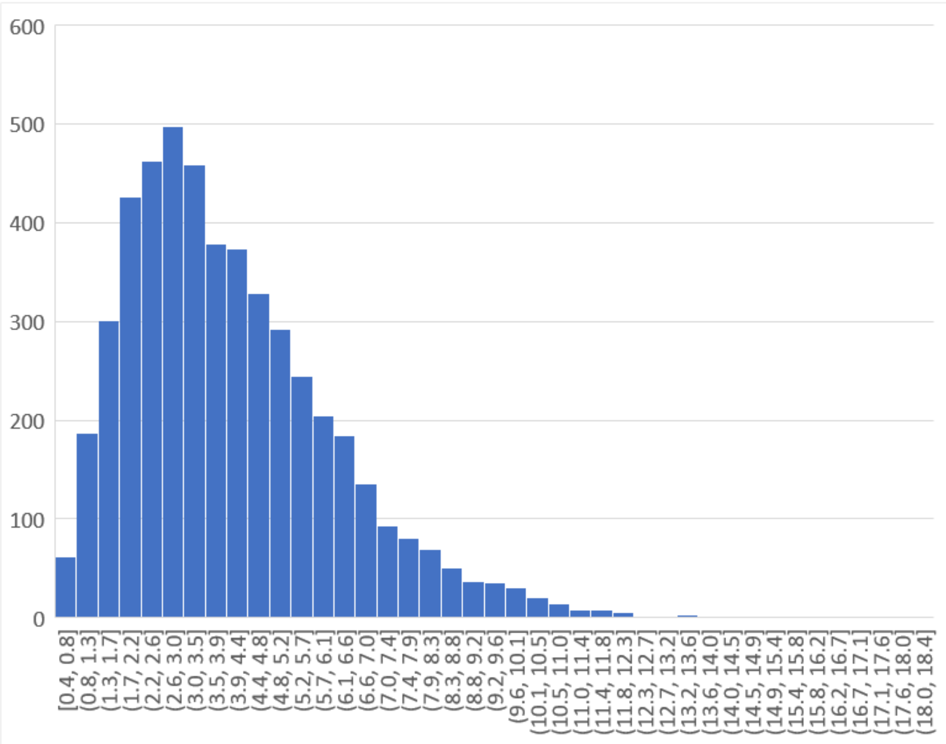

Figure C1. Example of generated Armington elasticities. Histogram. Sample size is 5000.