Böhringer, C., C. Fischer and K.E. Rosendahl (2014): Cost-Effective Unilateral Climate Policy Design: Size Matters, Journal of Environmental Economics and Management 67, 318–339

Cost-Effective Unilateral Climate Policy Design: Size Matters

Abstract

Given the bleak prospects for a global agreement on mitigating climate change, pressure for unilateral abatement is increasing. A major challenge is emissions leakage. Border carbon adjustments and output-based allocation of emissions allowances can increase effectiveness of unilateral action but introduce distortions of their own. We assess antileakage measures as a function of abatement coalition size. We first develop a partial equilibrium analytical framework to see how these instruments affect emissions within and outside the coalition. We then employ a computable general equilibrium model of international trade and energy use to assess the strategies as the coalition grows. We find that full border adjustments rank first in global cost-effectiveness, followed by import tariffs and output-based rebates. The differences across measures and their overall appeal decline as the abatement coalition grows. In terms of cost, the coalition countries prefer border carbon adjustments; countries outside the coalition prefer output-based rebates.

Key Words: emissions leakage, border carbon adjustments, output-based rebates

JEL Classification Numbers: Q2, Q43, H2, D61

1. Introduction

At the 16th Conference of the Parties in Cancún, the world community agreed on the objective of limiting the rise in global average temperature to no more than 2° Celsius above pre-industrial levels. The target implies drastic global emissions reductions over the next decades (IPCC 2007). Given the increasing share of the developing world in global emissions, the 2° Celsius target cannot be achieved without substantial abatement contributions from major developing regions, such as China or India. However, given the lack of globally coordinated action, high-income countries with historically high per-capita emissions may be expected to take a leading role in short- to mid-run abatement efforts.

The increasing pressure for unilateral action manifests itself in various domestic climate policy initiatives. Most notable is the European Union's Climate Action and Renewable Energy Package, which calls for unilateral greenhouse gas emissions reductions in 2020 by at least 20 percent compared to 1990 levels (European Union 2008). In a similar vein, there are policy proposals in other regions with unilateral emission reduction pledges over the next decades.[1]

A major challenge in the design of unilateral climate policies is the appropriate response to the threat of emissions leakage—that is, the increase in emissions in nonabating regions as a reaction to the reduction of emissions in abating regions (e.g., Hoel 1991; Felder and Rutherford 1993). Emissions leakage can occur when energy-intensive, trade-exposed (EITE) industries in countries with emissions ceilings lose competitiveness, thereby increasing emissions-intensive production in unconstrained regions. Leakage may also occur through other channels. In

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[1] Under the Cancún agreement, most industrialized *and* developing countries have submitted pledges for emissions levels or emissions intensities in 2020 (see e.g. Dellink et al., 2011). However, it remains unclear to what extent such pledges translate into binding emissions regulations.

particular, emissions constraints in larger open economies depress the demand for fossil fuels and thus induce a drop in world energy prices, which in turn could lead to increased energy demand in other regions. Note that emissions can also leak to other abating countries without emission ceilings, e.g., to countries with emission intensity targets (cf. footnote 1).

To reduce leakage through the EITE markets and thereby increase cost-effectiveness, various instruments are considered to complement unilateral emissions pricing. One policy measure is based on border carbon adjustments (BCA). On the import side, a tariff is levied on the embodied carbon of energy-intensive imports from nonabating regions assessed at the prevailing carbon price. On the export side, energy-intensive exports to nonabating countries get a full refund of carbon payments at the point of shipment. Full BCA would combine adjustments for imports and exports, effectively implementing destination-based carbon pricing. However, most policy proposals to date focus only on import adjustments.

Another option is output-based rebates (OBR) of carbon payments, or allocation of emissions allowances, to EITE sectors. While the emissions price continues to serve as an incentive to abate, the rebate (or the value of allowances) functions as a subsidy to production (Böhringer et al. 1998). In this way, eligible sectors preserve competitiveness compared to unregulated industries abroad, thereby reducing leakage.

BCA and OBR introduce distortions of their own but may be justified on efficiency grounds as second-best measures complementing unilateral emissions pricing.[2] The

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[2] Both BCA and OBR preserve the carbon price signal while affecting the output decision. Other instruments, such as tax exemptions, grandfathering (conditioned on continued operation), and voluntary exports restraints, would also decrease leakage through the EITE markets. In particular the two former instruments have been widely used in reality. Tax exemptions do not, however, give any incentives to cut emissions. Conditional grandfathering preserves the carbon price signal, and may affect output through mitigating closure or down-scaling (but less so than OBR).

attractiveness of these additional measures and their relative ranking in terms of global cost-effectiveness hinge on the magnitude of emissions leakage: the environmental effects of OBR and BCA would drop to zero if the coalition of abating countries comprised the whole world. Whereas BCA in this case would automatically become inactive,[3] OBR might continue to induce excess costs compared to uniform emissions pricing alone. Beyond the global cost-effectiveness dimension, abating countries may face different cost and emissions implications of antileakage instruments based on their specific trade, production, and consumption patterns (Fischer and Fox 2012), raising the question if individual countries within a coalition would easily agree on an antileakage strategy.

While the economic impacts of BCA and OBR have been addressed for a fixed number of abating regions (see e.g. Fischer and Fox 2012; Dong and Whalley 2009; Mattoo et al. 2009; Böhringer et al. 2010; Burniaux et al. 2010; Winchester 2013, Böhringer, Balistreri and Rutherford 2012), we are not aware of any study that systematically assesses the implications of these instruments as a function of the abatement coalition size toward more comprehensive coverage of global emissions. In this paper, we first develop a partial equilibrium analytical framework to gain generic insights on how three alternative antileakage instruments — output-based rebates, border adjustments for imports, and full border adjustment — affect emissions inside and outside the abatement coalition as it increases in size. We then perform numerical simulations using a large-scale computable general equilibrium (CGE) model of international trade and energy use to quantify the differential cost implications across the three strategies in an empirical setting.

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[3] This conclusion hinges on the assumption of equal emissions pricing across the coalition. If coalition countries have different carbon prices, or if some coalition countries have targets expressed in terms of emissions intensities (cf. the Cancún pledges referred to in footnote 1), BCA would still be relevant (cf. Whalley and Lockwood, 2010).

We find that of the three instruments, full border adjustments (FBA) are the most effective to reduce leakage. In theory, OBR can be more effective than border adjustment for imports (BAI) alone when the coalition size is sufficiently small. However, the parameterization of our CGE model finds a robust ranking: In terms of global cost-effectiveness (being agnostic on the regional distribution of costs), unilateral action achieves a given worldwide emissions reduction at lowest cost with FBA, but the cost advantage vis-à-vis BAI is small. The relative performance between these two instruments remains robust as the coalition size increases. OBR achieves the smallest cost savings among the three antileakage instruments compared to a reference policy that places a uniform price on carbon without additional leakage measures. Furthermore, they induce excess costs as the coalition size increases toward full coverage because the distortions of output subsidies prevail, while the antileakage effect becomes zero. The studies referred to above have somewhat mixed conclusions about the ranking with respect to global welfare costs, but some of these studies do not assume a given global emissions reduction, in which case it is difficult to compare welfare effects. If we instead consider a fixed price of carbon, we still find the same ranking as with a global emissions cap to a large degree, as e.g. border measures lead to both lower global emissions *and* lower global compliance costs.

Depending on the trade characteristics of the coalition, it might prefer BAI over FBA to increase the coalition’s indirect welfare gains from terms-of-trade shifts. This ranking reverses if we take the complementary perspective of countries outside the abatement coalition. The latter clearly prefer OBR over FBA or BAI. OBR induces distributional implications that are more similar to those triggered by carbon pricing alone. While OBR might be least controversial in the international policy debate, they also are the least cost-effective from a global perspective.

2. Theoretical Considerations

We develop a simple partial equilibrium framework to illustrate important economic mechanisms that drive emissions leakage for alternative unilateral climate policies. The main driver is the change in the pricing of emissions inside and outside the abatement coalition. Another important leakage determinant is the responsiveness to differential emissions pricing captured through own-price and cross-price elasticities in demand.

2.1 Analytical Model

Let there be *n* countries, each producing one good. Demand q_{ik} in country *i* for the good produced in country *k* exhibits constant elasticities η_{ikj} with respect to prices p_{ij} prevailing in country *i* for good *j*: $q_{ik} = a_{ik} \prod_j p_{ij}^{\eta_{ikj}}$, where a_{ik} denotes benchmark demand as initial prices are normalized to unity. We will assume that countries are symmetric, so benchmark demands are equal ($a_{ik} = a$), as are own-price elasticities ($\eta_{ikk} = -\eta_o$), and cross-price elasticities ($\eta_{ikj} = \eta_x$).[4]

Now we will distinguish between two country types: a regulating country *M* within the abatement coalition, and a nonregulating country *N* outside the coalition. Thus, we have symmetric prices for exchanges among identical country types, but prices will differ across those types. Let there be *m* countries of type *M* and hence (*n-m*) countries of type *N*. We then get:

$$q_{MM} = ap_{MM}^{-\eta_o} p_{MM}^{(m-1)\eta_x} p_{MN}^{(n-m)\eta_x}; \quad q_{MN} = ap_{MN}^{-\eta_o} p_{MM}^{m\eta_x} p_{MN}^{(n-m-1)\eta_x};$$
$$q_{NM} = ap_{NM}^{-\eta_o} p_{NM}^{(m-1)\eta_x} p_{NN}^{(n-m)\eta_x}; \quad q_{NN} = ap_{NN}^{-\eta_o} p_{NM}^{m\eta_x} p_{NN}^{(n-m-1)\eta_x}.$$

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[4] The symmetry assumption is convenient for laying out the effects in the theoretical model, but in practice emissions intensities are likely to differ widely across countries. If noncoalition countries have yet higher emissions intensities, leakage pressures will be higher, as will the effects of the anti-leakage policies. The numerical simulations will incorporate heterogeneity in emissions across countries.

Production of each good is the sum of demand from coalition and noncoalition countries:

$$y_M = mq_{MM} + (n-m)q_{NM}; \quad y_N = mq_{MN} + (n-m)q_{NN}.$$

We consider competitive markets, where goods are priced at marginal costs plus potential taxes or subsidies. Let $c(\mu)$ denote marginal production costs, which are assumed to be constant with respect to output, but increasing as the emissions intensity μ decreases from its baseline value μ_0 (i.e., $c' < 0$). This cost may be considered the long-run average cost, given a set of input prices. Implicitly, we assume that the single sector in this partial-equilibrium model is too small to influence broader input prices, which are determined on an economywide or global basis.[5]

Let $\mu(t)$ reflect the cost-minimizing emissions intensity at the carbon price t (i.e., solving $c'(\mu) = t$). In the benchmark, t=0, with $\mu_0 = \mu(0)$ indicating the initial emissions intensity and normalizing $p_0 = c(\mu_0) = 1$. We further note that, given any positive carbon price, t> 0, to the extent that producers in regulated countries respond by decreasing their emissions intensity, it must be to lower compliance costs, so $1 + t\mu_0 > c(\mu(t)) + t\mu(t)$.

Global emissions are:

$$GE = mE_M + (n-m)E_N = m\mu_M y_M + (n-m)\mu_N y_N .$$

where μ_i denotes the emissions intensity in country i, and E_i emissions in country i.

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[5] This simplifying assumption of constant per-unit costs corresponds to a price-taking representative firm with Leontief technology (as is generally assumed for material inputs in GTAP-based CGE models as ours), given a certain emissions intensity. Thus, this partial-equilibrium model abstracts from the general-equilibrium effects on input prices that may influence costs when sectoral production changes. In these CGE models, a large share of the unit cost changes under carbon pricing arise through energy price changes (since the carbon price is economy-wide), not through output changes in a given sector. However, since antileakage policies primarily influence output, and only in the given sectors, the general equilibrium effects on production costs are not pronounced (Fischer and Fox 2012). Therefore, the CGE models do predict larger leakage rates from carbon pricing, but given a carbon price, production costs do not seem sensitive to small changes in output.

The following assumption will be useful in the subsequent analysis:

Assumption 1: *Own-price effects are more important than cumulative cross-price effects. (See Appendix A for specific mathematical assumptions 1a, 1b, and 1c).*

This assumption ensures reasonable demand responses, such that demand declines if all prices go up the same amount, and raising the carbon price decreases demand for domestically produced goods in regulating countries, even if imported goods face border adjustments.[6]

2.2 Leakage Metrics

Fundamentally, the problem of carbon leakage relates to the extent noncoalition emissions increase as a result of coalition actions, or E_N / E_N^0. The overall effect on emissions and the scale by which we may judge the importance of leakage also depend on the extent coalition countries reduce their emissions, or E_M / E_M^0.

Conventionally, the *leakage rate* is defined as the absolute increase in noncoalition emissions relative to the reduction of coalition emissions. Formally, we can write this leakage variable, L_1, in terms of the emissions ratios we just referred to:

$$L_1 = \frac{(n-m)(E_N - E_N^0)}{m(E_M^0 - E_M)} = \left(\frac{E_N / E_N^0 - 1}{1 - E_M / E_M^0} \right) \frac{E_N^0}{E_M^0} \frac{(n-m)}{m} .$$

We also consider an alternative leakage variable, L_2, which is particularly relevant in the case with a fixed global cap on emissions. L_2 indicates the relative burden of the coalition members vis-à-vis noncoalition members in reaching the emissions target—or the relative

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[6] Assumption 1 is a sufficient, but not necessary, condition for clear comparisons.

benefit to a nonmember country of staying outside the coalition. It measures the emissions ratio of the noncoalition countries relative to the emissions ratio of the coalition countries:

$$L_2 = \frac{E_N}{E_N^0} \bigg/ \frac{E_M}{E_M^0}.$$

In our analytical model, L_2 is simplified by the fact that baseline emissions are symmetric, leaving $L_2 = E_N / E_M$. We will refer to L_2 as the *emissions differential*.

Both measures increase as emissions outside the abatement coalition increase. However, whereas the leakage rate L_1 increases with coalition emissions, the emissions differential L_2 increases when the coalition reduces its emissions. The two variables also differ in their responsiveness to changes in coalition membership: all else equal, L_1 decreases as the coalition grows, while the coalition size does not directly affect L_2, which rather expresses average emissions differentials between members and nonmembers.

Both metrics are useful indicators of leakage, and in the numerical section, we will present results for L_1 and L_2 when relevant. For the purposes of this section, L_2 has the benefit of being more analytically tractable. However, we note that in the case of meeting a fixed coalition cap, for both of these leakage metrics, comparing policies boils down to simply comparing noncoalition emissions in each scenario.[7] Furthermore, we show that policies with lower noncoalition emissions in the context of a fixed coalition cap also must have less leakage than other policies when the coalition targets are adjusted to meet the same global emissions cap. This point is important because the cost-effectiveness analysis conducted in the numerical section

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[7] Comparing policy *g* to *h*, $L_1^g / L_1^h = \left(E_N^g / E_N^0 - 1\right) / \left(E_N^h / E_N^0 - 1\right)$, while $L_2^g / L_2^h = E_N^g / E_N^h$.

holds the global environmental benefits constant by imposing a global cap on carbon emissions. We sum up these observations in the following lemma, which is proved in Appendix A:

Lemma 1: *In the case of a fixed* coalition *cap, the ranking of* L_1 *across policies follow the ranking of* L_2*. In the case of a fixed* global *cap, the ranking of* L_2 *across policies strictly follows the ranking of* L_2 *under a fixed* coalition *cap.*

Proof: See Appendix A.

2.3 Regulatory Measures

For our assessment of antileakage measures, we start with a reference climate policy in which the abatement coalition implements a carbon price through an emission tax or quota market. We then investigate how the addition of alternative antileakage measures—output-based rebates, border adjustments for imports, or full border adjustments—affect production and emissions inside and outside the abatement coalition for three different variants in which the carbon price, coalition emissions, or global emissions are fixed at the reference level. The latter two variants are useful in analyzing the environmental effectiveness from a coalition view or a global perspective—both require the carbon price to adjust accordingly from the reference level.

Carbon Price Alone

First consider a carbon price ($t > 0$) without any antileakage policy (*Tax*, sub-/superscript *T*). In this reference case, producers of goods in coalition countries adjust their emissions intensities and pay the carbon price on their remaining emissions. Thus, $p_{MM} = p_{NM} = c_T + t\mu_T$, where $c_T = c(\mu_T)$ and $\mu_T = \mu(t)$. Meanwhile, $p_{MN} = p_{NN} = c_0 = 1$. Hence, we have:

$$y_M^T = na(c_T + t\mu_T)^{-\eta_o+(m-1)\eta_x}; \quad y_N^T = na(c_T + t\mu_T)^{m\eta_x} .$$

Comparing to no policy (where $p_{ij} = p_0 = 1$, and $\mu_i = \mu_0$, for all *i,j*):

$$\frac{E_N^T}{E_N^0} = \frac{y_N^T}{y_N^0} = (c_T + t\mu_T)^{m\eta_x} > 1;$$
$$\frac{E_M^T}{E_M^0} = \frac{\mu_T y_M^T}{\mu_0 y_M^0} = \frac{\mu_T}{\mu_0}(c_T + t\mu_T)^{-\eta_o+(m-1)\eta_x} < 1.$$

Thus, carbon pricing reduces emissions in the coalition countries by reducing emissions intensity and output, while it expands emissions in the noncoalition countries by expanding output. The size of the coalition (*m*) strengthens the expansion of emissions in the remaining countries, and weakens the emissions reductions within the coalition, for a fixed carbon price. Still, as the coalition grows, so do global emissions reductions. As a result, the overall leakage rate shrinks, but the emission differential is unaffected by the coalition size:

$$L_2^T = \left(\mu_0 / \mu_T\right)(c_T + t\mu_T)^{\eta_x+\eta_o} .$$

Carbon Price with Output-Based Rebate

Output-based rebating (*OBR*, sub-/superscript *R*) mitigates leakage by suppressing the cost increase for domestic producers, so that the playing field does not tilt toward imports or competitors in export markets. Specifically, a rebate is offered to producers in proportion to their production, based on a benchmark that we assume is equal to the average emissions intensity of the sector, multiplied by the emissions tax.[8] As this allocation is updated according to production, the rebate functions as a de facto subsidy of $t\mu(t)$ per unit. As a result, the prices of

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[8] For example, this was the proposed allowance allocation method in the failed American Clean Energy and Security Act of 2009. The EU uses a somewhat less generous benchmarking method in Phase III of its ETS.

goods produced in coalition countries do not include the cost of the remaining embodied emissions, but the emissions intensities (and corresponding production costs) respond to the emissions price signal. Thus, we have $p_{MM} = p_{NM} = c_R$, where $c_R = c(\mu_R)$ and $\mu_R = \mu(t_R)$, while $p_{MN} = p_{NN} = c_0 = 1$. Hence:

$$y_M^R = nac_R^{-\eta_o+(m-1)\eta_x}; \quad y_N^R = nac_R^{m\eta_x}.$$

Here we make the aforementioned distinction as to whether OBR accompanies a fixed tax (*Rtax*) or a fixed coalition cap (*Rcap*). In the former case, the emissions price t is unchanged compared to the reference case, so $c_R = c_T$. With a fixed cap, the equilibrium price and emissions intensity will adjust under OBR to meet the same emissions as under Tax, i.e., $\mu_R y_M^R = \mu_T y_M^T$.

<u>Proposition 1</u>: *Given a fixed carbon price or a fixed coalition cap,* $L_2^R < L_2^T$.

<u>Proof:</u> See Appendix A.

In other words, rebating mitigates emissions leakage, as both noncoalition emissions and emissions reductions in the coalition decline. Thus, with a fixed tax, the net effect of rebating on global emissions can be ambiguous.[9] The emissions differential L_2 is insensitive to the coalition size m with a fixed tax, as both coalition and noncoalition countries increase their emissions. However, an increase in the coalition size tends to lower emissions under rebating relative to the Tax case for both coalition and noncoalition countries (see expressions in the Appendix).

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[9] See also Fischer and Fox (2012).

Under a fixed cap for coalition emissions, the ratio between L_2^{Rcap} and L_2^T declines with the coalition size. Thus, the bigger the coalition, the stronger is the effect of rebating in mitigating leakage.[10]

Now suppose OBR is implemented with a policy that is adjusted to meet the same *global* emissions target as the carbon price alone—i.e., the policy sets μ_R such that $GE_R = GE_T$. It then follows from Lemma 2 and Proposition 1 that the emissions differential will be lower under OBR. The intuition is that since noncoalition emissions are smaller under OBR for a given coalition cap, the carbon price can adjust downward to loosen the coalition cap and meet the same global emissions target as the carbon price alone. The net effect leaves noncoalition emissions smaller and coalition emissions higher, necessarily lowering the emissions differential.

Carbon Price with Border Adjustment for Imports

Border adjustment for imports (*BAI*, sub-/superscript *B*) mitigates leakage by raising the playing field for imports up to the same level as domestically produced goods. Specifically, a carbon tax on coalition emissions is combined with a corresponding levy (or allowance requirement) for goods imported into the coalition, in proportion to their embodied emissions.[11] As with the carbon tax alone, coalition producers adjust emissions intensities and pay the carbon price, so $p_{MM} = p_{NM} = c_B + t\mu_B$. Noncoalition producers do not face a direct carbon price, but consumers of their goods in coalition countries must pay for the embodied

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[10] See the proof of Proposition 1 in the Appendix. The carbon price with OBR is a function of the coalition size, so the full effect of expanding the coalition is somewhat more complicated than shown there.

[11] Although the model assumes symmetric countries and firms, in practice, embodied carbon varies across and within countries and can be difficult to calculate. Although average benchmarks might be used, good practice suggests allowing importers to demonstrate lower emissions intensities and qualify for a lower adjustment (Cosbey et al 2012).

emissions: $p_{MN} = c_0 + t\mu_0$.[12] Meanwhile, goods produced and consumed in noncoalition countries have no price change: $p_{NN} = c_0 = 1$. We then have:

$$\begin{aligned} y_M^B &= a(c_B + t_B\mu_B)^{-\eta_o+(m-1)\eta_x} \left(m(1+t_B\mu_0)^{(n-m)\eta_x} + (n-m) \right); \\ y_N^B &= a(c_B + t_B\mu_B)^{m\eta_x} \left(m(1+t_B\mu_0)^{-\eta_o+(n-m-1)\eta_x} + (n-m) \right). \end{aligned}$$

As before, we distinguish between a fixed price (*Btax*) and a fixed cap (*Bcap*). If we assume the same carbon tax rate $t_B = t$, so $c_B = c_T, \mu_B = \mu_T$, then we can easily show:

<u>Proposition 2:</u> *Given a fixed carbon price,* $L_2^{Btax} < L_2^T$.

<u>Proof:</u> See Appendix A.

Essentially, *BAI* causes noncoalition emissions to fall while coalition emissions rise, implying that leakage is mitigated.[13] However, the net effect on global emissions is again theoretically ambiguous.[14] The effect of BAI on noncoalition and coalition emissions (and therefore the emissions differential) cannot be easily compared to those under rebating, as OBR decreases the price of coalition goods while BAI increases the price of noncoalition goods within the coalition (cf. the expressions for $\frac{E_i^{Rtax}}{E_i^T}$ and $\frac{E_i^{Btax}}{E_i^T}$ in the proofs of Propositions 1-2).

Because coalition emissions rise with BAI given a fixed carbon price, the carbon price would have to rise for the case of a fixed coalition cap (i.e., $t_B > t$, so $\mu_B < \mu_T$, but implying

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[12] Carbon import tariffs are most likely based on industry-average measures of carbon embodied in imported goods and thus will not give a direct incentive for individual producers in noncoalition countries to adjust their emissions intensity so they can pay a lower import tax. If they were to reduce their intensity, leakage would decline compared to what we find here.

[13] Note that this result does rely in part on our model assumptions, particularly regarding the substitution elasticities. For goods that are complements, emissions changes can move in the same direction.

[14] As with the OBR case, see also Fischer and Fox (2012).

$c_B + t_B\mu_B > c_T + t\mu_T$). The result is both a higher tax on imports from noncoalition countries and more price pressure in those countries to substitute away from goods made in coalition countries. In this case, the increase in carbon price mitigates the decrease in noncoalition emissions under a fixed tax (see above), with an ambiguous net effect on the emissions differential ratio:

$$\frac{L_2^{Bcap}}{L_2^T} = \frac{E_N^{Bcap}}{E_N^T} = \underbrace{\left(\frac{m}{n}(1+t_B\mu_0)^{-\eta_o+(n-m-1)\eta_x} + \frac{(n-m)}{n}\right)}_{<1}\underbrace{\left(\frac{c_B+t_B\mu_B}{c_T+t\mu_T}\right)}_{>1}{}^{m\eta_x} .$$

It can be shown, however, that if global emissions decrease when a fixed carbon *price* is combined with BAI, which we think is likely, the first component dominates the second: leakage is then necessarily reduced when a fixed coalition *cap* is combined with BAI. The intuition is that noncoalition countries' emissions do not increase more than the emissions reduction in the coalition countries when the carbon price is increased to t_B in order to comply with the cap.

The size of the coalition can have ambiguous effects on this leakage ratio: it shrinks the first component because exports from the remaining noncoalition countries will be taxed more heavily by coalition countries, but it expands the second component because a larger share of the competing goods from coalition countries have higher costs. This latter effect is even stronger when compared to the OBR scheme because $c_R < c_T + t\mu_T$. Higher cross-price elasticities have an unambiguous effect of increasing leakage under BAI. The degree of carbon price adjustment also factors in and is endogenous to these other variables.

We conclude that, from a theoretical perspective, it is difficult to rank BAI vis-à-vis both Tax and OBR when it comes to leakage. From Lemma 2, we know that this ambiguity carries over to the case with a global cap.

Carbon Price with Full Border Adjustment

Full border adjustment (*FBA*, sub-/superscript *F*) aims to achieve a form of destination-based carbon pricing, combining an import adjustment as in *BAI* with a rebate for exports, so that both operate on level playing fields. This rebate is defined similarly as in *OBR* (the carbon price multiplied by average embodied emissions) but it is applied only to goods exported from the coalition to the noncoalition region. Thus, goods produced by the coalition have higher costs associated with lower emissions intensities, but only domestically consumed goods pay for remaining emissions: $p_{MM} = c_F + t_F \mu_F$ and $p_{NM} = c_F$. Imports face adjustment, so $p_{MN} = c_0 + t_F \mu_0$, while $p_{NN} = c_0 = 1$. We now get:

$$\begin{aligned} y_M^F &= ma(c_F + t_F \mu_F)^{-\eta_o+(m-1)\eta_x}(1+t_F\mu_0)^{(n-m)\eta_x} + (n-m)a{c_F}^{-\eta_o+(m-1)\eta_x}; \\ y_N^F &= ma(1+t_F\mu_0)^{-\eta_o+(n-m-1)\eta_x}(c_F + t_F\mu_F)^{m\eta_x} + (n-m)a{c_F}^{m\eta_x}. \end{aligned}$$

Consider first the variant of a fixed carbon price—i.e., $t_F = t$:

<u>*Proposition 3:*</u> *Given a fixed carbon price, i)* $E_N^{Ftax} < E_N^{Btax}$*, ii)* $L_2^{Ftax} < L_2^{Btax}$*, iii)* $E_N^{Ftax} < E_N^{Rtax}$ *, and iv)* $L_2^{Ftax} < L_2^{Rtax}$.

<u>Proof:</u> See Appendix A.

Thus, with a fixed carbon price, FBA has a stronger effect than BAI, OBR and Tax in terms of deterring leakage as well as reducing foreign output and emissions.[15] Comparing FBA to OBR, we notice from the proof of Proposition 3iii) that the ratio between E_N^{Ftax} and E_N^{Rtax} gets smaller as the coalition size gets larger.

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[15] FBA increases domestic emissions vis-à-vis BAI, whereas the comparison between FBA and OBR is ambiguous in this respect, depending on the relative effects of the import adjustments versus the rebate to domestically consumed production (exported production is rebated under OBR and FBA).

Next, we compare FBA to BAI, OBR and Tax with the same coalition cap. Given that with the same carbon price, FBA raise coalition emissions compared to BAI, to meet the same coalition cap, the FBA carbon price would have to rise ($t_F > t_B > t$), but the export price would still be less than under the carbon price alone. The net result is an unambiguous reduction in leakage compared to the Tax case. Due to the effect of the export rebate, FBA also has a stronger effect on reducing leakage to noncompliant countries than import adjustments only. Furthermore, we can show that FBA also outperforms OBR with regard to leakage:

<u>Proposition 4:</u> *Given a fixed coalition cap, i)* $L_2^{Fcap} < L_2^T$*, ii)* $L_2^{Fcap} < L_2^{Bcap}$*, and iii)* $L_2^{Fcap} < L_2^{Rcap}$.

<u>Proof</u>: See Appendix A.

From the expressions in Appendix A, we also notice that the size of the coalition has an unambiguous effect of reducing the ratio between L_2^{Fcap} and L_2^T: FBA becomes a more effective deterrent to leakage, relative to Tax, as the coalition grows larger.

The following proposition states that OBR leads to higher carbon prices than the other policy alternatives, given that coalition emissions are held fixed:

<u>Proposition 5</u>*: Given a fixed coalition cap, carbon prices are highest with OBR, then FBA, then BAI, then Tax (*$t_R > t_F > t_B > t$ *).*

<u>Proof</u>: The proposition follows from the derivations above (see proof of Proposition 4iii).

To sum up, we have shown that FBA implies lower leakage than all other policies under a fixed coalition cap. It follows from Lemma 2 that under a fixed global cap, the coalition members' burden share of meeting a certain global emissions target will be lowest under FBA. The intuition is the following: If FBA has lower noncoalition emissions for any given coalition cap, it can relax its corresponding carbon price to meet the global target, which further lowers the emissions differential. The ratio of noncoalition emissions falls due to less price pressure, while the ratio of coalition emissions rises.

2.4 Summary of Analytical Results

Carbon pricing induces leakage through trade of substitutable goods. As the coalition grows larger, the joining country reduces its emissions, but emissions increase among countries that remain outside the coalition. If the carbon price is fixed, emissions also increase in countries already inside the coalition. Above we have distinguished between a fixed carbon price, coalition cap, and global cap, and it is useful to keep this distinction when we summarize the results.

All of the antileakage measures mitigate the increase in noncoalition emissions,[16] but under a fixed price, coalition emissions are higher than with the carbon price alone. In terms of the emissions differential, L_2 (as opposed to absolute leakage), we find the same rankings with the fixed price and fixed coalition cap policies (see footnote 16, however), and therefore with the global emissions target. The rankings are shown in Table I.

Thus, in terms of emissions leakage (and global reductions when the coalition members implement a cap), FBA dominates OBR and BAI, which in turn dominate a carbon price alone. The comparison between OBR and BAI is more ambiguous: the relative effects of these two policies on coalition emissions (with fixed tax) and noncoalition emissions are hard to assess.

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[16] There is one possible exception to this: The effects of BAI on noncoalition emissions can be ambiguous under a fixed cap. However, as argued above, it is likely that emissions decline.

Table I. Relative Emissions Differentials across Unilateral Abatement Policies

$L_2^{\text{column}} / L_2^{\text{row}}$	Tax	OBR	BAI	FBA
Tax	1	<1	<1 (?)	<1
OBR		1	(?)	<1
BAI			1	<1
FBA				1

The size of the coalition tends to strengthen the expansion of emissions among nonregulating countries for a given emissions price, but weakens the emissions reductions within the coalition. An increase in the coalition size does not change the decrease in the emissions differential offered by OBR, but it does influence the relative effectiveness of BAI. For a given coalition emissions cap, the coalition size decreases the relative emissions differential under FBA and OBR versus Tax, while the effects of the import adjustment policy are more complex.

In order to explore the partly ambiguous implications of antileakage measures on emissions within and outside the coalition, as a function of the coalition size, we have performed two sets of numerical analysis. In the next section we will present the results of CGE analysis, whereas in Böhringer et al. (2011) we present simulation results of a parameterized version of the model framework analyzed above. Here we will briefly summarize the main findings from those simulations, where we focus on the case with a fixed price.

First of all, we find that FBA is unambiguously the most effective instrument for reducing noncoalition and global emissions, as well as both leakage measures (L_1 and L_2). This holds irrespective of coalition size.

Second, an interesting finding is that the relative performance between OBR and BAI highly depends on the coalition size, but also on the cross-price elasticity (η_x). If the elasticity is large, OBR is more effective than BAI in reducing noncoalition and global emissions as well as L_1 and L_2 for smaller coalition sizes, but this reverses as the coalition gets sufficiently big. On the other hand, for lower substitution elasticities, BAI strictly dominates OBR (except for L_2). OBR actually increases global emissions relative to Tax in this case, irrespective of coalition size. In any case, OBR becomes less and less attractive as the coalition grows.[17]

Third, we find that the antileakage measures, especially FBA and BAI, have largest effects on global emissions under medium-sized coalitions. This is intuitive: with small coalitions, the effects on global emissions are modest in any case, whereas with small non-coalitions, border measures have limited impacts. With regards to differences in emissions, both FBA and BAI (but not OBR) become more effective at compressing L_2 as the coalition expands.

3. Applied General Equilibrium Analysis

Our theoretical analysis provides basic insights into important leakage mechanisms and the effectiveness of antileakage measures as a function of the abatement coalition size. But the partial equilibrium framework is highly stylized and misses various real-world features that are important for drawing viable policy conclusions. For example, countries are heterogeneous in production and consumption. Economic adjustment to climate policy is driven through complex substitution, output and income effects across multiple markets following changes in relative prices. Furthermore, our theoretical framework does not feature a welfare metric that allows for a comprehensive cost-effectiveness comparison across alternative antileakage policies. A

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[17] In some additional analysis**,** we explored the role of the slope of the marginal cost of reducing the emissions intensity of production. While steeper marginal abatement costs do increase the dispersion of leakage measures, they have no effect on the rankings, unlike the coalition size and elasticity parameters.

computable general equilibrium (CGE) approach on the other hand allows for the quantification of allocative (in-)efficiencies associated with the implementation of alternative instruments.

We therefore undertake numerical simulations with a large-scale CGE model calibrated to empirical data of global trade and energy use to substantiate our theoretical considerations. We first provide a nontechnical summary of the CGE model and its parameterization, and point to important links to the analytical model; the detailed algebraic model formulation and graphical exposition of nesting structure in production are given in Appendix B. We then describe the scenarios to assess the cost-effectiveness of alternative climate policy regulations as a function of the abatement coalition size. Finally, we discuss simulation results from which we draw policy-relevant insights for climate policy design.

3.1 Model Structure and Parameterization

We use a generic multi-region, multi-sector CGE model of global trade and energy use established by Böhringer and Rutherford (see Böhringer and Rutherford 2010 or Böhringer et al. 2010 for recent applications). The model features a representative agent in each region that receives income from three primary factors: labor, capital, and fossil-fuel resources (coal, gas, and crude oil). Labor and capital are intersectorally mobile within a region but immobile between regions. Fossil-fuel resources are specific to fossil-fuel production sectors in each region. Production of commodities other than primary fossil fuels is captured by three-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, whereas different energy inputs (coal, gas, oil, and electricity) enter the energy composite subject to a CES. In the production of fossil fuels, 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.

Final consumption demand in each region is determined by the representative household who maximizes utility subject to a budget constraint with fixed investment and exogenous government provision of public goods and services. The household's total income consists of net factor income and tax revenues. Its consumption demand is given as a CES composite that combines consumption of nonelectric energy and composite of other consumption goods. A CES function reflects substitution patterns within the nonelectric energy bundle; other consumption goods trade off with each other at a unitary elasticity of substitution.

Bilateral trade is specified following the Armington (1969) approach of product heterogeneity, in which origin distinguishes all domestic and foreign goods except crude oil, where we assume product homogeneity. All goods used on the domestic market in intermediate and final demand correspond to an Armington CES composite that combines the domestically produced good and the imported good.[18] The balance-of-payment constraint, which is warranted through flexible exchange rates, incorporates the base-year trade deficit or surplus for each region.

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[18] The Armington elasticities, which describe the trade-off between the domestically produced good and the imported good of the same variety, correspond to the cross-price elasticities used in the analytical model.The demand elasticities in the analytical model are implicit to the Armington CES cost function (see Appendix B, equation 6); applying Shephard's lemma to the cost functions provides compensated demands.

The model links carbon dioxide (CO_2) emissions in fixed proportions to fossil-fuel use with fuel-specific CO_2 coefficients. CO_2 emissions intensity within a sector (μ in Section 2) can be reduced in the two ways: By substituting CO_2-intensive fuels with less CO_2-intensive or carbon-free fuels, and by substituting away from energy use towards other inputs (e.g. energy efficiency improvements through additional capital inputs). The costs of reducing the emissions intensity ($c(\mu)$ in Section 2) thus depend on the substitution elasticities and benchmark production cost shares, which differ across sectors and regions. Total domestic emissions can also be reduced by substituting between sectors, and by scaling down aggregate production and consumption activities. Net revenues from CO_2 taxes and tariffs are recycled lump-sum to the representative agent in the respective region.

As is customary in CGE analysis, base-year data and exogenous elasticities determine the free parameters of the model's functional forms. To this end, the model builds on the most recent Global Trade Analysis Project (GTAP) dataset with detailed accounts of regional production and consumption, bilateral trade flows, energy flows, and CO_2 emissions, all for the base year 2004 (Narayanan and Walmsley 2008).[19] The GTAP database is aggregated toward a composite dataset that accounts for the specific sectoral and regional requirements of our analysis.

At the sectoral level, the model captures details on sector-specific differences in factor intensities and substitutability, and price elasticities to trace the structural change in production induced by policy interference. The model identifies five energy goods, which is essential to distinguish energy goods by CO_2 intensity and the degree of substitutability. The model then

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[19] GTAP data are expressed in US dollars at market exchange rates astrade between countries takes place in actual market prices. By using market exchange rates, the economic activity levels in developing regions generally appear to be lower than they actually are when measured in purchasing power parity (PPP) units. As exchange rates have shifted substantially towards the BASIC countries since 2004, we may underestimate the contribution from these countries' welfare on global welfare. We return to this issue below, when we discuss the numerical results.

incorporates energy-intensive and trade-exposed (EITE) commodities, which are potentially most affected by unilateral climate policies and thus considered for antileakage measures. These industries are paper, pulp and print; chemical products; iron and steel; nonferrous metals (including copper and aluminum); and nonmetallic minerals (including cement and glass). The remaining sectors are transport services and a composite of all other industries and services. (See bottom of Table II).

Table II. Regional and sectoral disaggregation

Regions			
EU:	A1-Rest:	BASIC:	ROW:
European Union	Russia	Brazil	OPEC
	Japan	South Africa	Other Asia
US:	Canada	India	Other America
United States	Australia/New Zealand	China	Other Africa
	Other Annex 1		Other Former Soviet Union

Sectors		
Energy:	EITE:	Other:
Coal	Paper, pulp, print	Transport
Crude oil	Chemical	Other industries and services
Gas	Iron and steel	
Refined petroleum and coal	Non-ferrous metal	
Electricity	Non-metallic mineral	

Notes: EITE=Energy-intensive, trade-exposed industries

In Appendix C we display the carbon intensities for the five EITE sectors in the EU and the US in the benchmark data, and how the intensities change when a unilateral economy-wide carbon price is increased from zero up to 50 USD per ton carbon. This is equivalent to the $\mu(t)$ variable in Section 2. As shown in Figures C1 and C2, emission intensities are generally lower in the EU than in the US, whereas emission intensities in the US tend to be most responsive to carbon prices. None of the sectors display much response with respect to their emission intensity, however.

At the regional level, the model identifies all countries that are key players in international climate negotiations (top of Table II). The group of industrialized countries includes the European Union, the United States, Russia, Japan, Canada, Australia, New Zealand, and other Annex 1. The developing world is represented in part through the so-called BASIC countries (Brazil, South Africa, India and China), which are incorporated individually. Finally, the model captures the rest of the world (ROW) through regional composites for the Organization of Oil Exporting Countries (OPEC), other Asia, other America, other Africa, and other Former Soviet Union.

There are two sets of elasticities which are central to leakage (see e.g. Burniaux and Oliveira-Martins 2000). Fossil-fuel supply elasticities are key determinants for leakage through the energy market channel: The lower these elasticities, the stronger is the price decrease of fossil fuels induced by fuel demand reductions. We use empirical estimates for fossil fuel supply elasticities (Graham et al. 1999; Krichene 2002) to calibrate the CES in fossil fuel production. Armington elasticities govern leakage through trade in EITE products: the higher the Armington elasticities, the stronger is leakage through the EITE trade channel, as regions can more easily substitute new sources for EITE goods in response to the changes induced by the climate policy regime. The Armington trade elasticities are taken from the GTAP database. Reflecting the importance of fossil fuel supply elasticities and Armington elasticities for leakage, we include variations of these elasticity values in our sensitivity analysis (see footnote 27).

3.2 Policy Scenarios

To assess the economic appeal of additional antileakage measures, we start from a reference scenario *Tax*, where countries forming the abatement coalition levy a unilateral CO_2

tax. (Equivalently, these countries could establish a joint cap-and-trade system.) We then quantify how economic impacts change as we impose the antileakage measures analyzed in Section 2: i) output-based rebates (OBR), ii) border adjustment for imports (BAI), and iii) full border adjustments (FBA). The policies include the most often discussed design features and coverage (see Cosbey et al. 2012): First, they are imposed only upon the five EITE sectors, i.e., the sectors most likely to suffer leakage and justify an environmental exception for trade-distorting practices under WTO law. Second, the calculation of embedded carbon in EITE goods includes country-specific direct emissions for each EITE sector (OBR, BAI and FBA) and indirect emissions from their consumption of electricity generation (BAI and FBA). On the other hand, it excludes emissions that might be embodied in other inputs or transportation (see Böhringer, Bye, Fæhn and Rosendahl, 2012, for an analysis of different ways of calculating embedded carbon in tariffs). Thus, while the carbon price is economy-wide within the coalition, the antileakage measures are circumscribed.[20]

The implications of the four climate policy scenarios are measured with respect to business as usual (BAU) in the absence of climate policy, defined by the economic patterns in 2004, i.e., before the Kyoto Protocol entered into force.

Our main research interest lies in the relative performance of alternative antileakage measures as the size of the abatement coalition increases from a single country toward global coverage. Given the fact that the European Union is pushing most vividly for stringent emission

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[20] In terms of coverage, then, 1) emissions from fossil fuel combustion in the coalition are captured by the carbon price; 2) neither OBR nor export rebates would exempt fossil fuel emissions from the carbon price but they rather offer a compensating output or export subsidy; 3) downstream emissions of fossil fuels exported to or consumed in noncoalition countries are not captured except to the extent that they are combusted to produce EITE goods exported to the coalition and captured by the BCA. Indirectly, however, fossil fuel production and consumption worldwide is affected by global energy price changes. Taxing embodied carbon in fossil fuel exports has been analyzed by e.g. Hoel (1994).

regulations, we take it as the starting point for our coalition size variants (coalition EU).[21] Next, we consider the case that the United States joins (coalition EU+US), followed by all other Annex 1 regions (coalition A1). The fourth variant (coalition A1+BASIC) assumes that the BASIC developing regions join the abatement coalition, and the fifth variant (coalition All) adds the ROW. In this final variant, leakage by definition will not occur.

Considering that the climate is a global public good, a coherent analysis of antileakage measures requires that we keep global emissions constant for a given coalition unless we can value the damage from emissions. Acknowledging the huge uncertainties in cost estimates for climate change, we do not attempt to trade off the abatement cost with the benefit from avoided climate change but restrain ourselves to a cost-effectiveness analysis. Therefore, we require the abatement coalition to adjust its unilateral emissions reduction effort to meet a given global emission cap, defined as the coalition's emissions target plus the BAU emissions of noncoalition countries. In our core simulations, we set the unilateral emissions target at 80 percent of BAU emissions, but to "compensate" leakage, the effective unilateral cap will be lower.[22]

3.3 Numerical Results

Figure 1 illustrates how emissions in three different aggregate noncoalition regions—A1-Rest[23], BASIC, and ROW—change when the coalition expands and the region in question is still outside the coalition. Each line shows the emissions vis-à-vis BAU levels for a given region and

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[21] As a matter of fact, the European Union is the only region to date that has adopted legally binding post-Kyoto emissions reduction commitments.

[22] Technically, the global emissions constraint requires an endogenous uniform emissions tax across the countries of the abatement coalition to comply with the exogenous global emissions cap. If the coalition implements its initial emissions target as an explicit cap, it must be scaled endogenously to compensate leakage toward the exogenous global emissions constraint. In this case, the shadow price of the coalition's cap corresponds to the endogenous carbon tax under price regulation.

[23] We refer to the composite of Annex 1 regions without the EU and the US as A1-Rest.

climate policy but with different coalition sizes. For instance, the line “ROW OBR” shows how the ROW emissions change when the coalition expands from no coalition (BAU) to include the European Union (EU), then also the United States (EU+US), and so on, assuming the use of an output-based rebate to EITE sectors in each of the different coalitions.

In line with our theoretical findings (see e.g. beginning of Section 2.4), we see that emissions in noncoalition regions increase vis-à-vis their BAU emissions as the coalition expands. The magnitude of the increase depends on the trade intensity with the abatement coalition: because the European Union and the United States are most integrated with other Annex 1 regions, the A1-Rest emissions grow stronger for coalitions EU and EU+US than those in regions BASIC and ROW.

The figure further shows that emissions in any nonabating region are always highest when the coalition chooses Tax and lowest when it chooses FBA. This is consistent with the analytical results in Propositions 1-3 (remember that L_2 is proportional to noncoalition emissions under a fixed cap). OBR ranges closer to Tax than FBA. Note that for the sake of transparency, Figure 1 does not include policy BAI, which is closest to FBA and ranks second in reducing emissions increases in nonabating regions.

Figure 1. Emissions in Nonabating Regions

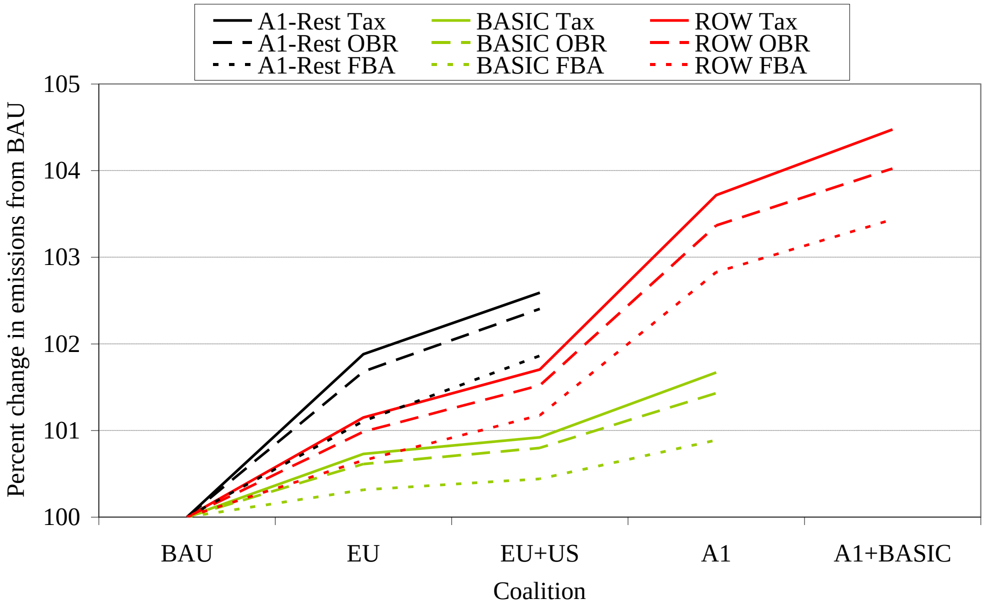

Figure 2a depicts changes in the leakage rate L_1. Not surprisingly, leakage rates decline and converge as the regional coverage of the abatement coalition expands.[24] Consistent with Figure 1, FBA is most effective at deterring leakage. While the ranking between BAI and OBR was ambiguous in the theoretical model, BAI clearly outperforms OBR in our numerical analysis and is much closer to FBA.

The ranking is necessarily the same in terms of the emissions differential (cf. Lemma 1), but the effects of expanding the coalition are different from the analytical findings. There we found that L_2 would be constant under Tax, and decline under OBR, FBA and (most likely) BAI as the coalition size is increased. The CGE model finds that L_2 increases as the coalition grows, and the effects of antileakage measures decline somewhat (Figure 2b). This difference reflects

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[24] Some reduction in L_1 from EU to EU+US occurs because leakage rates with EU unilateral policies are much higher (27 percent with Tax) than with U.S.unilateral policies (10 percent with Tax). To control for this, if we calculate the weighted average of L_1 under EU and US, we get leakage rates from 12 percent (FBA) to 17 percent (Tax), significantly above the corresponding EU+US leakage rates.

the importance of global fuel price changes omitted in our stylized theoretical analysis. Fuel prices become depressed through unilateral emissions abatement, which drive up emissions intensities among nonabating countries. Another contrast is the analytical model assumed away differences among the regions; in the CGE model, countries are heterogeneous, and expanding the coalition size also changes its composition. For example, the EU is less emissions-intensive than most of the trading partners that are included in later coalitions, so the coalition composition has its own effects on emissions prices and therefore leakage pressure.

Figure 2a. Leakage rate (L_1)

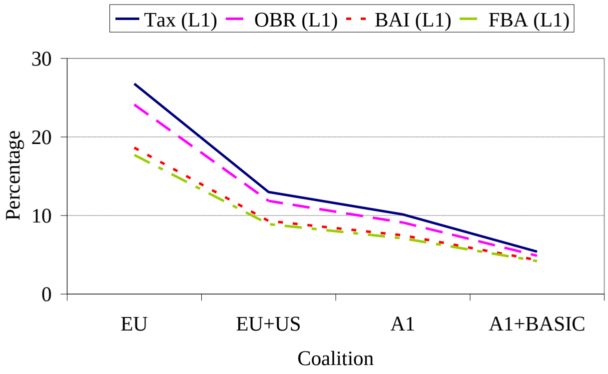
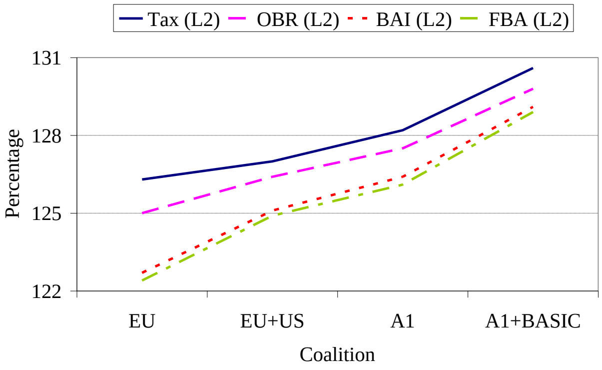


Figure 2b. Emissions differential (L_2)



If the emissions differential represents the cost of joining the coalition, FBA and BAI perform the best at supporting a coalition; indeed, the emissions differential with an all–Annex I coalition (A1) and FBA is less than that with the EU alone and a simple carbon price. But the increase in emissions differentials in response to coalition growth in the CGE model may indicate some difficulties in broadening a coalition beyond some size, as later joiners are likely to have lower willingness to accept costs.

The CGE model allows us to consider not only emissions and leakage effects, as in the analytical part, but also effects on compliance costs, measured here in terms of the Hicksian equivalent variation in income. Figure 3 reveals the differences in global cost-effectiveness of antileakage measures compared to Tax, as well as the global costs of the Tax scenario (compared to BAU). For global cost-effectiveness assessment, we add up money-metric utility with equal weights across all regions, being agnostic on the distribution of costs.[25] First, we notice that the global costs of uniform carbon pricing alone amount to 0.15-0.35 percent of global income, or $50-115 billion per year. Next, global compliance costs to achieve a certain global emissions reduction can be lowered if we supplement uniform emissions pricing in coalition countries with antileakage policies. Figure 3 shows that all antileakage measures for EITE sectors reduce global compliance costs as long as the coalition is not too big. The basic intuition is that simply replacing production of EITE goods in coalition countries by production of EITE goods in noncoalition countries is cost-inefficient, especially if emissions intensities are high in noncoalition countries.

The cost ranking is consistent with the leakage ranking: Costs are smallest for FBA, which most effectively reduces emissions relocation through leakage. Having only import tariffs is more costly from a global perspective but the cost advantage of FBA over BAI is relatively moderate. OBR provides some cost savings over unilateral emissions pricing only (Tax) for smaller coalitions, but among antileakage policies it is clearly the least cost-effective. For larger coalitions, such as A1+BASIC, OBR is also more costly than the Tax policy. OBR induces excess costs as they maintain distortionary subsidies for EITE production, whereas the cost savings through leakage reduction decline as the coalition expands. If the coalition attains global coverage, border measures (FBA and BAI) by definition coincide with the Tax policy.

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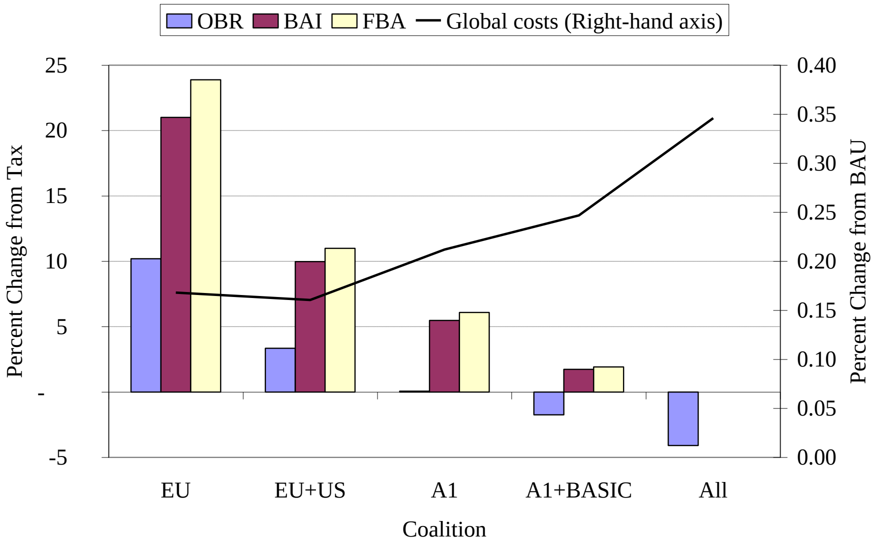
[25] See Böhringer, Carbone and Rutherford (2012) for alternative welfare aggregation measures.

Figure 3. Global Cost Savings of Antileakage Measures, and Global Costs of Tax



It should be noted that global cost savings of antileakage policies—measured in percentage of the costs of the Tax case—decline markedly as the coalition size expands. With respect to absolute cost savings, however, it must be considered that global compliance costs also increase for larger abatement coalitions in the Tax case (see the curve in Figure 3), as global emissions are further reduced when the coalition is expanded. Nevertheless, global cost savings fall substantially also in money terms—for instance, expanding the coalition from EU to A1 reduces the cost savings of FBA compared to Tax by two thirds (in the former case, the global cost savings of FBA are US$12 billion per year). From a broader international policy perspective, the quantitative results raise the critical question of whether the overall cost savings through antileakage measures outweigh the risks and efforts of implementation (including legal disputes, potential trade wars, costs of monitoring and verifying etc).

Our quantitative results are based on GTAP data with national accounts and bilateral trade flows stated in market exchange rates (MER). This may underestimate the weights of income changes in developing countries as compared to the use of purchasing power parity (PPP) units To test the importance of this, we have constructed weights on regional income changes depending on their relative PPP/MER ratios, and recalculated changes in global costs in the different scenarios. In the EU coalition case, the ranking across policy measures is unchanged. However, in the three other coalition cases, the ranking changes—TAX and OBR are then less costly than FBA and BAI. This reflects that non-coalition countries in general have higher PPP/MER ratios than coalition countries, and non-coalition countries generally prefer TAX or OBR over border adjustments (FBA/BAI), see e.g. Figure 6 below. Note, that the change in accounting metrics can be thought of as a change in the distributional weighing (see e.g. Böhringer, Carbone and Rutherford, 2012). Hence, if transfers were introduced from coalition to non-coalition countries, requiring unchanged costs across policy scenarios for non-coalition countries, the ranking would remain robust.

Figure 4 reports the shift in EITE production from coalition to noncoalition countries as antileakage measures are implemented. This exercise may be more analogous to the partial-equilibrium analytical model, as the output measure ignores general equilibrium changes in emissions intensities embodied in the leakage measures (aside from indirectly influencing the global emissions target). Border adjustments are consistently more effective than OBR in mitigating relocation of EITE output. However, in all scenarios, even with adjustments, coalition output declines and noncoalition output increases compared to BAU-levels, while global EITE output decreases.

Figure 4. Output of *EITE* Goods in Coalition and Noncoalition Countries

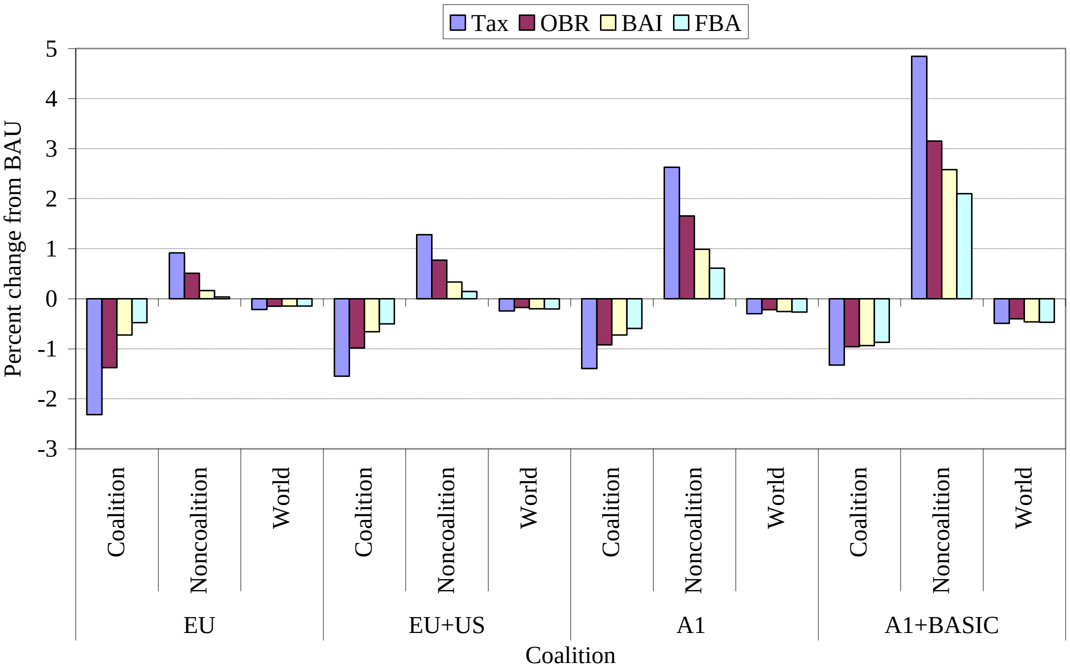
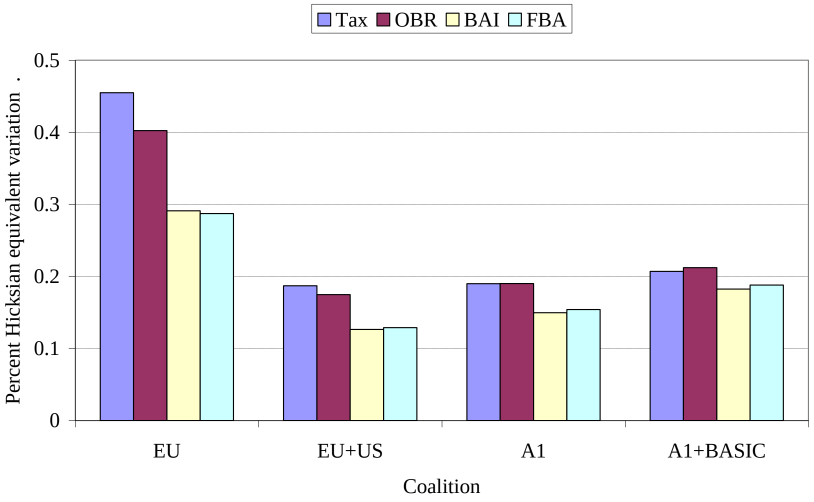


Figure 5 provides a cost-effectiveness assessment from the more narrow perspective of the abatement coalition: what is the cost for the abatement coalition to achieve a given global emissions reduction? As expected, the findings are broadly in line with the ranking of the emission differential L_2 across antileakage policies. Border measures still provide non-negligible cost savings compared to Tax and OBR, particularly for smaller coalition sizes, but the difference between FBA and BAI is smaller than from a global cost-effectiveness perspective. In fact, BAI may (slightly) outperform FBA in the simulations because of terms-of-trade effects. The abatement coalition is able to improve its terms of trade via import tariffs, thereby shifting more of the abatement cost burden to nonabating trading partners. Export rebates on top of this might be inferior for the abatement coalition if the reduction in EITE export prices dominates the gains from less leakage, which translates into less of an emissions reduction within the coalition. We also notice that OBR is more costly than Tax when the coalition is sufficiently large.

Figure 5. Compliance Cost for Abatement Coalition



Consistent with the results in Figure 5, the emissions prices are highest under the EU coalition (103-122 US$ per ton CO_2 vs 66-78 US$ per ton CO_2 with the other coalitions). The prices are highest in the Tax and OBR scenarios, and lowest in the BCA scenarios.[26]

As laid out in Böhringer et al. (2010), the incidence of unilateral climate policies across different regions may vary substantially. The economic implications from the perspective of a single region capture primary costs of emissions abatement should the country be part of the abatement coalition and indirect international spillover effects through changes of terms of trade. The terms-of-trade effects on fossil fuel markets explain most of the welfare impacts for regions outside the abatement coalition and can considerably lower or increase the direct cost of emissions reduction for countries within the abatement coalition. These effects, however, are

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[26] This is different from the ranking in Proposition 5, but there we considered the case with a fixed *coalition* cap.

fairly robust across unilateral abatement policies for a given coalition size because the global emission cap is fixed, and so is the pressure to cut back on fossil fuel consumption.

If we track the changes in the European Union's adjustment cost over the expansion of the coalition size, we find that emissions constraints in the United States adversely affect the European Union, whereas these negative repercussions are slightly ameliorated when all other Annex 1 regions join the coalition. Compliance costs in the European Union are then increased again when the BASIC countries join. Thus, expanding the coalition has no clear-cut implications for the European Union's marginal or total compliance costs, and the same pattern is observed for the United States. Again, the magnitude and direction of these changes hinge on the relative abatement costs and the trade patterns that the European Union (and the United States) have with major trading partners.

Whereas border measures are preferred from a coalition and a global perspective, they are almost always inferior to Tax and OBR for nonabating regions. More surprising, OBR is often preferred over Tax, even for noncoalition countries as a group. One example is Canada (see also Figure 6 on China below). If the United States adopts a climate policy alone or jointly with the European Union, Canada gains in comparative advantage because the United States is by far Canada's most important trading partner. This is especially true if the United States (or the EU+US coalition) does not apply any antileakage measures, or just keeps with OBR. However, the moderate gains turn into losses if the EU+US coalition levies tariffs on EITE imports—then the United States shifts part of its abatement burden via terms-of-trade changes to Canada.

Figure 6. Adjustment Cost for China

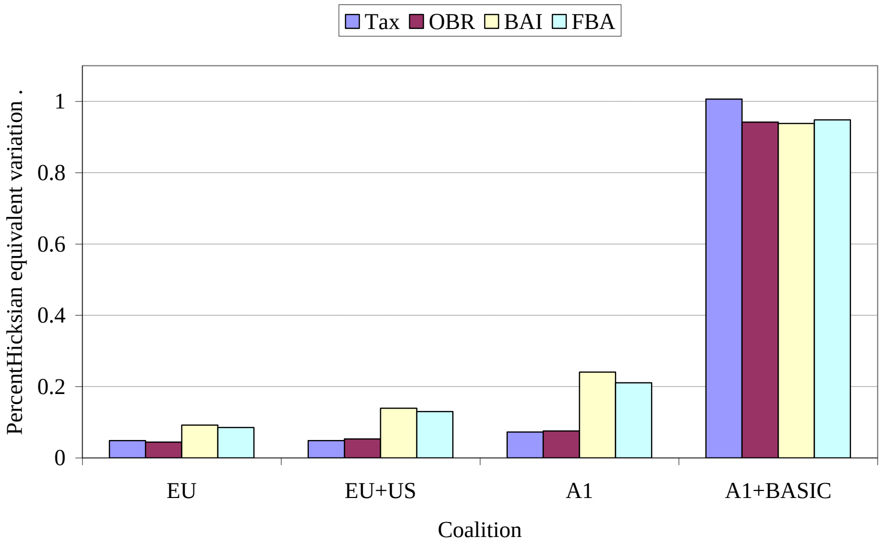

Figure 6 visualizes the adverse terms-of-trade effects for China, the major climate policy player in the developing world, if it is outside a coalition of industrialized nations that implements border adjustments. If the abatement coalition instead introduces OBR, the Chinese welfare loss is no higher than under a tax-alone regime. In reality, China is considering different forms of carbon regulation, so it is worth noting that once China joins the abatement coalition, its own preference switches in favor of border measures against nonabating regions.

To test the robustness of our findings, we have performed sensitivity analysis with respect to uncertainties in the parameterization space. The dimensions of sensitivity analysis include (i) the unilateral emissions reduction target of the abatement coalition, (ii) the abatement regulation across coalition members, (iii) the degree of product heterogeneity in traded goods

(Armington elasticities), and (iv) the price responsiveness of fossil-fuel supplies. We find that all our qualitative insights based on the central case simulations remain robust.[27]

We have also examined the effects of combining antileakage measures with a fixed carbon price, in which case the additional measures may lead to lower or higher global emissions. Hence, it is not straightforward to compare welfare effects. Nevertheless, we find that border adjustments (FBA and BAI) give lower global emissions *and* lower global compliance costs compared to OBR and Tax, irrespective of coalition. FBA ranks above BAI in most cases, but gives somewhat higher emissions with the biggest coalition. OBR gives lower global compliance costs than Tax, but induces higher global emissions if the coalition is big. Thus, in general we conclude that the ranking of policy measures is to a large degree the same as under a fixed global emissions cap.

4. Conclusions

Various industrialized countries are in the process of legislating domestic emissions regulations to lead the fight against man-made climate change. A major challenge in the design of unilateral climate policies is the appropriate response to the threat of emissions leakage. Second-best measures such as output-based emissions allocation or border adjustments for

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[27] Alternative model and scenario parameterizations involve (i) reduction targets of 10 percent and 30 percent; (ii) noncoordinated abatement action across coalition members (in which each must meet the same reduction target, as compared to the default of a common emissions price); (iii) a doubling and halving of GTAP-based Armington elasticities; and (iv) a doubling and halving of the central-case fossil-fuel supply elasticities. The latter elasticities have large impacts on overall leakage rates (L_1 is increasing from 21 to 33 percent in the EU-Tax scenario when going from high to low elasticities), but the ranking of policy measures is not altered as these measures target leakage through the EITE markets.

energy-intensive and trade-exposed industries can increase effectiveness of unilateral action but introduce distortions of their own.

In this paper, we have assessed the relative attractiveness of politically debated antileakage measures as a function of the abatement coalition size. We find a robust ranking in terms of leakage reduction and global cost-effectiveness with full border adjustment coming first, followed by import tariffs, and then output-based rebates. The differences across antileakage measures and the overall appeal of such measures decline with the size of the abatement coalition. Whereas border adjustment measures become inactive with global coverage of the coalition, the distortionary effects of output-based rebates persist even in the case of a global abatement coalition, without reaping any benefits in terms of reduced leakage.

Full border adjustment is consistently the most cost-effective option in a utilitarian sense, but it is also likely to face the greatest practical barriers. While many trade law experts believe that import adjustments can be made compatible with WTO obligations, the export rebates may constitute an illegal subsidy under the Agreement on Subsidies and Countervailing Measures, which has no explicit exceptions for environmental purposes (Cosbey et al. 2012). However, we find relatively small additional efficiency gains from export rebates; most of the benefits of border adjustment are driven by the import tariffs.

Even if restricted to imports, border adjustment may face strong international political opposition. Border adjustment measures for energy-intensive and trade-exposed sectors can have substantial negative welfare effects for countries outside the abatement coalition due to adverse terms-of-trade shifts: while border adjustments clearly dominate output-based rebates from a global or coalition perspective, nonabating countries prefer output-based rebates over tariffs and full border adjustments if antileakage measures cannot be avoided. This preference could change, however, if tariff revenues were returned to the exporters (cf. Böhringer, Balistreri and Rutherford. 2012).

Output-based rebates create economic impacts for noncoalition countries that closely resemble the implications triggered by a tax-alone (cap-alone) unilateral climate policy at the macro level. As a result, output-based rebates might be more attractive than border measures from a global or coalition perspective because the risk of trade conflict is higher if border measures are chosen. Although output-based rebates perform more poorly in terms of global cost-effectiveness than import tariffs or full border adjustments, the cost savings of the latter are not huge when compared to potential losses of subsequent trade wars. This might explain the lack of border measures in current climate policy legislation such as the EU Emissions Trading System.

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Appendix A. Supplements to the Analytical Model

Assumption 1: Own-price effects dominate the cumulative cross-price effects.

This statement involves three specific assumptions:

Assumption 1a: $-\eta_o + (n-1)\eta_x < 0$.

This assumption ensures that demand declines if all prices increase by the same amount.

Assumption 1b: Let $\phi(t) = (1+t\mu_0)^{-\eta_o+(n-m-1)\eta_x}\left(c(\mu(t))+t\mu(t)\right)^{m\eta_x}$ *, where* $\phi(0)=1$*.Then for t>0,* $\phi'(t) < 0$.

Assumption 1b follows from $1+t\mu_0 > c(\mu(t))+t\mu(t)$ and Assumption 1a, which imply that $\phi(t) < (c(\mu(t))+t\mu(t))^{-\eta_o+(n-1)\eta_x} < 1$, so more generally, $\phi'(t) < 0$.

Assumption 1c: Let $\psi(t) = (c(\mu(t))+t\mu(t))^{-\eta_o+(m-1)\eta_x}(1+t\mu_0)^{(n-m)\eta_x}$ *, where* $\psi(0)=1$ *and parameters remain in a range such that* $\psi'(t) < 0$.

Assumption 1c says that as we increase the carbon price *t*, demand for domestically produced goods in regulating countries will fall even if imported goods from nonregulating countries are taxed through border adjustments. This assumption will be a sufficient but not a necessary condition for clear comparisons. It is simple to show that $\psi'(0) < 0$. Thus, we effectively consider carbon prices and abatement costs within a reasonable range in which the first-term effect dominates the second.

Lemma 1*: In the case of a fixed* coalition *cap, the ranking of L_1 across policies follow the ranking of L_2. In the case of a fixed* global *cap, the ranking of L_2 across policies strictly follows the ranking of L_2 under a fixed* coalition *cap.*

Proof: With a fixed coalition cap, $E_M^j = E_M^k$, for any two policies *j* and *k*. Then $L_2^j / L_2^k =$ E_N^j / E_N^k and $L_1^j / L_1^k = \frac{(E_N^j - E_N^0)}{(E_N^k - E_N^0)}$. Thus, if $L_2^j < L_2^k$, $E_N^j < E_N^k$ and $L_1^j < L_1^k$ (and vice-versa).

The proof of the second part follows from the fact that coalition emissions are decreasing and noncoalition emissions are increasing in the coalition carbon price, given any policy. If $L_2^j < L_2^k$ under a fixed coalition cap, then $GE^j < GE^k$. Thus, to meet the same global cap as in policy *k*, we need to lower the carbon price in policy *j* from that with the coalition cap t_j to t_j'. This means that $E_M^{j\,\prime} > E_M^k$. Furthermore, with less leakage pressure, $E_N^{j\,\prime} < E_N^j$. Thus, $L_2^{j\prime} < L_2^j < L_2^k$.

Proposition 1*: Given a fixed carbon price or a fixed coalition cap,* $L_2^R < L_2^T$.

Proof: In the case of a fixed tax, noncoalition emissions are smaller (y_N^R is lower), but so are domestic reductions (y_M^R is higher and μ_M is unchanged):

$$\frac{E_N^{Rtax}}{E_N^T} = \left(\frac{c_T}{c_T + t\mu_T}\right)^{m\eta_x} < 1;$$

$$\frac{E_M^{Rtax}}{E_M^T} = \left(\frac{c_T}{c_T + t\mu_T}\right)^{-\eta_o + (m-1)\eta_x} > 1.$$

Thus, the emission differential L_2 is necessarily smaller with OBR, i.e., $L_2^{Rtax} < L_2^T$.

In the case with a fixed coalition cap, as with output-based allocation of emissions allowances, output is higher than with a carbon price alone. Thus, to meet the same target, emissions intensity must be lower ($\mu_R < \mu_T$), implying that $c_T < c_R < c_T + t\mu_T$. Then we can show:

$$\frac{L_2^{Rcap}}{L_2^T} = \frac{E_N^{Rcap}}{E_N^T} = \left(\frac{c_R}{c_T + t\mu_T} \right)^{m\eta_x} < 1 .$$

Proposition 2: *Given a fixed carbon price,* $L_2^{Btax} / L_2^T < 1$.

Proof: We have that noncoalition emissions fall while coalition emissions rise, relative to the Tax case:

$$\begin{aligned} \frac{E_N^{Btax}}{E_N^T} &= \frac{y_N^{Btax}}{y_N^T} = \frac{m}{n}(1+t\mu_0)^{-\eta_o+(n-m-1)\eta_x} + \frac{(n-m)}{n} < 1; \\ \frac{E_M^{Btax}}{E_M^T} &= \frac{y_M^{Btax}}{y_M^T} = \frac{m}{n}(1+t\mu_0)^{(n-m)\eta_x} + \frac{(n-m)}{n} > 1. \end{aligned}$$

By definition, then, the emissions differential is mitigated ($L_2^{Btax} / L_2^T < 1$),

Proposition 3: *Given a fixed carbon price, i)* $E_N^{Ftax} < E_N^{Btax}$ *, ii)* $E_N^{Ftax} < E_N^{Rtax}$ *, iii)* $L_2^{Ftax} < L_2^{Btax}$*, and iv)* $L_2^{Ftax} < L_2^{Rtax}$.

Proposition 3: *Given a fixed carbon price, i)* $E_N^{Ftax} < E_N^{Rtax}$ *, and ii)* $L_2^{Ftax} / L_2^{Rtax} < 1$.

Proof: Consider first i) and ii). We then have:[28]

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[28] Note that emission intensities are the same across policies when the carbon price is fixed, so $\mu_F = \mu_T$ and $c_F = c_T$.

$$\frac{E_N^{Ftax}}{E_N^T}=\frac{y_N^{Ftax}}{y_N^T}=\frac{m}{n}(1+t\mu_0)^{-\eta_o+(n-m-1)\eta_x}+\frac{(n-m)}{n}\left(\frac{c_T}{c_T+t\mu_T}\right)^{m\eta_x}<\frac{E_N^{Btax}}{E_N^T}<1;$$

$$\frac{E_M^{Ftax}}{E_M^T}=\frac{y_M^{Ftax}}{y_M^T}=\frac{m}{n}(1+t\mu_0)^{(n-m)\eta_x}+\frac{(n-m)}{n}\left(\frac{c_T}{c_T+t\mu_T}\right)^{-\eta_o+(m-1)\eta_x}>\frac{E_M^{Btax}}{E_M^T}>1.$$

Thus, it follows that $L_2^{Ftax}<L_2^{Btax}<L_2^T$.

Next, we prove iii) by using $\phi(t)$ as defined in Assumption 1b, showing that FBA yields unambiguously lower emissions than OBR in countries outside the coalition:

$$\frac{E_N^{Ftax}}{E_N^{Rtax}}=\frac{y_N^{Ftax}}{y_N^{Rtax}}=\frac{m}{n}\underset{<1}{\phi(t)}\,\underset{<1}{c_T{}^{-m\eta_x}}+\frac{(n-m)}{n}<1.$$

To prove iv), we first compare the effects on coalition emissions:

$$\frac{E_M^{Ftax}}{E_M^{Rtax}}=\frac{y_M^{Ftax}}{y_M^{Rtax}}=\frac{m}{n}\underbrace{(1+t\mu_0)^{(n-m)\eta_x}}_{>1}\underbrace{\left((c_T+t\mu_T)/c_T\right)^{-\eta_o+(m-1)\eta_x}}_{<1}+\frac{(n-m)}{n}.$$

Thus, emissions in coalition countries can be higher or lower with FBA than OBR. However, since $1+t\mu_0>c(\mu(t))+t\mu(t)$, we have:

$$\frac{E_M^{Ftax}}{E_M^{Rtax}}>\frac{m}{n}\frac{\left(c_T+t\mu_T\right)^{-\eta_o+(n-1)\eta_x}}{c_T{}^{m\eta_x}}c_T{}^{\eta_o+\eta_x}+\frac{(n-m)}{n}.$$

Since $E_N^{Ftax}/E_N^{Rtax}<1$, it then follows that $\frac{L_2^{Ftax}}{L_2^{Rtax}}=\frac{E_N^{Ftax}}{E_N^{Rtax}}\bigg/\frac{E_M^{Ftax}}{E_M^{Rtax}}<1$.

Proposition 4: *Given a fixed coalition cap, i)* $L_2^{Fcap}<L_2^T$, *ii)* $L_2^{Fcap}/L_2^{Bcap}<1$, *and iii)* $L_2^{Fcap}/L_2^{Rcap}<1$.

Proof: i) Using Assumption 1b,

$$\frac{L_2^{Fcap}}{L_2^T} = \frac{E_N^{Fcap}}{E_N^T} = \frac{y_N^{Fcap}}{y_N^T} = \frac{m}{n}\underset{<1}{\phi(t_F)}\underbrace{\left(c_T + t\mu_T\right)}_{<1}^{-m\eta_x} + \frac{(n-m)}{n}\underbrace{\left(\frac{c_F}{c_T + t\mu_T}\right)}_{<1}^{m\eta_x} < 1.$$

ii) As $t_F > t_B$, by Assumption 1b, $\dfrac{L_2^{Fcap}}{L_2^{Bcap}} = \dfrac{E_N^{Fcap}}{E_N^{Bcap}} = \dfrac{m\phi(t_F) + (n-m){c_F}^{m\eta_x}}{m\phi(t_B) + (n-m)\left(c_B + t_B\mu_B\right)^{m\eta_x}} < 1.$

iii) First we prove that $p_F < p_R$. Assume instead $p_F = p_R$; Assumption 1c then implies:

$$\begin{aligned} E_M^F - E_M^R &= ma(p_F + t_F\mu_F)^{-\eta_o+(m-1)\eta_x}(1+t_F\mu_0)^{(n-m)\eta_x} + (n-m)a{p_F}^{-\eta_o+(m-1)\eta_x} - na{p_F}^{m\eta_x} \\ &= ma\left(\underset{<1}{\psi(t_F)} - {p_F}^{m\eta_x}\right) + (n-m)a{p_F}^{m\eta_x}({p_F}^{-\eta_o-\eta_x} - 1) < 0, \end{aligned}$$

implying that to meet the same coalition target, a lower *t* is needed with FBA than with OBR.

Next, with $p_F < p_R$ and Assumption 1b, we have

$$\frac{E_N^{Fcap}}{E_N^{Rcap}} = \frac{m}{n}\frac{\phi(t_F)}{{p_R}^{m\eta_x}} + \frac{(n-m)}{n}\left(\frac{p_F}{p_R}\right)^{m\eta_x} < 1.$$

Appendix B. Algebraic Summary of the Computable General Equilibrium Model

The computable general equilibrium model is formulated as a system of nonlinear inequalities. The inequalities correspond to the two classes of conditions associated with a general equilibrium: (i) exhaustion of product (zero profit) conditions for producers with constant returns to scale; and (ii) market clearance for all goods and factors. The former class determines activity levels, and the latter determines price levels. In equilibrium, each variable is linked to one inequality condition: an activity level to an exhaustion of product constraint and a commodity price to a market clearance condition.

In our algebraic exposition, the notation Π_{ir}^{z} is used to denote the unit profit function (calculated as the difference between unit revenue and unit cost) for production with constant returns to scale of sector i in region r, where z is the name assigned to the associated production activity. Differentiating the unit profit function with respect to input and output prices provides compensated demand and supply coefficients (Hotelling's lemma), which appear subsequently in the market clearance conditions. We use g as an index comprising all sectors/commodities i ($g=i$), the final consumption composite ($g=C$), the public good composite ($g=G$), and investment composite ($g=I$). The index r (aliased with s) denotes regions. The index EG represents the subset of energy goods coal, oil, gas, electricity, and the label FF denotes the subset of fossil fuels coal, oil, gas. Tables B1–B6 explain the notations for variables and parameters employed within our algebraic exposition. Figures B1–B3 provide a graphical exposition of the production structure. Numerically, the model is implemented in GAMS (Brooke et al. 1996)[29] and solved using PATH (Dirkse and Ferris 1995)[30].

Zero Profit Conditions:

1. Production of goods except fossil fuels (*g* ∉ *FF*):

$$\Pi_{gr}^{Y} = p_{gr} - \left[\theta_{gr}^{M} p_{gr}^{M(1-\sigma_{gr}^{KLEM})} + \left(1-\theta_{gr}^{M}\right) \left[\theta_{gr}^{E} p_{gr}^{E\,(1-\sigma_{gr}^{KLE})} + \left(1-\theta_{gr}^{E}\right) p_{gr}^{KL(1-\sigma_{gr}^{KLE})} \right]^{(1-\sigma_{gr}^{KLEM})/(1-\sigma_{gr}^{KLE})} \right]^{1/(1-\sigma_{gr}^{KLEM})} \leq 0.$$

2. Sector-specific material aggregate:

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

3. Sector-specific energy aggregate:

$$\Pi_{gr}^{E} = p_{gr}^{E} - \left[\sum_{i \in EG} \theta_{igr}^{EN} \left(p_{igr}^{A} + p_{r}^{CO_2} a_{igr}^{CO_2} \right)^{1-\sigma_{gr}^{E}} \right]^{1/(1-\sigma_{gr}^{E})} \leq 0.$$

4. Sector-specific value-added aggregate:

$$\Pi_{gr}^{KL} = p_{gr}^{KL} - \left[\theta_{gr}^{K} v^{(1-\sigma_{gr}^{KL})} + \left(1-\theta_{gr}^{K}\right) w^{(1-\sigma_{gr}^{KL})} \right]^{1/(1-\sigma_{gr}^{KL})} \leq 0.$$

5. Production of fossil fuels (*g* ∈ *FF*):

$$\Pi_{gr}^{Y} = p_{gr} - \left[\theta_{gr}^{Q} q_{gr}^{1-\sigma_{gr}^{Q}} + (1-\theta_{gr}^{Q}) \left(\theta_{gr}^{L} w_{r} + \theta_{gr}^{K} v_{r} + \sum_{i \notin FF} \theta_{igr}^{FF} p_{igr}^{A} \right)^{1-\sigma_{gr}^{Q}} \right]^{1/(1-\sigma_{gr}^{Q})} \leq 0.$$

6. Armington aggregate:

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

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

$$\prod^{A}_{igr} = p^{A}_{igr} - \left(\theta^{A}_{igr} \, p_{ir}^{1-\sigma^{A}_{ir}} + (1-\theta^{A}_{igr}) \, p_{ir}^{IM^{1-\sigma^{A}_{ir}}} \right)^{1/(1-\sigma^{A}_{ir})} \le 0.$$

7. Aggregate imports across import regions:

$$\prod^{IM}_{ir} = p^{IM}_{ir} - \left[\sum_{s} \theta^{IM}_{isr} \left(p_{is} \right)^{1-\sigma^{IM}_{ir}} \right]^{1/(1-\sigma^{IM}_{ir})} \le 0.$$

Market Clearance Conditions:

8. Labor:

$$\bar{L}_{r} \ge \sum_{g} Y^{KL}_{gr} \frac{\partial \Pi^{KL}_{gr}}{\partial w_{r}}.$$

9. Capital:

$$\bar{K}_{gr} \ge Y^{KL}_{gr} \frac{\partial \Pi^{KL}_{gr}}{\partial v_{gr}}.$$

10. Fossil-fuel resources (g $\in$ *FF*):

$$\bar{Q}_{gr} \ge Y_{gr} \frac{\partial \Pi^{Y}_{gr}}{\partial q_{gr}}.$$

11. Material composite:

$$M_{gr} \ge Y_{gr} \frac{\partial \Pi^{Y}_{gr}}{\partial p^{M}_{gr}}.$$

12. Energy composite:

$$E_{gr} \ge Y_{gr} \frac{\partial \Pi^{Y}_{gr}}{\partial p^{E}_{gr}}.$$

13. Value-added composite:

$$KL_{gr} \geq Y_{gr} \frac{\partial \Pi^{Y}_{gr}}{\partial p^{KL}_{gr}} .$$

14. Import composite:

$$IM_{ir} \geq \sum_{g} A_{igr} \frac{\partial \Pi^{A}_{igr}}{\partial p^{IM}_{ir}} .$$

15. Armington aggregate:

$$A_{igr} = Y_{gr} \frac{\partial \Pi^{Y}_{gr}}{\partial \ p^{A}_{igr}} .$$

16. Commodities (*g*=*i*):

$$Y_{ir} \geq \sum_{g} A_{igr} \frac{\partial \Pi^{A}_{igr}}{\partial p_{ir}} + \sum_{s \neq r} IM_{is} \frac{\partial \Pi^{IM}_{is}}{\partial p_{ir}} .$$

17. Private consumption composite (*g*=*C*):

$$Y_{Cr} p_{Cr} \geq w_{r} \overline{L}_{r} + \sum_{g} v_{gr} \overline{K}_{gr} + \sum_{i \in FF} q_{ir} \overline{Q}_{ir} + p^{CO_2}_{r} \overline{CO}_{2r} + \overline{B}_{r} .$$

18. Public consumption composite (*g*=*G*):

$$Y_{Gr} \geq \overline{G}_{r} .$$

19. Investment composite (*g*=*I*):

$$Y_{Ir} \geq \bar{I}_{r} .$$

20. Carbon emissions:

$$\overline{CO}_{2r} \geq \sum_{g} \sum_{i \in FF} E_{gr} \frac{\partial \Pi^{E}_{gr}}{\partial \left(p^{A}_{igr} + p^{CO_2}_{r} a^{CO_2}_{igr} \right)} a^{CO_2}_{igr} .$$

Table B1. Indices (sets)

G	Sectors and commodities (*g*=*i*), final consumption composite (*g*=*C*), public good composite (*g*=*G*), investment composite (*g*=*I*)
I	Sectors and commodities
r (alias *s*)	Regions
EG	Energy goods: coal, crude oil, refined oil, gas, and electricity
FF	Fossil fuels: coal, crude oil, and gas

Table B2. Activity Variables

Y_{gr}	Production of item *g* in region *r*
M_{gr}	Material composite for item *g* in region *r*
E_{gr}	Energy composite for item *g* in region *r*
KL_{gr}	Value-added composite for item *g* in region *r*
A_{igr}	Armington aggregate of commodity *i* for demand category (item) *g* in region *r*
IM_{ir}	Aggregate imports of commodity *i* and region *r*

Table B3. Price Variables

p_{gr}	Price of item *g* in region *r*
p^{M}_{gr}	Price of material composite for item *g* in region *r*
p^{E}_{gr}	Price of energy composite for item *g* in region *r*
p^{KL}_{gr}	Price of value-added composite for item *g* in region *r*
p^{A}_{igr}	Price of Armington good *i* for demand category (item) *g* in region *r*
p^{IM}_{ir}	Price of import composite for good *i* in region *r*

w_r	Price of labor (wage rate) in region *r*
v_{ir}	Price of capital services (rental rate) in sector *i* and region *r*
q_{ir}	Rent to fossil-fuel resources in region *r* ($i \in$ FF)
$p_r^{CO_2}$	Carbon value in region *r*

Table B4. Endowments and Emissions Coefficients

$\overline{L}_r$	Aggregate labor endowment for region *r*
$\overline{K}_{ir}$	Capital endowment of sector *i* in region *r*
$\overline{Q}_{ir}$	Endowment of fossil-fuel resource *i* for region *r* ($i \in$FF)
$\overline{B}_r$	Initial balance of payment deficit or surplus in region *r* (note: $\sum_r \overline{B}_r = 0$)
$\overline{CO}_{2r}$	Endowment of carbon emissions rights in region *r*
$a_{igr}^{CO_2}$	Carbon emissions coefficient for fossil fuel *i* in demand category *g* of region *r* ($i \in FF$)

Table B5. Cost Shares

θ_{gr}^{M}	Cost share of the material composite in production of item *g* in region *r*
θ_{gr}^{E}	Cost share of the energy composite in the aggregate of energy and value-added of item *g* in region *r*
θ_{igr}^{MN}	Cost share of the material input *i* in the material composite of item *g* in region *r*
θ_{igr}^{EN}	Cost share of the energy input *i* in the energy composite of item *g* in region *r*
θ_{gr}^{K}	Cost share of capital within the value-added of item *g* in region *r*
θ_{gr}^{Q}	Cost share of fossil-fuel resource in fossil-fuel production ($g \in FF$) of region *r*

θ_{gr}^{L}	Cost share of labor in nonresource inputs to fossil-fuel production ($g \in FF$) of region r
θ_{gr}^{K}	Cost share of capital in nonresource inputs to fossil-fuel production ($g \in FF$) of region r
θ_{igr}^{FF}	Cost share of good i in nonresource inputs to fossil-fuel production ($g \in FF$) of region r
θ_{igr}^{A}	Cost share of domestic output i within the Armington item g of region r
θ_{isr}^{M}	Cost share of exports of good i from region s in the import composite of good i in region r

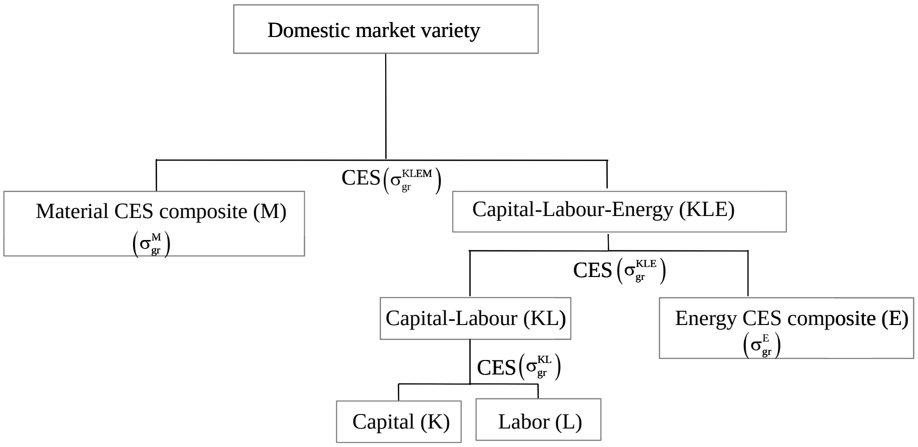
Table B6. Elasticities

σ_{gr}^{KLEM}	Substitution between the material composite and the energy value–added aggregate in the production of item g in region r^{*}
σ_{gr}^{KLE}	Substitution between energy and the value-added nest of production of item g in region r^{*}
σ_{gr}^{M}	Substitution between material inputs within the energy composite in the production of item g in region r^{*}
σ_{gr}^{KL}	Substitution between capital and labor within the value-added composite in the production of item g in region r^{*}
σ_{gr}^{E}	Substitution between energy inputs within the energy composite in the production of item g in region r (by default: 0.5)
σ_{gr}^{Q}	Substitution between natural resource input and the composite of other inputs in fossil-fuel production ($g \in$ FF) of region r (calibrated consistently to exogenous supply elasticities)
σ_{ir}^{A}	Substitution between the import composite and the domestic input to Armington production of good i in region r^{**}
σ_{ir}^{IM}	Substitution between imports from different regions within the import composite for good i in region r^{**}

*See Okagawa, A., and K. Ban. 2008. Estimation of Substitution Elasticities for CGE Models. Mimeo. Osaka, Japan: Osaka University.

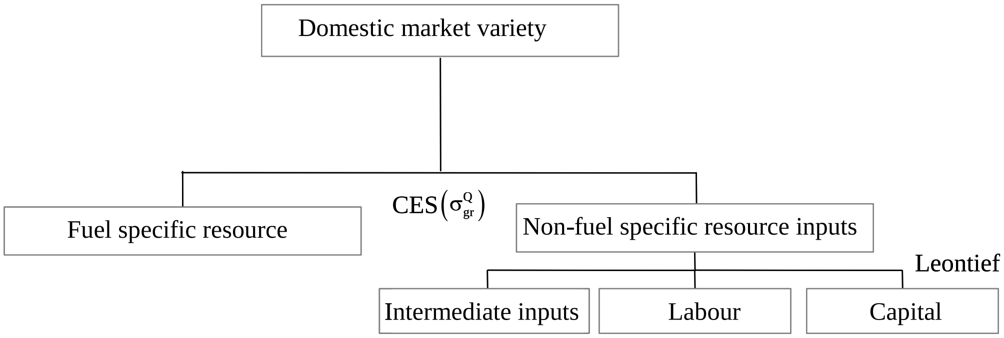
**See Badri, N.G., and T.L. Walmsley. 2008. Global Trade, Assistance, and Production: The GTAP 7 Data Base. West Lafayette, IN: Center for Global Trade Analysis, Purdue University.

Figure B1. Nesting in Nonfossil-Fuel Production



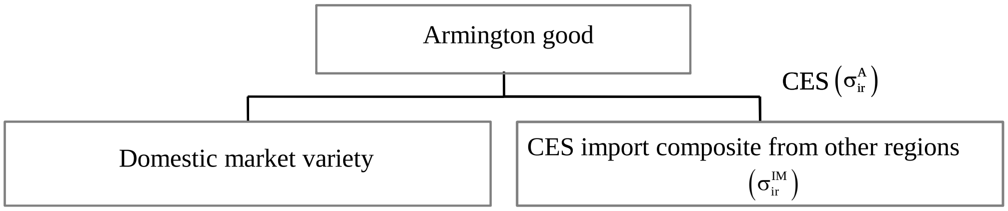
Note: CES=constant elasticity of substitution.

Figure B2. Nesting in Fossil-Fuel Production



Note: CES=constant elasticity of substitution.

Figure B3. Nesting in Armington Production



Note: CES=constant elasticity of substitution.

Appendix C. Carbon emissions intensities in the EU and the US

Here we display carbon intensities for the five EITE sectors in the EU and the US in the benchmark data, and how the intensities change when a unilateral economy-wide carbon price is increased from zero up to 50 USD per ton carbon. Figure C1 shows intensities for the EU, while Figure C2 shows intensities for the US.

Figure C1. Carbon intensities in the EU as a function of the carbon price. Ton carbon per USD_{2004} production value

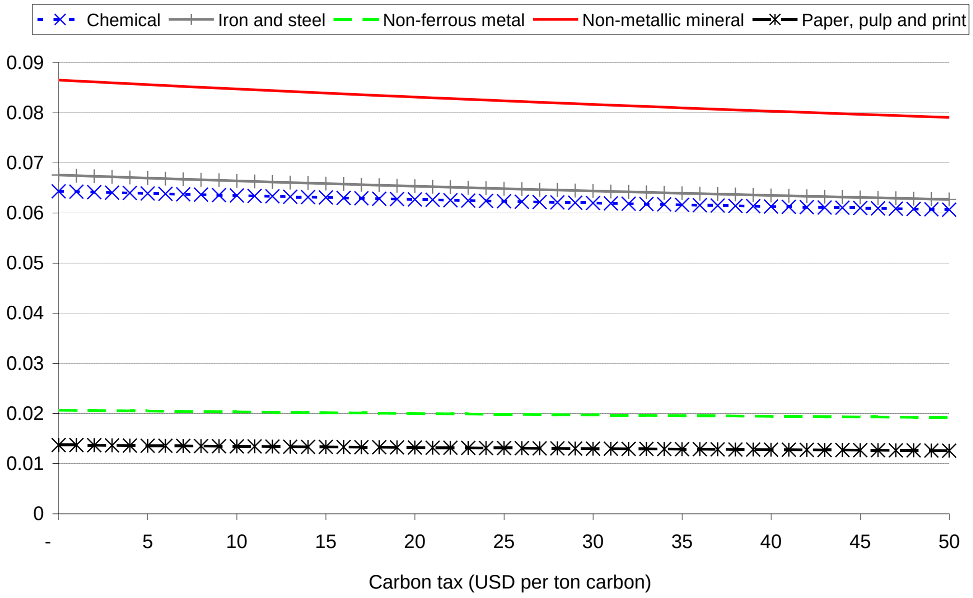


Figure C2. Carbon intensities in the US as a function of the carbon price. Ton carbon per USD$_{2004}$ production value