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Cost-Effective Unilateral Climate Policy Design: Size Matters

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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 allocation

JEL Classification Numbers: Q2, Q43, H2, D61

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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 to prevent dangerous anthropogenic interference with the climate system. The target implies drastic global emissions reductions over the next decades of roughly 50 percent compared to 1990 levels (IPCC 2007). Given the increasing share of the developing world in global anthropogenic greenhouse gas emissions, the 2° Celsius target cannot be achieved without substantial abatement contributions from major developing regions, such as China or India. At the same time, because high-income industrialized countries historically had (and still have) much higher per-capita emissions than low-income developing countries, it seems inevitable that industrialized countries take a leading role in short- to mid-run abatement efforts before the developing countries will follow suit.

The increasing pressure for unilateral action manifests itself in various domestic climate policy initiatives by industrialized countries. 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 and by 30 percent if other developed countries commit themselves to comparable reduction targets (European Union 2008). These targets were put into legal force in December 2008. In a similar vein, there are policy proposals in other OECD regions with substantial unilateral emission reduction pledges over the next decades.

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 also occurs when emissions constraints in larger open economies depress the demand for fossil fuels and thus induce a significant drop in world energy prices, which in turn could lead to an increase in the level of energy demand in other regions.

To reduce leakage and thereby increase cost-effectiveness, various instruments are considered to complement unilateral emissions pricing. One policy measure is based on border carbon adjustments. 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 border adjustment would combine adjustments for imports and exports, effectively implementing destination-based carbon pricing (Whalley and Lockwood 2010). However, most policy proposals to date focus only on import adjustments.

Another option is output-based rebates (under a fixed carbon price) or allocation of emissions allowances (under a fixed quota) to EITE sectors. The rebate, or the value of additional 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.

Border carbon adjustments and output-based rebates introduce distortions of their own but may be justified on efficiency grounds as second-best measures complementing unilateral emissions pricing. The attractiveness of these additional measures and their relative ranking in terms of global cost-effectiveness hinge on the magnitude of emissions leakage: the environmental effectiveness of output-based rebates and border carbon adjustments would drop to zero if the coalition of abating countries comprised the whole world. Whereas border carbon adjustments in this case would automatically become inactive, output-based rebates to energy-intensive industries might continue to induce excess costs of emissions abatement compared to the first-best option of uniform emissions pricing alone.

Beyond the global cost-effectiveness dimension, abating countries may face quite different cost and emissions implications of antileakage instruments based on their specific trade, production, and consumption patterns (Fischer and Fox 2009; Böhringer et al. 2010). This immediately raises the question if individual countries joining some abatement coalition would easily agree on an antileakage strategy.

While the economic impacts of border adjustment measures and output-based rebates have been addressed for a fixed number of abating regions, we are not aware of any study that assesses the implications of these antileakage 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.

We find that of the three instruments, full border adjustments are the most effective to reduce leakage. In theory, output-based rebates can be more effective than import adjustments alone when goods are stronger substitutes and the coalition size is sufficiently small. However, the parameterization of our CGE model with empirical data 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 full border adjustment, but the cost advantage vis-à-vis tariffs is small. The relative performance between these two instruments remains robust as the coalition size increases. Output-based rebates achieve the smallest cost savings among the three antileakage instruments compared to a reference climate 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.

Depending on the trade characteristics of the coalition, it might prefer import tariffs over full border adjustments 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 output-based rebates over full border adjustments or tariffs. Output-based rebates induce economic implications that are more similar to those triggered by unilateral climate policies without antileakage instruments. While they 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 with respect to prices p_{ij} prevailing in country *i* for good *j*, where the elasticities are η_{ikj} for country *i* consuming good *k* with respect to the price of the good from country *j*:

$$q_{ik} = a_{ik} \prod_{j} (p_{ij})^{\eta_{ikj}} ,$$

where a_{ik} denotes benchmark demand as initial prices are normalized to unity.

Suppose countries are symmetric, so benchmark demands are equal ($a_{ik} = a$), as are own-price elasticities ($\eta_{ikk} = -\eta_o$), and cross-price elasticities ($\eta_{ikj} = \eta_x$). Then,

$$q_{ik} = a(p_{ik})^{-\eta_o} (\prod_{j \neq k} p_{ij})^{\eta_x} .$$

Now we will distinguish between two country types: a regulating country *M* within the coalition, and a nonregulating country *N* outside the abatement 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*.

Simplifying demand, we get:

$$\begin{aligned}
q_{MM} &= a(p_{MM})^{-\eta_o} p_{MM}{}^{(m-1)\eta_x} p_{MN}{}^{(n-m)\eta_x};\\
q_{MN} &= a(p_{MN})^{-\eta_o} p_{MM}{}^{m\eta_x} p_{MN}{}^{(n-m-1)\eta_x};\\
q_{NM} &= a(p_{NM})^{-\eta_o} p_{NM}{}^{(m-1)\eta_x} p_{NN}{}^{(n-m)\eta_x};\\
q_{NN} &= a(p_{NN})^{-\eta_o} p_{NM}{}^{m\eta_x} p_{NN}{}^{(n-m-1)\eta_x}.
\end{aligned}$$

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

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

We consider competitive markets, where goods are priced at marginal costs plus potential taxes or subsidies. Let $c(\mu)$ denote production cost, where $\mu(t)$ reflects the cost-minimizing emissions intensity at the carbon price t. In the benchmark, t=0, with $\mu_0 = \mu(0)$ indicating the initial emissions intensity and $p_0 = c(\mu_0) = 1$. Marginal production costs increase as the emissions intensity decreases from μ_0, i.e., $c' < 0$. The emissions intensity of production in country i is noted for brevity as μ_i, and emissions in country i are denoted with E_i. Global emissions are then:

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

The following lemma and assumption will be useful in the subsequent analysis:

Lemma 1: Given any carbon price, $t > 0, 1 + t\mu_0 > c(\mu(t)) + t\mu(t)$.

This follows by the definitions of $\mu(t)$ and $c(\mu)$above (and $p_0 = 1$); as carbon prices are imposed, producers in regulated countries respond by decreasing their emissions intensity to lower compliance costs.

<u>Assumption 1:</u> 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.[1]

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

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

members vis-à-vis noncoalition members in reaching the emissions target—or the relative 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.[2] 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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[2] 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 lemmas, which are proved in Appendix A:

Lemma 2: In the case of a fixed coalition cap, the ranking of L_1 across policies will follow the ranking of L_2.

Lemma 3: The ranking of L_2 across policies under a fixed global cap strictly follows the ranking of L_2 under a fixed coalition cap.

Proof: See Appendix A.

2.2 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) without additional antileakage measures. 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 initial reference level.

Carbon Price Alone

First consider a carbon price, implemented via a carbon tax or a quota market, without any antileakage policy (*Tax*, denoted as *T*). In this reference case, producers of goods in coalition countries both 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, $p_{MN} = p_{NN} = c_0 = 1$.

Simplifying our expressions for output from coalition and noncoalition countries:

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

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 nonparticipating countries by expanding output. The size of the coalition (*m*) strengthens the expansion of emissions in the remaining countries, as does the size of the cross-price elasticity (substitutability) of the goods (η_x). These same factors weaken the emissions reductions within the coalition, for a fixed carbon price. As the coalition size grows, so do global emissions reductions. As a result, the overall leakage rate shrinks, but for a given carbon price, the emission differential is unaffected by the coalition size:

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

Carbon Price with Output-Based Rebate

With output-based rebating (*OBR*, denoted as *R*), the prices of 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. As a result, $p_{MM} = p_{NM} = c_R$, where $c_R = c(\mu_R)$ and $\mu_R = \mu(t_R)$, while $p_{MN} = p_{NN} = c_0 = 1$.

Simplifying output:

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

Here we make the aforementioned distinction as to whether the rebating policy accompanies a fixed tax (denoted with superscript *Rtax*) or a fixed cap (denoted with superscript *Rcap*). In the case of a rebated tax, the emissions price *t* is unchanged compared to the reference case, so $c_R = c(\mu(t)) = c_T$. Thus, noncoalition emissions are smaller (y_N^R is lower), but so are domestic reductions (y_M^R is higher and μ_M is unchanged):

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

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

Given this result, the emission differential L_2 is necessarily smaller with OBR, but the net effect of rebating on global emissions can be ambiguous. Meanwhile, both emissions ratios above are decreasing in *m*, meaning that an increase in the coalition size tends to lower emissions under rebating relative to the reference case for participating and nonparticipating countries. Note that the emissions differential is insensitive to the coalition size *m* (in the fixed price case).

Turning to the case with a fixed coalition cap, the equilibrium price and emissions intensity will adjust under OBR to meet the same emissions target as for Tax, i.e., $\mu_R y_M^R = \mu_T y_M^T$.

<u>*Proposition 1*</u>*: For a given coalition emissions cap,* $L_2^{Rcap} < L_2^T$.

Proof: Suppose that the rebate is implemented with a fixed cap, as with output-based allocation of emissions allowances. Because output is higher than with a carbon price alone, 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:

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

In other words, rebating mitigates emissions leakage, and the magnitude of that effect increases with the cross-price elasticity and the coalition size, which together determine the cross-price pressure in those remaining countries.[3]

Now suppose the rebate 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 3 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 with OBR 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

With border adjustment for imports (*BAI*, denoted as *B*), coalition producers adjust emissions intensities and pay the carbon price, so $p_{MM} = p_{NM} = c_B + t\mu_B$. Importers of goods into

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[3] Of course, the carbon price with OBR is a function of the coalition size, so the full effect of expanding the coalition is somewhat more complicated.

coalition countries pay for their embodied emissions: $p_{MN} = c_0 + t\mu_0$.[4] Meanwhile, for goods produced and consumed in noncoalition countries, $p_{NN} = c_0 = 1$.

Simplifying the production expressions:

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

As before, we will distinguish between a fixed carbon price (denoted with superscript *Btax*) and a fixed emissions cap either for the coalition or globally (denoted with superscript *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 that noncoalition emissions fall while coalition emissions rise:

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

By definition, then, the emissions differential is mitigated ($L_2^{Btax} / L_2^T < 1$), but the net effect on global emissions is ambiguous. Nor can the effect of import adjustments on noncoalition and coalition emissions (and therefore the emissions differential) be easily compared to those under rebating.

$$
\frac{E_N^{Btax}}{E_N^{Rtax}} = \underbrace{\left(\frac{m}{n}(1+t\mu_0)^{-\eta_o+(n-m-1)\eta_x} + \frac{(n-m)}{n}\right)}_{<1}\underbrace{\left(\frac{c_T + t\mu_T}{c_T}\right)^{m\eta_x}}_{>1};
$$

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[4] 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.

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

Because coalition emissions rise with the import adjustment 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 $c_B + t_B\mu_B > c_T + t\mu_T$). 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:

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

It can be shown, however, that if global emissions decrease when a fixed carbon price is combined with border adjustments for imports, the first component dominates the second: leakage is 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 $c_R < c_T + t\mu_T$. Thus, it is difficult to rank these two policies in terms of their effectiveness in reducing leakage. However, we see that BAI is more likely to increase leakage at higher cross-price elasticities (which raise the second term and brings the first closer to 1) and smaller coalition sizes (which bring the first term closer to 1 more rapidly than the second term). The degree of carbon price adjustment also factors in and is endogenous to these other variables.

We conclude that it is difficult to rank BAI vis-à-vis both carbon price alone (Tax) and OBR when it comes to leakage. From Lemma 3, we know that this ambiguity carries over to the case with a fixed global cap.

Carbon Price with Full Border Adjustment

With full border adjustment (*FBA*, denoted as *F*), 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 $p_{NN} = c_0 = 1$.

Substituting into the production formula and simplifying with our normalization, we get:

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

As we compare FBA to Tax and BAI for the variant of a fixed carbon price—i.e., $t_F = t$—we obtain:[5]

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[5] Remember that emission intensities are the same across policies when the carbon price is fixed.

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

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

Thus, with a fixed carbon price, FBA has a stronger effect than BAI and Tax in terms of deterring leakage as well as repatriating output and emissions ($L_2^{Ftax} < L_2^{Btax} < L_2^T$).

The following proposition compares FBA with OBR, saying in particular that the emission differential is unambiguously smaller under FBA:

Proposition 2: Given a fixed carbon price, i) $E_N^{Ftax} < E_N^{Rtax}$ *, and ii)* $L_2^{Ftax} / L_2^{Rtax} < 1$.

<u>Proof:</u> We prove i) by using $\phi(t)$ as defined in Assumption 1b, showing that FBA yields unambiguously lower emissions than OBR in countries outside the coalition:

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

We notice that this result gets stronger as the coalition size gets larger.

To prove ii), 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, depending on the relative effects of the import adjustments versus the rebate to domestically consumed production (exported production is rebated under OBR and FBA).

Turning to the emissions differential L_2, by Lemma 1 we have:

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

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

Next, we compare FBA to OBR and Tax with the same coalition cap. Given that with the same carbon price, border adjustments raise coalition emissions compared to import adjustment, 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.

Proposition 3: Given a fixed coalition cap, $L_2^{Fcap} < L_2^T$.

Proof: Using Assumption 1b,

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

Furthermore, the size of the coalition has an unambiguous effect of reducing this ratio: FBA becomes a more effective deterrent to leakage, relative to Tax, as the coalition grows larger.

Due to the effect of the export rebate, we also see that full border adjustment has a stronger effect on reducing leakage to noncompliant countries than import adjustments only.

Proposition 4: With a fixed coalition cap, $L_2^{Fcap} / L_2^{Bcap} < 1$.

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

Furthermore, we can show that FBA also outperforms OBR with regard to leakage:

Proposition 5: With a fixed coalition cap, leakage is smaller with FBA than with OBR ($L_2^{Fcap} / L_2^{Rcap} < 1$).

Proof: See Appendix A.

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

Proposition 6: For a given coalition cap, carbon prices are highest with OBR, then FBA, then BAI, then Tax ($t_R > t_F > t_B > t$).

Proof: The proposition follows from the derivations above (see proof of Proposition 5).

To sum up, we have shown that FBA implies lower leakage than all other policies when the coalition cap is fixed. It follows from Lemma 3 that under a fixed global cap, the coalition members' burden share of meeting a certain global emissions target will be lowest under full border adjustments. 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.

2.3 Summary of Analytical Results

Carbon pricing induces leakage, and the extent of that leakage depends on the substitutability of traded goods. As the coalition grows larger, the joining country reduces its emissions, but emissions increase in countries that remain outside the coalition. If the carbon price is fixed, emissions also increase in countries already inside the coalition. In the theoretical analysis of antileakage measures, 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.

With a fixed carbon price, all of the antileakage measures mitigate the increase in noncoalition emissions, but 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,[6]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 output-based rebating and import adjustments, which in turn dominate a carbon price alone (given our Assumption 1). The comparison between OBR and BAI, however, is more ambiguous: the relative effects of these two policies on coalition emissions (with fixed tax) and noncoalition emissions are hard to assess.

Table I. Relative Emissions Differentials across Unilateral Abatement Policies

$L_2^{\text{column}} / L_2^{\text{row}}$	Tax	Output-based rebates	Border adjustment for imports	Full border adjustment
Tax	1	<1	<1 (?)	<1
Output-based rebates		1	(?)	<1
Border adjustment for imports			1	<1
Full border adjustment				1

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[6] There is one exception to this: The ranking between Tax and BAI is unambiguous under a fixed price but can be ambiguous under a fixed cap. However, if import tariffs decrease noncoalition emissions under a fixed coalition cap, which we find most likely, the ranking is unambiguous and the same as with a fixed price.

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 OBR versus Tax, while the effects of the border adjustment policies are more complex.

Substitution elasticities also play an important role for the effectiveness of antileakage measures. In general, higher elasticities tend to increase carbon leakage. Higher elasticities strengthen the effects of OBR on mitigating leakage, whereas the opposite is the case under BAI. The reason is that the effects of higher consumer prices under BAI are to a larger extent mitigated when cross-price elasticities are increased.

2.4 Stylized Numerical Illustrations

Exploring the partly ambiguous implications of antileakage measures on output and emissions within and outside an abatement coalition as a function of the coalition size requires numerical analysis even for our simple partial equilibrium framework. Here we focus on the case with a fixed carbon price.[7] For our illustrative simulations, we initialize the model with $n=10, a=0.1, p_0=1, c_T=1.1, \mu_0=1, t=0.3, \mu_T=0.8, \ \eta_o=2$. These settings reflect quite high cost increases for a 20 percent reduction in emissions intensity, intensifying leakage and the

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[7] In the CGE analysis, we consider the case with a fixed global cap on emissions as we aim for empirical evidence on the global cost-effectiveness and region-specific cost implications of alternative unilateral climate policy designs.

differences among scenarios.[8] To explore the role of the substitution elasticities, we consider a high cross-price elasticity case ($\eta_x = 0.2$) and a low cross-price elasticity case ($\eta_x = 0.1$).

Our reference scenario is the Tax case, compared with OBR, BAI, and FBA. Figures 1–4 show how output, emissions, and leakage measures evolve across the four scenarios as a function of the coalition size, as well as the degree of substitutability.

Figure 1. Output of Noncoalition Country (Fixed Emissions Price)

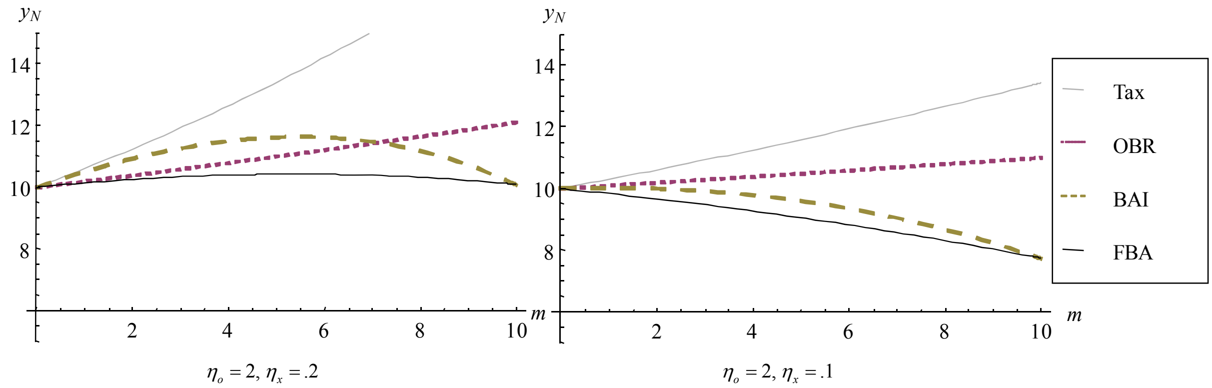
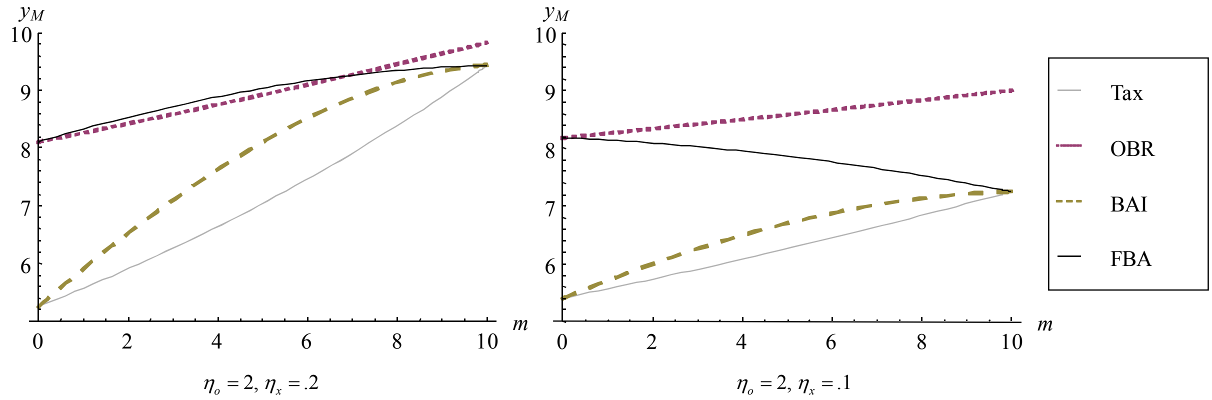


Figure 2. Output of a Coalition Country (Fixed Emissions Price)



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[8] For example, presumptively eligible industries for antileakage measures in H.R. 2454 (House of Representatives 2009) would have at least 5 percent energy intensity (or carbon dioxide intensity at $20/ton); few meet the latter criteria, so a 10 percent cost increase would require a substantial increase—up to 200 percent—in energy costs.

Figure 3. Total Emissions

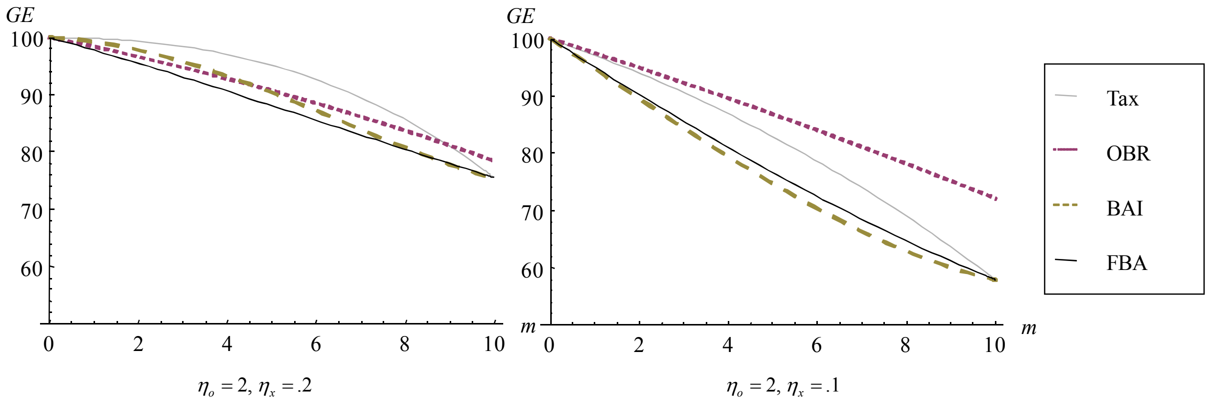


Figure 4a. Leakage Rate (*L*₁)

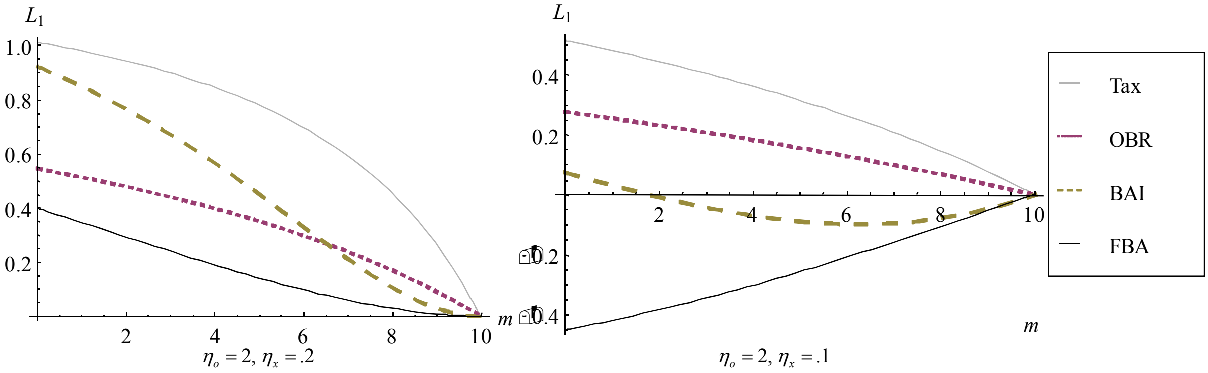
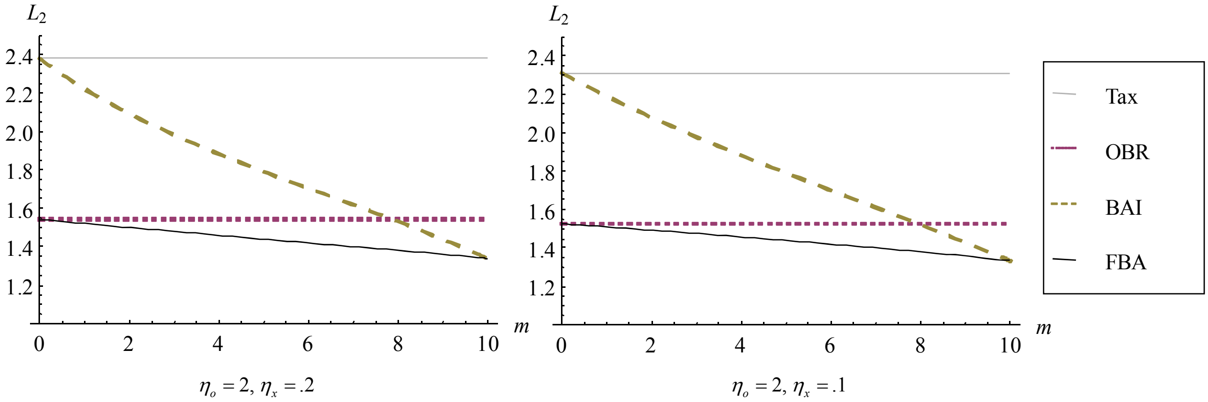


Figure 4b. Emission Differential (*L*₂)



Following the theoretical propositions, the tax-alone scenario increases output and thus emissions in the remaining noncoalition countries as the coalition size goes up (Figure 1).[9] Furthermore, the effectiveness of antileakage measures increases with the coalition size, with FBA dominating OBR or BAI. The relative performance between OBR and BAI is ambiguous for our parameterization: when the cross-price elasticity is large, the OBR dominates BAI for smaller coalition sizes, but this reverses as the coalition gets sufficiently big. On the other hand, for lower substitution elasticities, BAI can strictly dominate OBR, while BAI and FBA can cause noncoalition emissions to decrease vis-à-vis benchmark levels.

Antileakage measures repatriate output and emissions to countries within the abatement coalition, leading to greater emissions than in the tax-alone case (Figure 2). If the coalition has global coverage, emissions in the tax-alone and two border-measure scenarios must coincide because there are no longer countries outside the coalition to which border measures could be applied. However, OBR leads to higher output and emissions in this case, a distortion that grows larger as the cross-price elasticity declines.

Total emissions across all countries decrease as the coalition size increases—and more so as the cross-price elasticities shrink (Figure 3). We again see that FBA is unambiguously the most effective instrument for reducing global emissions, whereas the ranking between OBR and BAI depends on the coalition size and the substitution elasticity. The differences between total emissions under FBA and BAI decline as we move toward global coverage, whereas output-based rebate becomes less and less attractive as the coalition grows. At the lower cross-price

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[9] Note that with a fixed carbon price, the emissions intensity in coalition countries is fixed across coalition sizes and policy scenarios because it only depends on the carbon price. Thus, the effects on emissions reflect equivalently the effects on output.

elasticity, OBR actually increases total emissions relative to the emissions tax. We also notice that the antileakage measures, especially FBA and BAI, have largest effects on medium-sized coalitions. This is intuitive: with small coalitions, the effects on global emissions are modest in any case, whereas with small noncoalitions, border measures have limited impacts.

Figure 4a depicts the leakage rate (L_1) as the ratio of emissions changes in the nonabating countries over the emissions reduction in the abatement coalition. The leakage rate is most effectively reduced through FBA, while the ranking between OBR and BAI switches from a certain coalition size onward when the substitution elasticity is sufficiently high. Furthermore, at the lower cross-price elasticity, leakage under BAI is strictly lower than with OBR irrespective of coalition size and is negative when the coalition is sufficiently large. Full border adjustments induce negative leakage also with small coalitions in this case.

The emissions differential (L_2), on the other hand, is less sensitive to the substitutability of goods (Figure 4b). FBA is again the most effective policy, followed by OBR up until a sufficiently large coalition size, at which point BAI is preferred. Both border adjustment policies become more effective at compressing differences in emissions as the coalition size 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 to draw 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. In particular, terms-of-trade effects on fossil fuel markets play an important role for leakage. Furthermore, our theoretical framework does not feature a welfare metric that allows for a comprehensive cost-effectiveness comparison across alternative antileakage policy measures.

We therefore undertake numerical simulations with a large-scale computable general equilibrium 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. 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

Our impact assessment of unilateral carbon abatement strategies builds on a generic multiregional, multisectoral CGE model of global trade and energy use established by Böhringer and Rutherford for the economy-wide analysis of carbon emission regulation (see Böhringer and Rutherford 2010 or Böhringer et al. 2010 for recent applications). A multiregional setting is indispensable for the economic impact analysis of climate policy regimes: policy interference in larger open economies not only causes adjustment of domestic production and consumption patterns but also influences international prices via changes in exports and imports. These price changes imply secondary effects that can significantly alter the impacts of the primary domestic policy. In addition to a consistent representation of trade links, detailed tracking of energy flows as the main source for carbon emissions is a prerequisite for the assessment of climate policies.

In the following, we provide a nontechnical model summary; the detailed algebraic model formulation and graphical exposition of nesting structure in production are given in Appendix B.

The CGE model used for our numerical analysis 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. The latter is calibrated to be generally consistent with empirical estimates for the supply elasticity of the specific fossil fuel.

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 a CES composite that combines the domestically produced good and the imported good differentiated by demand category. As a result, the composition of the Armington good differs across sectors and final demand components. The balance-of-payment constraint, which is warranted through flexible exchange rates, incorporates the base-year trade deficit or surplus for each region.

The model links carbon dioxide (CO_2) emissions in fixed proportions to fossil-fuel use with fuel-specific CO_2 coefficients. Revenues from CO_2 taxes or the auctioning of emissions allowances 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 (Badri and Walmsley 2008). Key elasticities in international trade are based on empirical estimates reported by GTAP. The GTAP database is aggregated toward a composite dataset that accounts for the specific sectoral and regional requirements of our analysis (Table II).

At the sectoral level, the model captures details on sector-specific differences in factor intensities, factor substitutability, and price elasticities to trace the structural change in production induced by policy interference. The model identifies the energy goods coal, crude oil, natural gas, refined oil products, and electricity. This disaggregation is essential to distinguish energy goods by CO_2 intensity and the degree of substitutability. The model then incorporates energy-intensive and trade-exposed commodities, which are potentially most affected by unilateral climate policies and thus considered for supplemental 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.

Table II. Regional and sectoral disaggregation

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

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

At the regional level, the model identifies all countries that are key players in international climate negotiations. The group of industrialized countries includes parties that are listed in Annex 1 of the Kyoto Protocol: 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.

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 following supplemental emissions-leakage policy measures for EITE sectors: i) output-based rebates, ii) tariffs on the embodied carbon of EITE goods imported from nonabating regions, and iii) full border adjustments. The implications of the four climate policy scenarios are measured with respect to business as usual (BAU) in the absence of climate policy action, 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 regulations, we take it as the starting point for our coalition size variants (coalition EU).[10] 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.

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

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 size unless we can value the damage from emissions. Acknowledging the huge uncertainties in external cost estimates for climate change, we do not attempt to trade off the cost of emissions abatement with the benefit from avoided climate change but restrain ourselves to a standard cost-effectiveness analysis. Therefore, we require the abatement coalition to adjust its unilateral emissions reduction effort to meet a given global emission cap, which is defined as its unilateral emissions target plus the BAU emissions of the countries outside the coalition. 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.[11]

3.3 Numerical Results

Figure 5 illustrates how emissions in three different aggregate noncoalition regions—A1-Rest[12], 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 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.

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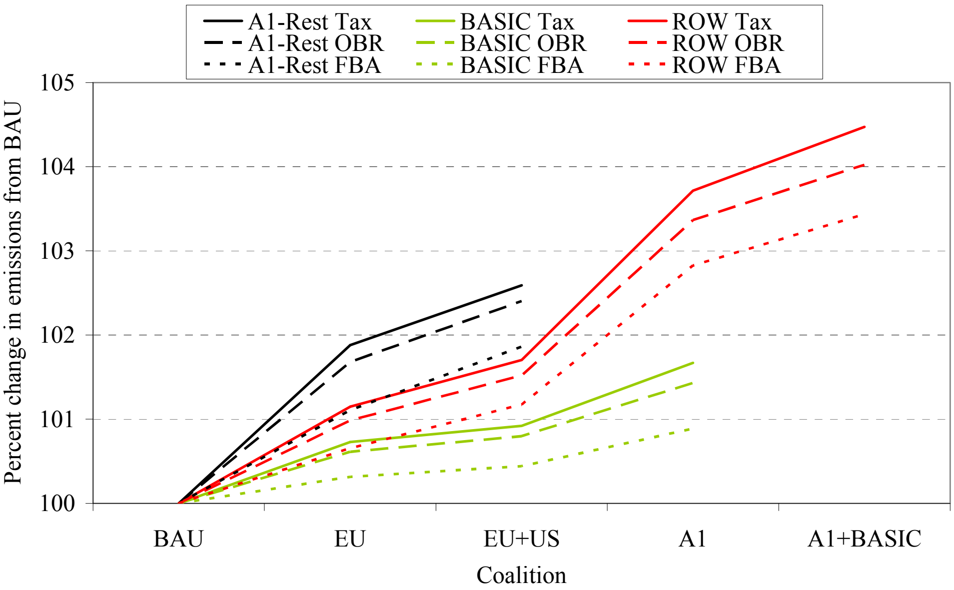
[11] Technically, the global emissions constraint requires an endogenous uniform emissions tax across the countries ofthe abatement coalition to comply with the exogenous global emissions cap.If the coalition implements its initial emissions target as an explicit cap, it must be scaled endogenously to 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.

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

Figure 5. Emissions in Nonabating Regions



In line with our theoretical findings, 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. OBR ranges closer to Tax than FBA. Note that for the sake of transparency, Figure 5 does not include policy BAI, which is closest to FBA and ranks second in reducing emissions increases in nonabating regions.

Figure 6a. Leakage rate (L_1)

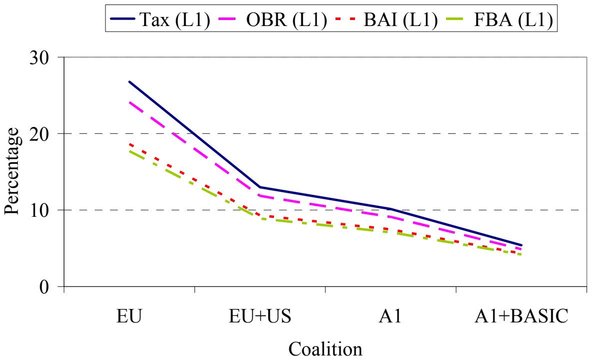


Figure 6b. Emissions differential (L_2)

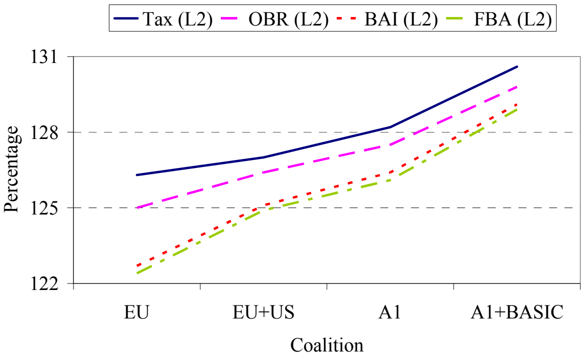


Figure 6a depicts changes in the leakage rate L_1. Not surprisingly, leakage rates decline and converge as the regional coverage of the abatement coalition expands.[13] Consistent with our analytical results, FBA is most effective at deterring leakage. While the ranking between BAI and OBR was ambiguous in the theoretical model, BAI clearly outperforms OBR in our numerical analysis and is much closer to FBA.

The ranking is the same in terms of the emissions differential, but in contrast to the partial equilibrium model, which found L_2 to be constant or decreasing in coalition size, the CGE model finds that L_2 increases as the coalition grows (Figure 6b). This difference reflects the importance of global fuel price changes omitted in our stylized theoretical analysis. International fuel prices become depressed through unilateral emissions abatement, which drive up emissions intensities among nonabating countries. If this 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

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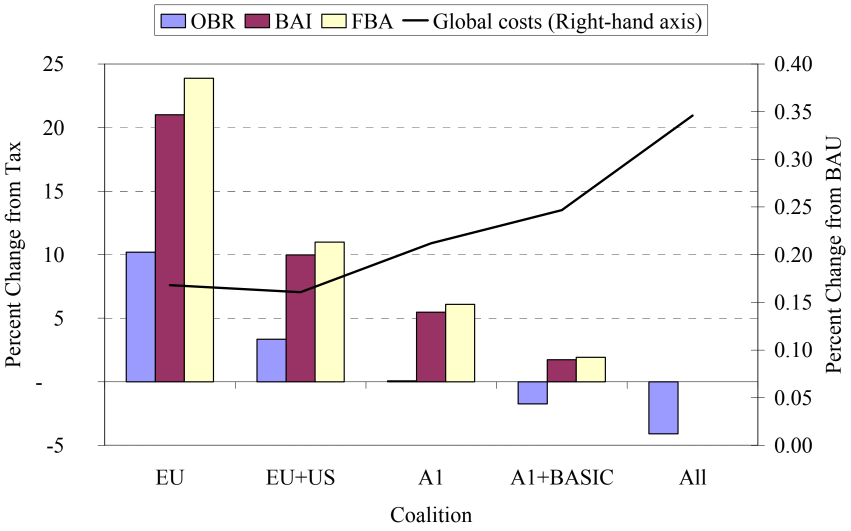
[13] Some reduction in L_1 from EU to EU+US occurs because leakage rates with EU unilateral policies are much higher (27 percent with Tax) than with U.S.unilateral policies (10 percent with Tax). To control for this, if we calculate the weighted average of L_1 under EU and US, we get leakage rates from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

alone and a simple carbon price. But the increase in relative 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.

Figure 7 reveals the differences in global cost-effectiveness of antileakage policy measures compared to Tax, as well as the global costs of the Tax scenario (compared to BAU). Adjustment costs are measured in terms of the Hicksian equivalent variation in income. For global cost-effectiveness assessment, we add up money-metric utility with equal weights across all regions, being agnostic on the distribution of costs. Global compliance costs to achieve a certain global emissions reduction can be lowered if we supplement uniform emissions pricing in coalition countries with additional antileakage policies. Figure 7 shows that all antileakage measures 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 higher in noncoalition countries. Figure 8 reports the shift in EITE production from coalition to noncoalition countries while global output of EITE goods declines in all scenarios.

Costs are smallest for full border adjustments, which most effectively reduces counterproductive 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 still 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.

Figure 7. 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 7). 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 are US$12 billion). From a broader international policy perspective, the quantitative results raise the critical question of whether the overall economic cost savings through antileakage measures outweigh the risks and efforts of implementation (including legal disputes and potential subsequent trade wars, the costs of monitoring and verifying, and the like).

Figure 8. Output of *EITE* Goods in Coalition and Noncoalition Countries

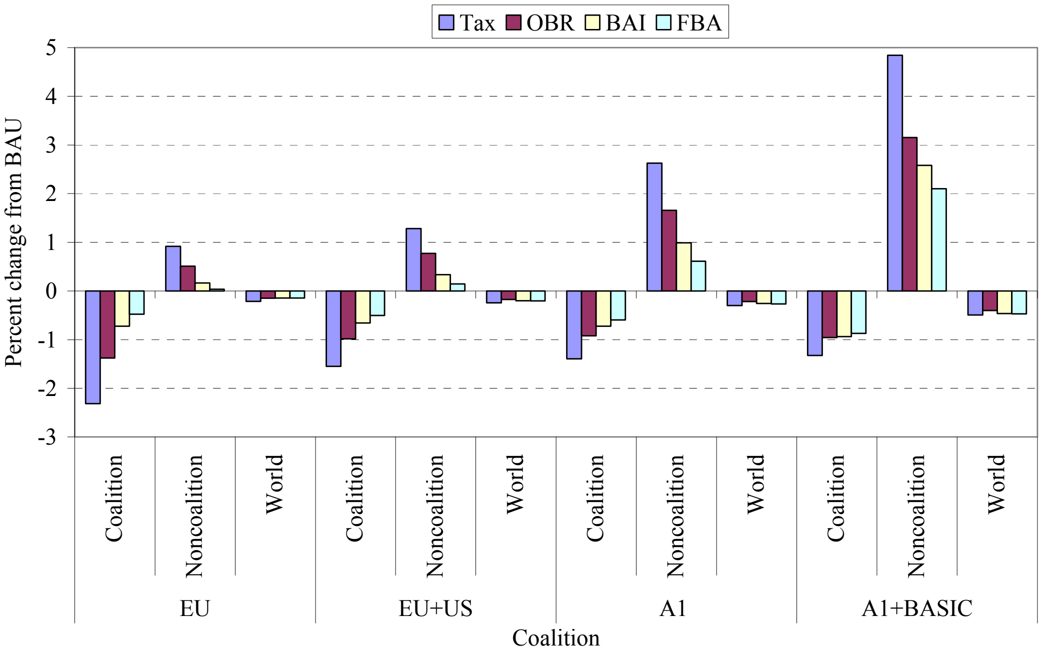
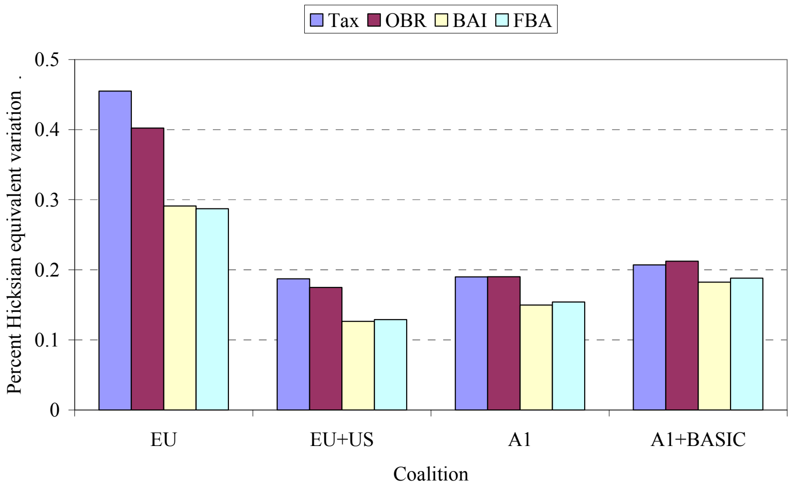


Figure 9 provides a cost-effectiveness assessment for unilateral climate policies from the more narrow perspective of the abatement coalition: what is the minimum cost for the abatement coalition to achieve a given global emissions reduction? Border measures still provide non-negligible cost savings compared to Tax and OBR (particularly for smaller coalition sizes), but the difference between partial and comprehensive border adjustments are 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 border measures, thereby shifting more of the abatement cost burden to nonabating trading partners. Export rebates on top of import tariffs 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 9. Compliance Cost for Abatement Coalition



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 latter effects can be substantial and mainly work through price changes in international energy markets (Böhringer and Rutherford 2002): the cutback in global demand for coal and crude oil implies a drop in their prices, providing economic gains to fossil-fuel importers and losses to exporters. 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 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.

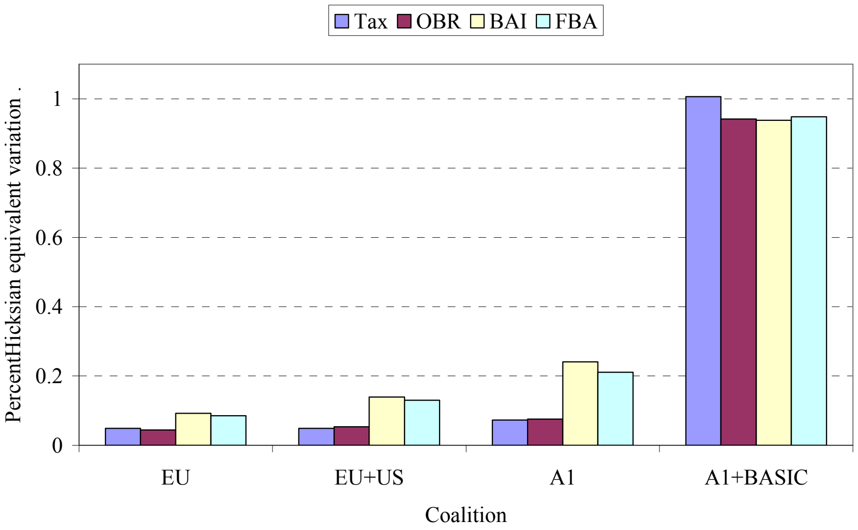
Consistent with Figure 9, border measures remain the most cost-effective strategy across all coalition sizes for the European Union and the United States, with hardly any differences between FBA and BAI. If we track the changes in the European Union's adjustment cost over the expansion of the coalition 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 compliance costs, and the same pattern is observed for the United States. Again, the magnitude and direction of these changes hinge on 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. OBR is often preferred over Tax, even for noncoalition countries as a group. One example is Canada (see also Figure 10 on China below). When the United States adopts a climate policy alone or jointly with the European Union, Canada can gain 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. The moderate gains for Canada, however, 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.

Another example is OPEC, which suffers most in all our scenarios despite being outside the coalitions. Due to the depression of the international crude oil price, OPEC's welfare losses become more and more pronounced with the magnitude of the global emissions reduction. OPEC would clearly prefer no antileakage measures or output-based rebates over border adjustment policies, as the latter induce additional terms-of-trade losses on international EITE markets.

Figure 10 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.

Figure 10. Adjustment Cost for China



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.[14]

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 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.

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[14] Alternative model and scenario parameterizations involve (i) reduction targets of 10 percent and 30 percent; (ii) noncoordinated abatement action across coalition members (compared to the default with intracoalition emissions trading); (iii) a doubling and halving of GTAP-based Armington elasticities; and (iv) a doubling and halving of the central-case fossil-fuel supply elasticities

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 clearly prefer output-based rebates over tariffs and full border adjustments if antileakage measures cannot be avoided.

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 poorer 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.

Independent of the choice of specific antileakage measures, a larger part of the economic impacts from unilateral climate policies are transmitted through rather robust adjustments of international energy markets, which provide significant indirect benefits to fuel importers and losses to exporters.

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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 Lemma 1 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 2: In the case of a fixed coalition cap, the ranking of L_1 *across policies will follow the ranking of* L_2*.*

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).

Lemma 3: The ranking of L₂ across policies under a fixed global cap strictly follows the ranking of L₂ under a fixed coalition cap.

Proof: The proof 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 $E_M^{j}{}' > E_M^k$. Furthermore, with less leakage pressure, $E_N^{j}{}' < E_N^j$. Thus, $L_2^{j}{}' < L_2^j < L_2^k$.

Proposition 5: With a fixed coalition cap, the leakage is smaller with full border adjustment than with output-based rebates ($L_2^{Fcap} / L_2^{Rcap} < 1$).

Proof: First we prove that $p_F < p_R$. Assume instead $p_F = p_R$; assumption 2 then implies:

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

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 Lemma 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) and solved using PATH (Dirkse and Ferris 1995).

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:

$$\Pi_{igr}^{A} = p_{igr}^{A} - \left(\theta_{igr}^{A} p_{ir}^{1-\sigma_{ir}^{A}} + (1-\theta_{igr}^{A}) p_{ir}^{IM^{1-\sigma_{ir}^{A}}} \right)^{1/(1-\sigma_{ir}^{A})} \leq 0.$$

7. Aggregate imports across import regions:

$$\Pi_{ir}^{IM} = p_{ir}^{IM} - \left[\sum_{s} \theta_{isr}^{IM} \left(p_{is} \right)^{1-\sigma_{ir}^{IM}} \right]^{1/(1-\sigma_{ir}^{IM})} \leq 0.$$

Market Clearance Conditions:

8. Labor:

$$\overline{L}_r \geq \sum_g Y_{gr}^{KL} \frac{\partial \Pi_{gr}^{KL}}{\partial w_r}.$$

9. Capital:

$$\overline{K}_{gr} \geq Y_{gr}^{KL} \frac{\partial \Pi_{gr}^{KL}}{\partial v_{gr}}.$$

10. Fossil-fuel resources (g∈*FF*):

$$\overline{Q}_{gr} \geq Y_{gr} \frac{\partial \Pi_{gr}^{Y}}{\partial q_{gr}}.$$

11. Material composite:

$$M_{gr} \geq Y_{gr} \frac{\partial \Pi_{gr}^{Y}}{\partial p_{gr}^{M}}.$$

12. Energy composite:

$$E_{gr} \geq Y_{gr} \frac{\partial \Pi_{gr}^{Y}}{\partial p_{gr}^{E}}.$$

13. Value-added composite:

$$KL_{gr} \geq Y_{gr} \frac{\partial \Pi_{gr}^{Y}}{\partial p_{gr}^{KL}}.$$

14. Import composite:

$$IM_{ir} \geq \sum_g A_{igr} \frac{\partial \Pi_{igr}^{A}}{\partial p_{ir}^{IM}}.$$

15. Armington aggregate:

$$A_{igr} = Y_{gr} \frac{\partial \Pi_{gr}^{Y}}{\partial\ p_{igr}^{A}} \quad .$$

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

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

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

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

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

$$Y_{Gr} \geq \overline{G}_r \quad .$$

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

$$Y_{Ir} \geq \overline{I}_r \, .$$

20. Carbon emissions:

$$\overline{CO}_{2r} \geq \sum_{g} \sum_{i \in FF} E_{gr} \frac{\partial \Pi_{gr}^{E}}{\partial \left(p_{igr}^{A} + p_r^{CO_2} a_{igr}^{CO_2} \right)} a_{igr}^{CO_2} \, .$$

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)
$p^{CO_2}_{r}$	Carbon value in region *r*

Table B4. Endowments and Emissions Coefficients

$\overline{L}_r$	Aggregate labor endowment for region *r*
$\overline{\mathrm{K}}_{\mathrm{ir}}$	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: $\sum_r \overline{B}_r = 0$)
$\overline{\mathrm{CO}}_{2\mathrm{r}}$	Endowment of carbon emissions rights in region *r*
$\mathrm{a}_{\mathrm{igr}}^{\mathrm{CO}_2}$	Carbon emissions coefficient for fossil fuel *i* in demand category *g* of region *r* ($i \in FF$)

Table B5. Cost Shares

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

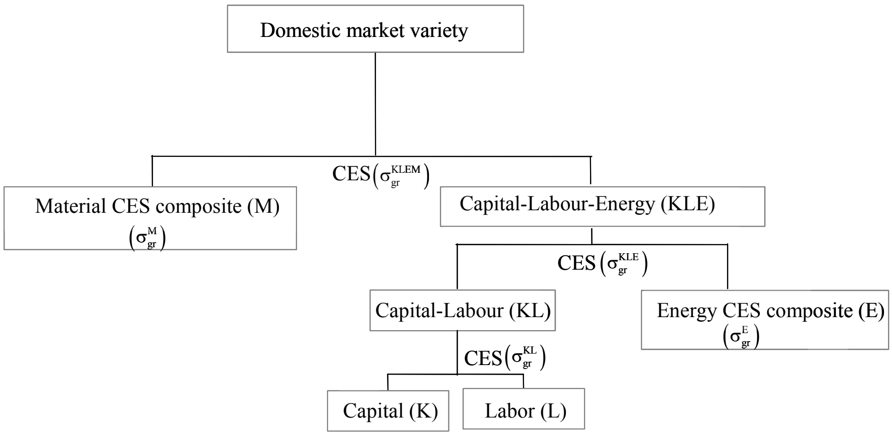
Table B6. Elasticities

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 and Ban 2008.

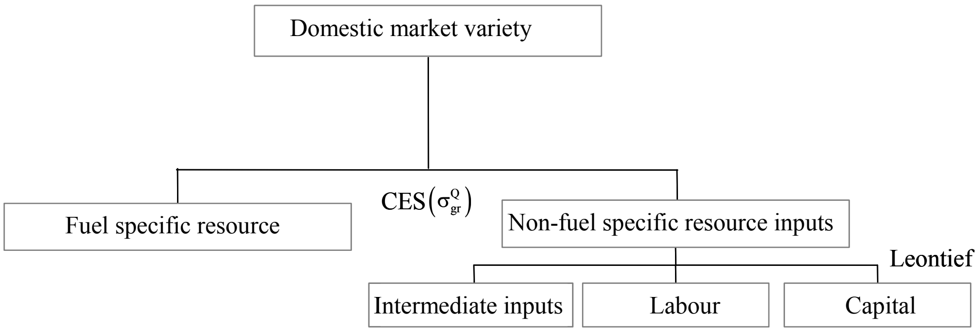
**See Badri and Walmsley 2008.

Figure B1. Nesting in Nonfossil-Fuel Production



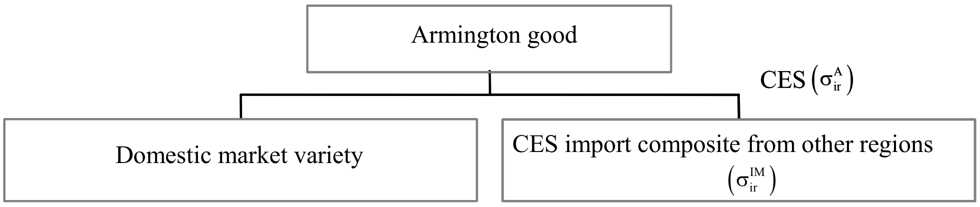
Note: CES=constant elasticity of substitution.

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.