Oldenburg Discussion
Papers in Economics

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V-346-12

June 2012

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Efficiency and Equity Implications of Alternative Instruments to Reduce Carbon Leakage

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Abstract:

The cost-effectiveness of unilateral emission abatement can be seriously hampered by emission leakage. We assess three widely-discussed proposals for leakage reduction targeted at energy-intensive and trade-exposed industries: border tax adjustments, output-based allocation and industry exemptions. We find that none of these measures amounts to a "magic bullet" when both efficiency and equity criteria matter. Border tax adjustments reduce leakage and provide global cost savings but exacerbate regional inequality. Exemptions produce very little leakage reduction and run the risk of increasing efficiency cost of climate policy. Output-based allocation does no harm but also does relatively little good by our outcome measures.

Keywords:

Unilateral Climate Policy, Leakage, Efficiency, Equity

1 Introduction

Cost-effectiveness of unilateral emission abatement can be seriously hampered by emission leakage, i.e., the relocation of emissions to parts of the world economy subject to weaker regulation. There are two main channels through which leakage may occur. As unilaterally abating regions reduce their demand for fossil fuels (the main source of anthropogenic greenhouse gas emissions) international fuel prices fall, inducing areas with weaker regulations to increase their fuel demand and emissions. Similarly, energy-intensive and trade-exposed (EITE) industries in unilaterally abating countries lose competitiveness on world markets when they face higher (abatement) cost compared to international rivals which, incentives the relocation of these industries.

In order to reduce leakage and improve global cost-effectiveness of unilateral action, a number of policy measures have been proposed. Principal among these are border adjustments where emissions embodied in imports from non-regulating regions are taxed at the emission price of the regulating region and emission payments for exports to non-regulating countries are rebated. From a global efficiency perspective such a combination of import tariffs and export rebates qualifies as a second-best measure complementing (unilateral) uniform emission pricing (Markusen 1975, Hoel 1991). However, border measures are controversial from the perspective of international trade agreements and their political feasibility questionable. When border measures are unavailable, differential emission pricing in favor of domestic EITE industries may serve as a substitute (Hoel 1996). In policy practice, the theoretical argument for differential emission pricing often translates into exemption of EITE industries as a response to concerns on losses of competitiveness and adverse employment impacts. A third suggestion involves the allocation of free emission allowances to EITE industries conditional on production. Contrary to auctioning of emission allowances or unconditional free allowance allocation such an output-based grandfathering system effectively works as an subsidy to production to recover (part) of losses in comparative advantage (Böhringer, Ferris and Rutherford 1997). In the more recent climate policy literature this measure is referred to as output-based allocation (Fischer 2001). The EU climate and energy policy package provides a prominent example of output-based allocation where EITE industries receive emission rights for free to remedy counterproductive emission leakage to EU trading partners without emission regulation.

All of these anti-leakage policy measures – border tax adjustment, industry exemptions, and output-based allowance allocation – are second-best policy instruments. Thus, they induce distortions of their own which must be weighed against the potential efficiency gains they promise. For example, providing exemptions to EITE industries clearly violates the first-best dictum of equating marginal abatement cost across polluters. Thus, the increase in abatement cost must be traded off with the economic gains from attenuating leakage.

The theoretical as well as applied economic literature tend to focus on the efficiency effects of alternative anti-leakage policy measures, but their burden-shifting implications are likely to be as or more important `for the role they can play in the international climate policy debate. International price changes that are at the core of the leakage problem also produce terms-of-trade effects. Böhringer and Rutherford (2002) show that these terms-of-trade effects can dominate the direct abatement cost for unilaterally acting countries and likewise induce substantial losses or gains to countries without abatement action. One reason that equity issues seem to take a back seat in the discussion of anti-leakage measures is that unilaterally abating regions are viewed as socially responsible forerunners that are willing to take a loss in first place for enhancing the prospects of global environmental cooperation in a subsequent step. We show that this perspective must be questioned when we account for the burden-shifting effects of anti-leakage measures.

In this paper, we use simulations from a large-scale computable general equilibrium (CGE) model of global trade and energy use to illustrate and compare the efficiency and equity trade-offs associated with border tax adjustments, industry exemptions and output-based allowance allocation to EITE industries of unilaterally abating regions.

With respect to leakage reduction, we find that border tax adjustments are by far the most effective instrument since they directly level the playing field between regulated domestic EITE production and unregulated EITE production abroad. Output-based allocation and exemptions are much more blunt instruments to preserve of international competitiveness of unilaterally regulated EITE industries – their effectiveness in leakage reduction is three to four times lower than that of border tax adjustments.

Despite effective leakage reduction, global cost savings of border tax adjustments remain rather limited. When we consider the case of a small abatement coalition with ambitious reduction targets – two assumptions that should place border measures in a favorable light -- the cost savings relative to our reference unilateral policy without anti-leakage measure is smaller than 20%. Cost savings through output-based allocation are substantially smaller (ranging between 1% and 9% as a function of the coalition size and the reduction target) and exemptions can even increase rather than decrease global economic adjustment cost. The poor efficiency performance of exemptions is due to the sharp trade-off between leakage reduction and the increase in direct abatement cost as cheap abatement options in EITE industries are foregone.

While border tax adjustments do have some appeal based on their leakage and cost-effectiveness effects, they look less promising when their distributional effects are taken into account. In fact, border tax adjustments work as a substitute for optimal tariffs shifting a larger part of the economic abatement from abating regions to non-abating regions. Since countries contemplating or currently enacting unilateral climate policies are among the wealthiest nations in the world, border tax adjustments amplify existing income equalities (Böhringer, Carbone and Rutherford 2011). As a consequence, these instruments fair poorly when our welfare measures account for even a modest degree of inequality aversion and there is no mechanism in place to compensate losers in the border-tax-adjustment regime. Output-based allocation and exemptions, on the other hand, have only small additional terms-of-trade effects compared to the reference policy scenario and therefore are preferable to border tax adjustments as one cares for cost distribution.

Paying attention to both – efficiency and equity – impact dimensions output-based allocation may be ranked first across our three anti-leakage measures: it provides some global cost savings without inflicting (too much) on cost distribution. From a pure utilitarian perspective, border tax adjustments would be most attractive but they come along with controversial burden shifting to poorer regions. Exemptions to EITE industries appear least attractive since they can get much more costly than the reference policy and at the same time do not work as an effective re-distributional instrument.

The remainder of this paper is as follows. In Section 2 we give a non-technical description of the model structure and its parameterization. In section 3 we lay out our policy simulations and interpret simulation results. In section 5 we provide some final remarks.

2 Model Structure and Parameterization

2.1 Model Structure

Our quantitative assessment of the trade-offs between equity and efficiency for alternative anti-leakage measures is based on a static multi-region, multi-sector computable general equilibrium model of the global economy (for an algebraic representation of the core model logic see the Appendix). The model is based on Böhringer, Carbone and Rutherford (2011), extended to compare the efficiency and equity impacts of alternative anti-leakage measures.

2.1.1 Factor Markets

Primary factors include labor and capital which are assumed to be mobile across sectors within each region but not internationally mobile. In fossil fuel production part of the capital is treated as a sector-specific resource, consistent with exogenous own-price elasticities of supply. Factor markets are perfectly competitive.

2.1.2 Production

Nested, separable constant elasticity of substitution (CES) production functions are employed to specify substitution possibilities in domestic production between capital, labor, energy and material inputs. At the top level material inputs are used in fixed proportions, together with an aggregate of energy and a value-added composite of labor and capital. The value-added composite is a CES function of labor and capital. The energy aggregate is produced with a CES function of primary energy inputs (coal, natural gas, refined oil) and electricity.[1] In fossil fuel production 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 constant elasticity of substitution to match exogenous estimates of fossil fuel supply elasticities.

2.1.3 Public Expenditure and Investment Demand

Government and investment demands within each region are fixed at exogenous real levels. Public goods and services as well as the composite investment good are produced with a Leontief aggregation of commodity inputs.

2.1.4 Final Consumption Demand

Final demand of the representative consumer in each region is given as a CES composite which combines consumption of a CES energy aggregate (see above) and a non-energy consumption bundle where non-energy goods trade off at a constant elasticity of substitution. Final consumption demand in each region is determined by the representative agent who maximizes welfare subject to a budget constraint with fixed investment and exogenous government provision of public goods and services. Total income of the representative household consists of net factor income and tax revenues.

2.1.5 International Trade

Trade between regions is specified using the Armington approach to product heterogeneity, so domestic and foreign goods of the same variety are distinguished by origin (Armington 1969). The Armington composite for a traded good is a CES function of an imported composite and domestic production for that sector. The import composite is then a CES function of production from all other countries. A balance of payment constraint incorporates the base-year trade deficit or surplus for each region.

2.1.6 CO_2 emissions

CO_2 emissions are linked in fixed proportions to the use of fossil fuels, with CO_2 coefficients differentiated by the specific carbon content of fuels. Restrictions to the use of CO_2 emissions in production and consumption are implemented through exogenous emission constraints or likewise CO_2 taxes. CO_2 emission abatement then takes place by fuel switching (interfuel substitution) or energy savings (either by fuel-non-fuel substitution or by a scale reduction of production and final demand activities)

2.2 Parameterization

For our empirical assessment we employ the GTAP 7.1 database which includes detailed national accounts for 2004 on production and consumption (input-output tables) together with bilateral trade flows and CO_2 emissions for up to 112 regions and 57 sectors (Narayanan and Walmsley 2008). The 2004. benchmark prices and quantities together with exogenous elasticities are used to calibrate free parameters of functional forms which characterize technologies and preferences in our model.

We aggregate the GTAP data to a composite dataset tailored to the specific requirements of our policy issue. The composite dataset in use includes all major primary and secondary energy

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[1] Crude oil enters the material composite as a feedstock input.

carriers: coal, crude oil, natural gas, refined oil products, and electricity. This disaggregation is essential in order to distinguish energy goods by CO_2 intensity and the degree of substitutability. In addition, we separate the main emission-intensive and trade-exposed sectors: chemical products, non-metallic minerals, iron and steel products, and non-ferrous metals, as they will be the most affected by emission control policies and the prime candidates for embodied carbon tariffs. Regarding regional coverage, we explicitly include all major industrialized and developing countries to capture international market responses to unilateral emission regulation. Table 1 summarizes the sectors (commodities) and regions present in our actual impact analysis of alternative carbon tariff schemes.

Table 1: Model sectors and regions[2]

Sectors and commodities	*Countries and regions*
Energy	*Annex 1 (industrialized) regions*
Coal (COL)	Europe – EU-27 plus EFTA (EUR)
Crude oil (CRU)	United States of America (USA)
Natural gas (GAS)	Russia (RUS)
Refined oil products (OIL)*	Remaining Annex 1 (RA1)
Electricity (ELE)	
	Non-Annex1 regions
*Energy-intensive goods**	China (CHN)
Chemical products (CRP)	India (IND)
Non-metallic minerals (NMM)	Energy exporting countries excl. Mexico (EEX)
Iron and steel industry (I_S)	Other middle income countries (MIC)
Non-ferrous metals (NFM)	Other low income countries (LIC)
Air transport (ATP)	
Water transport (WTP)	
Other transport (OTP)	
Rest of industry and services	
All other goods (AOG)	

*Included in the *energy-intensive and trade-exposed* (EITE) *industries*

The carbon content embodied in the production of goods across regions includes direct and indirect emissions. In addition to the direct carbon emissions stemming from the combustion of fossil fuel inputs there are indirect carbon emissions associated with intermediate non-fossil inputs which may be further decomposed into indirect carbon from electricity inputs and indirect carbon from all other (non-electric and non-fossil) inputs. Following Böhringer, Carbone and Rutherford (2011), one can use the multi-region input-output accounts from the GTAP dataset to compute the total carbon content of production across sectors and regions. In our policy analysis below, we restrict the application of border tariffs to direct emissions and indirect emissions from electricity inputs.[3]

The economic responses of the representative agents to price changes triggered by policy regulation are determined by a set of exogenous elasticities taken from the GTAP database or complementary data sources.

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[2] In brackets, wee provide the 3-digit acronyms for sectors and regions which can be used for the more disaggregation exposition of simulation results.

[3] In this case, we even do not need ot apply the multi-region input-output calculus.

3 Policy Scenarios and Simulation Results

3.1 Policy Scenarios

We want to investigate how alternative anti-leakage measures change the global cost-effectiveness and distributional impacts of unilateral emission abatement. Our reference scenario (*ref*) captures a situation in which a coalition of unilaterally abating countries focuses on the efficient implementation of domestic emission reduction targets when ignoring leakage concerns. In this reference case (i.e.,in the absence of second-best aspects), abating regions pursue uniform emission pricing across all emission sources within the abatement coalition. Uniform emission pricing is achieved through a cap-and-trade system. We compare the outcome of the reference scenario with three policy variations where abating regions employ the alternative anti-leakage measures we consider.

The first variation concerns border tax adjustments (*bta)* where tariffs are levied on the carbon content (direct emissions plus indirect emission from electricity inputs) of imported EITE goods from outside the abatement coalition; at the same time, border tax adjustments include rebates of emission payments for EITE exports from regulating countries to non-regulating countries.

In the second variation we consider output-based allocation (*oba*) which commands that EITE industries are allocated a fixed budget of free emission allowances. As the firm-specific allocation in EITE industries hinges on production, additional production from the firm perspective garners additional allowances, the value of which functions as a subsidy to production thereby lowering marginal cost. In our core simulations, the total amount of free emission allowances to EITE industries equals their benchmark emissions scaled down by the unilateral emission reduction target.

The third variation features exemptions (*exe*) from emission payments for EITE industries such that marginal abatement cost in this segment of the economy are zero and differential emission pricing applies.

For all unilateral climate policy designs, revenues from emission regulation accrue to the representative agent in each region. We measure economic impacts with respect to the benchmark equilibrium – the so-called business as usual (*bau*) where no emission regulation applies.

The two central indicators for our discussion of results are the leakage rate and measures of global welfare based on varying degrees of inequality aversion. The leakage rate is defined as the change in foreign (non-coalition) emissions as a share of the domestic (coalition) emission reduction. A leakage rate of 50%, for example, means that half of the domestic emission reduction is offset by increases in emissions abroad. Global welfare impacts are based on social welfare metrics that exhibit differing degrees of inequality aversion. The general form of the social welfare function is

$$SWF = \left(\sum_r \gamma_r W_r^{(1-1/\sigma)}\right)^{1/(1-1/\sigma)}$$

where W_r represents the money-metric per-capita welfare level in model region r, σ is the inequality aversion parameter, and γ_r is region r's share in global population. The social welfare function provides a convenient metric to investigate the trade-offs between efficiency and equity across alternative unilateral climate policy designs. For an infinite value of σ we are agnostic on the distribution of climate policy cost and adopt a utilitarian (Benthamite) perspective on efficiency where utility changes of individual regions are perfectly substitutable. On the other extreme, σ takes over a zero value which provides a Rawlsian perspective, where it is the welfare level of the poorest region that determines global welfare (in our dataset the composite of low income countries is the poorest region).

For our cross-comparison of alternative anti-leakage measures we hold global emissions constant at the level achieved through the reference climate policy without anti-leakage measures. The gross benefit of abatement for a given (representative) household in each region is then constant across all policy scenarios which allows us to do coherent welfare analysis without the need for external cost etimates from CO_2 emissions. The global emission constraint requires that the initial emission cap of the abating coalition is scaled endogenously to “compensate” for changes in emission leakage from the reference policy level.

In our core simulations we investigate the economic impacts of alternative climate policy designs as a function of the size of the abatement coalition and the stringency of the emission reduction target. Regarding coalition size, we distinguish three variants: the variant in which Europe – i.e., EU-27 plus EFTA countries – goes ahead with unilateral action (EUR), the variant where other Annex-1 regions except for Russia join an abatement coalition with the EU (A1xR)[4] and finally the variant in which China enters the A1xR coalition (A1xR_CHN). As to reduction targets, we assess unilateral abatement pledges of 10%, 20%, and 30% relative to the benchmark (*bau*) emission level of coalition countries. The abatement pledges are the same for all coalition countries and can be traded within the coalition – emission regulation thus boils down to an emissions trading system across coalition members where the emission price emerges as the shadow value of the aggregate coalition’s emission cap.

3.2 Simulation results

3.2.1 Leakage and EITE competitiveness

Table 2 presents leakage rates, EITE output, CO_2 reduction and CO_2 prices for our core scenarios. Confirming basic economic intuition leakage rates increase with the abatement target and decrease with the size of the abatement coalition.[5] Border tax adjustments are by far the most effective instrument across the three anti-leakage measures to reduce carbon leakage. Border tariffs joint with export rebate for EITE industries cut the reference leakage rates (without anti-leakage measures) between a third and a half. In turn, output-based allocation or exemptions achieve only leakage reductions between less than 10 % and 15 % from the reference leakage level.

The distinct superiority of border adjustment measures with respect to leakage reduction can be traced back to their targeted treatment of embodied carbon in EITE trade. Import tariffs and export rebates level the playing field between domestic and foreign production thereby counteracting leakage through EITE trade. Output-based allocation and exemptions are less effective since they address leakage only indirectly through output or input subsidies to domestic EITE production. In both cases, the comparative disadvantage for domestic EITE industries is not offset as much as in the case of border adjustments.[6]

The differential effects of anti-leakage measures on the competitiveness of EITE production in the unilaterally abating region are directly reflected in EITE output changes. Starting with the reference policy scenario, output losses in domestic EITE industries are the more pronounced the smaller the coalition size and the higher the unilateral abatement target is. The negative repercussions on domestic EITE production that show up in the reference case are strongly reduced for border measures whereas exemptions and output-based allocation can only achieve a fraction of this alleviation.

For any given coalition size and unilateral abatement pledge global emissions are kept constant at the outcome of the reference scenario. Leakage reduction therefore translates into a cutback of the coalition’s implicit abatement requirement to comply with the global emission constraint. The domestic emission reductions are distinctly lowest for the case of border measures followed by exemptions and output-based allocation that rank very close.

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[4] More specifically, the A1xR coalition then includes EU-27, EFTA, Canada, Japan, Belarus, Ukraine, Australia, New Zealand, and Turkey.

[5] Böhringer, Fischer and Rosendahl (2011) provide a formal analysis on how the coalition size impacts on the cost-effective design of unilateral climate policies.

[6] Note that border tariffs are levied on the direct emission content plus indirect emissions from electricity use. Indirect emissions from electricity inputs constitute an important share of total embodied emissions for EITE produciton in many countries (see Böhringer, Carbone and Rutherford. 2011) which are not targeted under exemptions or output-based allocation. In turn, carbon tariffs could then even increase the competitiveness of domestic EITE industries if their emission intensity is lower than that of foreign production.

Table 2: Leakage, EITE output, CO_2 emissions, CO_2 prices

Coalition	EUR			A1xR			A1xR_CHN		
Target	10%	20%	30%	10%	20%	30%	10%	20%	30%
				Leakage rate (in %)					
ref	15,3	17,9	21,0	7,3	8,6	10,2	4,0	4,8	5,8
bta	10,1	11,2	12,6	4,2	4,6	5,0	2,3	2,6	2,8
oba	13,7	16,0	18,6	6,3	7,4	8,8	3,4	4,1	4,9
exe	13,9	16,4	19,4	6,2	7,4	8,7	3,5	4,2	5,1
				Change in leakage rate (in % from *ref*)					
bta	-33,6	-37,2	-39,8	-42,5	-47,3	-51,4	-41,4	-46,0	-51,1
oba	-10,4	-10,9	-11,5	-13,5	-13,9	-14,3	-14,1	-14,3	-14,7
exe	-9,2	-8,5	-7,4	-14,9	-14,8	-14,9	-12,3	-11,9	-11,6
				EITE output (in % from *bau*)					
ref	-1,0	-2,6	-4,9	-0,9	-2,2	-4,2	-0,6	-1,4	-2,9
bta	-0,2	-0,4	-0,7	-0,3	-0,7	-1,3	-0,2	-0,6	-1,2
oba	-0,6	-1,6	-3,1	-0,6	-1,5	-3,0	-0,4	-1,0	-2,0
exe	-0,6	-1,7	-3,1	-0,6	-1,6	-3,0	-0,4	-1,1	-2,3
				Global CO_2 emissions (in % from *bau*)					
	-1,3	-2,6	-3,8	-4,6	-9,0	-13,3	-6,4	-12,6	-18,7
				Coalition's CO_2 emissions (in % from *bau*)					
ref	-10,0	-20,0	-30,0	-10,0	-20,0	-30,0	-10,0	-20,0	-30,0
bta	-9,4	-18,5	-27,1	-9,7	-19,1	-28,3	-9,8	-19,5	-29,1
oba	-9,8	-19,5	-29,1	-9,9	-19,7	-29,5	-9,9	-19,9	-29,7
exe	-9,8	-19,6	-29,4	-9,9	-19,7	-29,5	-9,9	-19,9	-29,8
				CO_2 price (in $US per ton)					
ref	13,9	38,8	82,0	11,1	30,6	64,0	7,5	20,5	43,5
bta	13,1	35,1	69,7	10,8	29,2	58,8	7,4	20,0	41,7
oba	13,8	38,3	79,9	11,2	30,7	64,0	7,5	20,6	43,6
exe	15,1	43,9	96,7	11,9	34,0	73,4	8,6	24,8	55,4

CO_2 prices in the reference scenario reflect fundamental correlations with the stringency in reduction targets. For a given coalition size, marginal abatement cost increase as carbon abatement gets increasingly more expensive towards higher reduction targets as low-cost options (e.g., fuel-switching in electricity production from coal to gas) have been exhausted. For a given emission reduction target differences across coalition sizes echo differences in carbon intensities of production and consumption and the ease of carbon substitution through fuel switching or energy savings. In our scenarios, the expansion path of the coalition (from Europe via Annex1 to Annex 1 with China) adds more low-cost abatement options. Since coalition members can trade their emission reduction pledges among each other, the CO_2 price for a given reduction target decreases as the coalition size goes up.

For the case of border tax adjustments, leakage reduction (and thus lower domestic abatement requirements) imply lower CO_2 prices compared to the reference scenario. The price difference is most pronounced for a small coalition size and high reduction targets but remain rather modest. Output-based allocation hardly changes the reference CO_2 price: the downward pressure through leakage production is more or less offset through the upward pressure emerging from implicit subsidies to EITE production. For the case of exemptions the CO_2 prices consistently exceed the reference price level: the non-exempted parts of the domestic economy must face higher CO_2 prices than in the reference scenario to make up for the preferential treatment of EITE sectors.

3.2.2 Efficiency and equity

Table 3 provides insights into trade-offs between efficiency and equity across alternative anti-leakage measures. We start with an efficiency perspective on the global cost-effectiveness of unilateral climate policy designs where the distribution of adjustment cost is neglected. The global economic cost to meet some given global emission reduction target is then based on a utilitarian metric where we simply add up the changes in Hicksian equivalent variation (HEV) across all regions. It is worth emphasizing that our welfare metric does not show any effects from the reduction in global carbon emissions. We implicitly assume that the gross benefits of emission reduction are separable from the welfare derived from consumption of private goods, and focus on the latter.[7]

Our benchmark to judge the different anti-leakage measures is provided by the reference scenario. Global compliance cost are primarily determined by the magnitude of the unilateral emission reduction target; as we move from a reduction target of 10% to 30% economic adjustment cost go up by an order of magnitude reflecting that abatement becomes increasingly expensive. There is some variation in the range of abatement cost for different coalition sizes which captures the heterogeneity of emission intensities across coalition countries. In line with the magnitude of leakage reduction, border tax adjustments provide much higher efficiency gains than output-based allocation. At the maximum, these gains amount to roughly 17% of cost savings compared to the reference scenario for the case of a small coalition (EUR) with high reduction targets (30%) – output-based allocation only achieves around 9% of cost savings for this setting. As the coalition size increase and leakage becomes less of an issue, the relative cost savings for border tax adjustments and output-based allocation become rather small ranging between 1% and 4% as the coalition includes Annex1 (without Russia) plus China.

Exemptions to EITE industries are ill-suited to the task of improving global cost-effectiveness – only for small coalition sizes and modest reduction targets is there scope for small efficiency gains. If reduction targets are more ambitious or the coalition size becomes bigger then exemptions are likely to decrease rather than increase global cost-effectiveness. In our simulations the global compliance cost of coalition A1xR_CHN for a 30% emission reduction pledge is more than 15% higher than in the reference scenario. The reason is that the increase in direct abatement cost (caused by the fact that marginal abatement costs are not equalized across coalition sectors under the exemption policy) dominates the second-best gains of leakage reduction.

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[7] An alternative approach would be to specify some explicit damage function but this suffers from the lack of hard data on region-specific cost valuations from climate change.

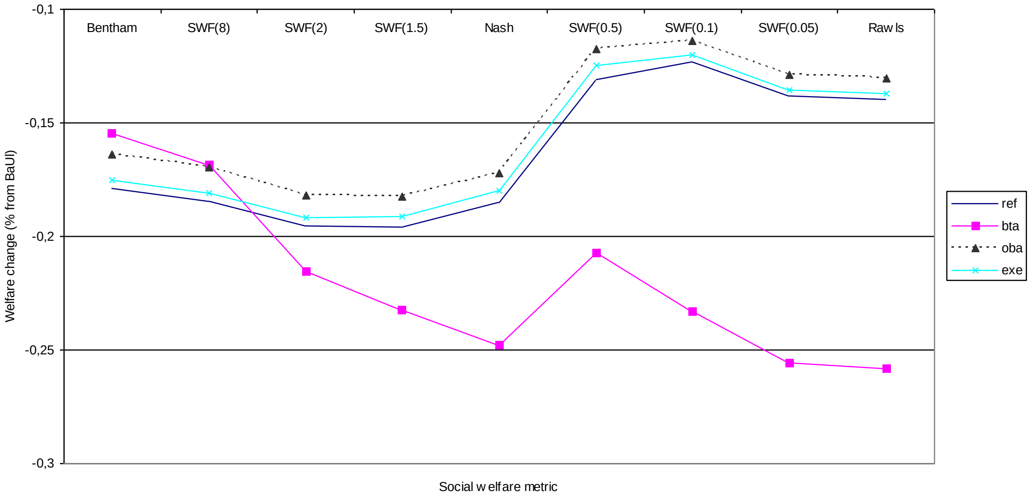
Table 3: Cost-effectiveness and burden sharing

Coalition	EUR			A1xR			A1xR_CHN		
Target	10%	20%	30%	10%	20%	30%	10%	20%	30%
Global economic cost (in % HEV from *bau*)									
ref	-0,058	-0,179	-0,391	-0,087	-0,289	-0,672	-0,060	-0,215	-0,531
bta	-0,052	-0,155	-0,325	-0,083	-0,270	-0,612	-0,059	-0,210	-0,511
oba	-0,053	-0,164	-0,357	-0,084	-0,278	-0,645	-0,059	-0,212	-0,523
exe	-0,054	-0,175	-0,398	-0,085	-0,291	-0,695	-0,065	-0,243	-0,620
Change in global economic cost by anti-leakage measure (in % from *ref*)									
bta	-11,1	-13,4	-17,0	-5,6	-6,7	-9,0	-1,6	-2,3	-3,7
oba	-8,9	-8,3	-8,8	-4,3	-3,8	-4,1	-1,3	-1,2	-1,4
exe	-6,4	-2,0	1,6	-3,1	0,6	3,3	8,4	13,0	16,8
Burden sharing ration between coalition and non-coaltion									
ref	2,4	3,3	4,3	1,1	1,8	2,7	1,1	2,0	3,0
bta	1,1	1,6	2,1	0,4	0,9	1,4	0,4	1,0	1,6
oba	2,2	3,1	4,0	1,1	1,8	2,6	1,1	1,9	2,8
exe	2,3	3,2	4,1	1,1	1,8	2,7	1,2	2,1	3,1

The final section of Table 3 reveals the equity tension of anti-leakage measures in terms of a burden sharing coefficient which is defined as the share of the coalition in global adjustment cost over the share of the non-coalition in global adjustment cost. First of all, we see that even in the reference scenario non-coalition countries on average face a substantial economic cost due to adverse terms-of-trade effects. Effectively, the economic burden of domestic emission prices can in part be shifted to trading partners outside the coalition: countries which are exporters of fossil fuels will be adversely affected by a fall in international fuel prices which emerge from the reduction in global fuel consumption; likewise countries that are larger importers of EITE products from the abatement coalition will suffer from higher EITE import prices. We see that output-based allocation and exemptions result in very little change in the burden sharing ratio of the reference policy. In contrast, border tax adjustments come along with a dramatic shift in the abatement cost burden to the average non-coalition country. Border taxes and export rebates work as a substitute for optimal tariffs which can shift the bulk of global adjustment cost upon the composite non-coalition region.

Figures 1-5 visualize the distributional effects of the different policies by comparing global welfare changes using social welfare functions that exhibit different degrees of inequality aversion. We report percentage changes in the social welfare function from the pre-policy business-as-usual (*bau*) level under different assumption about the value that the inequality aversion parameter σ takes on. Entry "Bentham" on the left-hand side captures the one extreme where cost distribution across regions does not matter; entry "Rawls" captures the other extreme where only the poorest region in our dataset (here: the composite of low-income countries) matters. Entries listed in between these two extreme cases on the x-axis describe results based on intermediate values of σ descending from infinite to zero. Note that the entry for "Bentham" corresponds to the global efficiency cost that we have reported before in Table 2. We restrict the exposition of results to a subset of all core simulations which capture our robust insights with respect to coalition size and the stringency of the reduction targets: Figures 1-3 keep the reduction target of 20% as fixed and vary the coalition size. Figures 4-5 maintain a given coalition size – Annex 1 without Russia – and vary the reduction target (note that Figure 3 reports on the impacts for a 20% reduction target on behalf of Annex 1 without Russia) . Across all simulations, we find that border tax adjustments are preferable as an element of unilateral climate policy only when the distribution of cost across regions is not an important element in the welfare criteria. As inequality aversion becomes a more important, border tax adjustment quickly lose in attractiveness and fare much worse than output-based allocation, exemptions or the reference policy design without complementary anti-leakage measure at all. The bad "equity performance" of border tax adjustments reflect their burden shifting mechanism through changes in international prices. As unilaterally abating regions more generally constitute the richer part in the global economy, border tax measures tend to exacerbate pre-existing inequalities through adverse terms-of-trade effects on poorer countries without emission regulation.[8]

Figure 1: Global welfare changes for 20% emission reduction and coalition size EUR



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[8] Note that the ranking of policy measures can become quite sensitive to the regional decomposition of the data set as σ approaches zero. If, for example, the poorest region is a larger exporter of EITE products or a larger importer of fossil fuels it may effectively gain from the terms-of-trade changes induces by border tax adjustments.

Figure 2: Global welfare changes for 20% emission reduction and coalition size A1xR

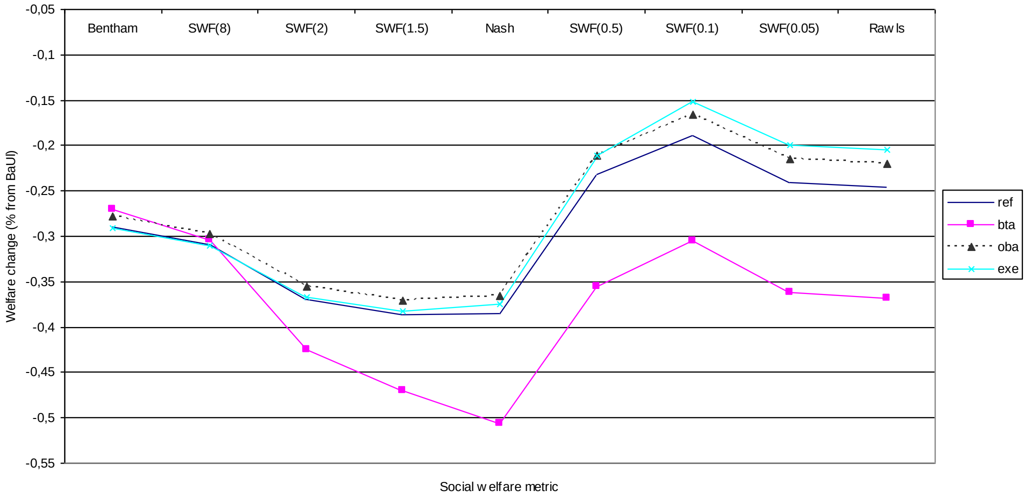


Figure 3: Global welfare changes for 20% emission reduction and coalition size A1xR_CHN

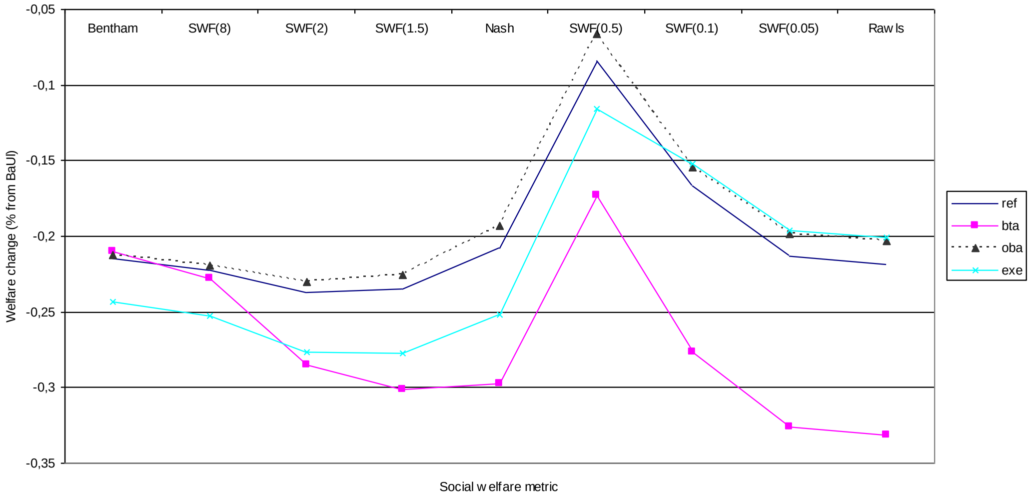


Figure 4: Global welfare changes for 10% emission reduction and coalition size A1xR

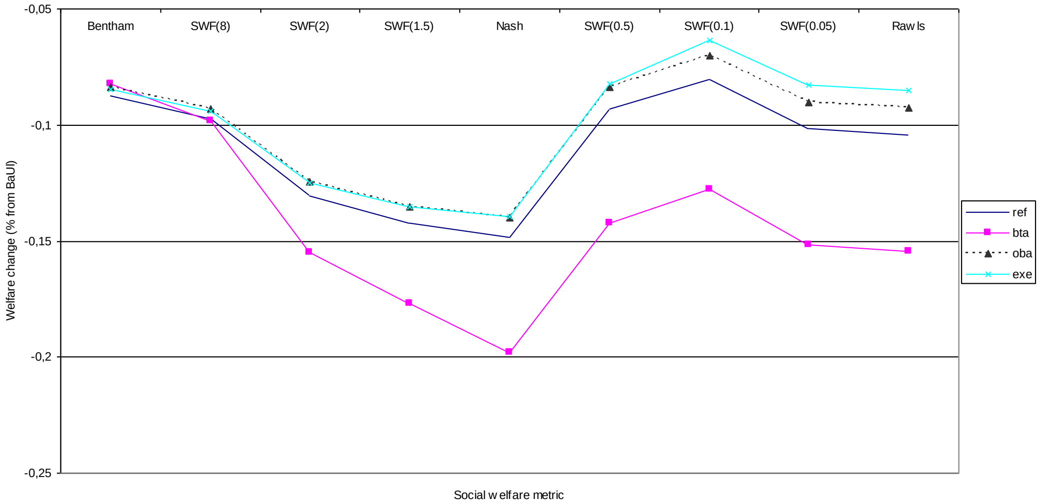
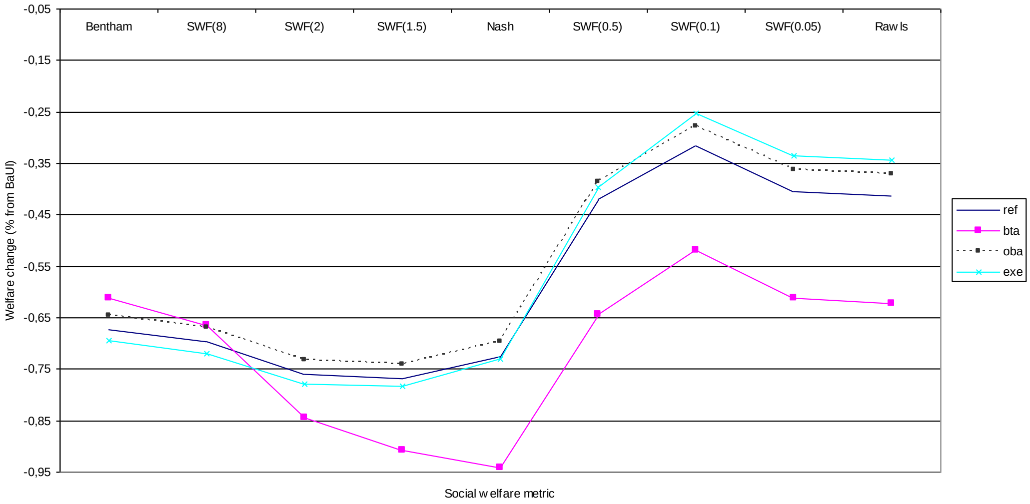


Figure 5: Global welfare changes for 30% emission reduction and coalition size A1xR



From an equity perspective, output-based allocation and tax exemptions pretty much retain the incidence triggered in the reference policy without anti-leakage measures. This finding is in line with the weak impacts these two instruments have on the international price system.

An important qualifier to our analysis of efficiency-equity trade-offs is that it assumes that lump-sum transfers cannot be used to compensate losers in our alternative policy scenarios. If this were possible, then the policy that yields the lowest welfare cost by the Benthamite measure would be the preferred policy as total surplus is maximized under this policy.[9]

4 Concluding Remarks

Instruments designed to offset carbon leakage associated with sub-global climate policies, are taking on increasing importance in policy discussions as evidence of climate change mounts and the world continues to struggle to develop a coordinated response. The principal motivation for such measures – supported by economic theory – is to improve global cost-effectiveness of unilateral action. However, the focus on the efficiency dimension ignores important equity implications of anti-leakage measures.

In this paper, we have used computable general equilibrium analysis to assess three major types of anti-leakage instruments -- border tax adjustments, output-based allocation and industry exemptions -- and compare both their efficiency and equity implications. We find that no one instrument emerges as a clear winner by both sets of criteria. While border tax adjustments are most effective in cutting leakage and reducing global cost compared to a reference scenario with uniform emission pricing only, they exacerbate regional inequality. Exemptions avoid equity conflicts, as they do not reinforce the adverse terms-of-trade effects generated by our reference policy. But they have also have very little potential for generating global cost savings and even run the risk to increase global economic adjustmen cost. The performance of output-based allocation lies somewhere in between that of border adjustments and industry exemptions; it produces efficiency gains without the unattractive equity shift of border adjustments. At the same time, the efficiency gains from output-based allocation are rather limited and, as a result, may not be worth the trouble to design and implement it in policy practice.

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[9] This conclusion relies on the assumption that there are no strong income effects or larger transactions cost asscociated to transfers that could overturn the pre-transfer efficiency ranking of the policies.

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Appendix: Algebraic Model Summary

The CGE 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 A1–A6 explain the notations for variables and parameters employed within our algebraic exposition. 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 ($g \notin FF$):

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

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 ($g \in FF$):

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

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:

$$\bar{L}_{r} \geq \sum_{g} Y_{gr}^{KL} \frac{\partial \Pi_{gr}^{KL}}{\partial w_{r}}.$$

9. Capital:

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

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

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

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

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

20. Carbon emissions:

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

Table A1. 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 A2. 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*
$\mathrm{KL}_{\mathrm{gr}}$	Value-added composite for item *g* in region *r*
$\mathrm{A}_{\mathrm{igr}}$	Armington aggregate of commodity *i* for demand category (item) *g* in region *r*
$\mathrm{IM}_{\mathrm{ir}}$	Aggregate imports of commodity *i* and region *r*

Table A3. Price Variables

p_{gr}	Price of item *g* in region *r*
$\mathrm{p}_{\mathrm{gr}}^{\mathrm{M}}$	Price of material composite for item *g* in region *r*
$\mathrm{p}_{\mathrm{gr}}^{\mathrm{E}}$	Price of energy composite for item *g* in region *r*
$\mathrm{p}_{\mathrm{gr}}^{\mathrm{KL}}$	Price of value-added composite for item *g* in region *r*
$\mathrm{p}_{\mathrm{igr}}^{\mathrm{A}}$	Price of Armington good *i* for demand category (item) *g* in region *r*
$\mathrm{p}_{\mathrm{ir}}^{\mathrm{IM}}$	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)
$\mathrm{p}_{\mathrm{r}}^{\mathrm{CO_2}}$	Carbon value in region *r*

Table A4. 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 A5. 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 non-resource inputs to fossil-fuel production ($g \in FF$) of region *r*
$\theta_{\mathrm{gr}}^{\mathrm{K}}$	Cost share of capital in non-resource inputs to fossil-fuel production ($g \in FF$) of region *r*
$\theta_{\mathrm{igr}}^{\mathrm{FF}}$	Cost share of good *i* in non-resource 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 A6. 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*

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