Unilateral Climate Policy Design:

Efficiency and Equity Implications of Alternative Instruments to Reduce Carbon Leakage

Christoph Böhringer

University of Oldenburg, Germany

boehringer@uni-oldenburg.de

Jared C. Carbone

University of Calgary, Canada

jccarbon@ucalgary.ca

Thomas F. Rutherford

University of Wisconsin, USA

trutherford@wisc.edu

Abstract:

The cost-effectiveness of unilateral emission abatement can be seriously hampered by carbon leakage. We assess three widely discussed proposals for leakage reduction targeted at energy-intensive and trade-exposed industries: carbon-motivated border tax adjustments, industry exemptions from carbon regulation, and output-based allocation of emission allowances. 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 climate policy cost. Output-based allocation does no harm but also does relatively little good by our outcome measures.

Keywords:

Unilateral Climate Policy, Leakage, Border Tax Adjustments, Output-Based Allocation, Exemptions, Efficiency-Equity Trade-Offs

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 incentivizes 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 is 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 boils down to complete exemptions of EITE industries as a response to concerns on losses of competitiveness and adverse employment impacts. A third proposal 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 (EU 2008).

All of these anti-leakage policy measures – border tax adjustments, 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 principle of equating marginal abatement cost across polluters. Thus, the increase in direct abatement cost must be traded off with the indirect 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 even 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 overall economic impacts 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 – in our quantitative simulations 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 (here: Europe) with ambitious reduction targets (here: a 30% cut from business-as-usual emission levels) – two assumptions that should place border measures in a favorable light – the cost savings relative to our reference unilateral policy without anti-leakage measure are below 20%. Cost savings further shrink for output-based allocation (ranging only between 1% and 9% as a function of the coalition size and the reduction target) and exemptions may 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 "exempted".

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 et al. 2011a). As a consequence, border tax adjustments fare poorly when our welfare measures account for even a modest degree of inequality aversion and there is no transfer mechanism in place to compensate losers under 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.

There is a large body of numerical studies that quantify the economic impacts of regulatory measures to reduce leakage and thereby enhance cost-effectiveness of unilateral emission abatement. Many of these studies build on multi-sector, multi-region general equilibrium models which account for price-dependent market interactions in a comprehensive economy-wide framework. Border tax adjustments combining import tariffs with export rebates are found to be effective instruments for leakage reduction with scope for (limited) efficiency gains but also the potential for adverse distributional impacts on developing countries that are subjected to this measure (e.g. Babiker and Rutherford 2005, Mattoo et al. 2009, McKibben and Wilcoxen 2009, Dissou and Eyland 2009, Winchester et al. 2011, Böhringer et al. 2011b – see Zhang (forthcoming) for a review of the literature). Output-based allocation can help to improve the cost-effectiveness of unilateral action if leakage rates are substantial (Böhringer et al. 1998, Fischer and Fox 2009) but they are ranked inferior on cost-effectiveness grounds compared to border adjustments. Böhringer et al. (2011b) show that as the climate coalition gets larger, the efficiency costs of implied output subsidies ultimately outweigh the benefits of reducing emission leakage. As to preferential emission pricing for EITE industries Böhringer et al. (2010) as well as Böhringer and Talebi (2012) find substantial justification for emissions price differentiation to deter leakage but caution on substantial excess cost is warranted as unilateral reduction targets are more moderate and EITE industries get close to exemptions.[1]

Our contribution to the economic literature on unilateral climate policy design is twofold. First, we provide a coherent cross-comparison on the economic implications of border tax adjustments, output-based allocation and industry exemptions as alternative anti-leakage measures. Second, our cross-comparison does not only include cost-effectiveness as a common evaluation criterion but also addresses burden shifting implications thereby offering important insights into efficiency and equity trade-offs of unilateral climate policy design.

[1] In an early quantitative assessment for the for the European Union, Böhringer (1998) finds that sector-specific exemptions from unilateral carbon taxes in Germany substantially reduce leakage but magnify the total costs of EU-wide emission abatement vis-à-vis a unilateral uniform carbon tax.

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 (see Appendix or likewise Böhringer and Rutherford 2010 for an algebraic representation of the core model logic).

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

2.1.5 International Trade

Trade between regions is specified using the Armington assumption of 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 includes all major primary and secondary energy 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 energy-intensive and trade-exposed (EITE) sectors: chemical products, non-metallic minerals, iron and steel products, and non-ferrous metals, as they will be potentially most affected by emission control policies and are thus prime candidates for protective anti-leakage measures. 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 unilateral climate policy designs.

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 et al. (2011a), one can use the multi-region input-output (MRIO) 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 and complementary data sources.

[3] In this case, we even do not need to apply the MRIO calculus.

Table 1: Model sectors and regions[4]

Sectors and commodities	*Countries and regions*
Energy goods	*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
Non-energy 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)	
All other goods (AOG)	

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

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, abating regions implement 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 alternative anti-leakage measures for energy-intensive and trade-exposed (EITE) industries: border tax adjustments, output-based allocation of emission allowances, or exemptions.

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 of production. In our core simulations, the total amount of free emission allowances

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

to EITE industries equals their benchmark emissions scaled down by the unilateral emission reduction target.

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

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.

Key indicators for our discussion of results include 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, i.e. unilateral emission pricing without anti-leakage measures. The gross benefit of abatement for a given (representative) household in each region is then constant across all policy scenarios. This allows us – given implicit assumption that the gross benefits of emission reduction are separable from the welfare derived from consumption of private goods – to do coherent welfare analysis without the need for external cost etimates from CO_2 emissions.[5] 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)[6] 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.

[5] 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.

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

3.2 Simulation Results

3.2.1 Leakage and EITE Output

Table 2 presents leakage rates, EITE output (as well as output of non-EITE sectors), 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 (Table 2A.).[7] Border tax adjustments are by far the most effective instrument across the three anti-leakage measures to reduce carbon leakage (Table 2B.). 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 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 implicit 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.[8]

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 (Table 2C.). 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. The output implications for non-EITE industries (Table 2D) are mirror-inverted indicating burden shifting of the anti-leakage measures at the cross-sector level.

For any given coalition size and unilateral abatement pledge global emissions are kept constant at the outcome of the reference scenario (Table 2E). Leakage reduction therefore translates into a cutback of the coalition's implicit abatement requirement to comply with the global emission constraint (Table 2F). The domestic emission reductions are distinctly lowest for the case of border measures followed by exemptions and output-based allocation that produce almost identical outcomes.

CO_2 prices are closely correlated with the stringency in reduction targets that apply to regulated economic activities (Table 2G.). For a given coalition size, marginal abatement cost increase 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.

[7] Böhringer et al. (2011b) provide a theoretical analysis on how the coalition size impacts on the cost-effective design of unilateral climate policies.

[8] 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 et al. 2011a) 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 and non-EITE output, CO_2 emissions, CO_2 prices

Coalition	EUR			A1xR			A1xR_CHN		
Target	10%	20%	30%	10%	20%	30%	10%	20%	30%
A.	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
B.	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
C.	EITE output (in % from *bau*)								
ref	-1,02	-2,61	-4,95	-0,85	-2,20	-4,19	-0,55	-1,45	-2,85
bta	-0,20	-0,45	-0,73	-0,31	-0,74	-1,29	-0,25	-0,63	-1,15
oba	-0,61	-1,61	-3,08	-0,57	-1,52	-2,95	-0,37	-1,00	-2,03
exe	-0,64	-1,65	-3,13	-0,60	-1,57	-3,01	-0,42	-1,15	-2,31
D.	Non-EITE output (in % from *bau*)								
ref	0,00	-0,03	-0,08	0,00	-0,02	-0,07	0,01	0,00	-0,03
bta	-0,05	-0,13	-0,27	-0,03	-0,09	-0,19	-0,01	-0,04	-0,12
oba	-0,02	-0,07	-0,16	-0,01	-0,05	-0,12	0,00	-0,03	-0,08
exe	-0,02	-0,08	-0,18	-0,01	-0,05	-0,12	0,00	-0,02	-0,09
E.	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
F.	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
G.	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

The price difference is most pronounced for a small coalition size and a high reduction target but remains rather modest overall. 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 distinctly exceed the reference price level: the non-exempted parts of the domestic economy must pay higher CO_2 prices than in the reference scenario to make up for the exemption of EITE sectors.

3.2.2 Efficiency and Equity

Table 3 and Figures 1-5 provide 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 reach some given global emission reduction target is then based on a utilitarian social welfare function where we simply add up the changes in Hicksian equivalent variation (HEV) in income across all regions.

Note that our cost-effectiveness analysis does not include benefits from emission abatement but focuses on the gross economic cost to comply with a prescribed constant reduction of global emissions. Nonetheless, it makes sense to quantify the (gross) economic cost for all abatement scenarios with respect to the business-as-usual (*bau*). In this way, we can not only quantify the cost differentials of additional anti-leakage measures on top of the reference climate policy but also provide information on how costly abatement from *bau* emission levels gets. The latter information is a central input to the international climate policy debate on burden sharing which is dominated by concerns on the short- to mid-term cost of emission abatement while benefits are more uncertain and occur in the long run.

Global compliance cost are primarily determined by the magnitude of the unilateral emission reduction target; when 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 as low-cost abatement options are exhausted (Table 3A.). There is some variation in the range of abatement cost for different coalition sizes which captures the heterogeneity of emission intensities across coalition countries.

Table 3B. quantifies the potential cost savings of anti-leakage measures compared to the reference abatement scenario. In line with the magnitude of leakage reduction, border tax adjustments provide much higher efficiency gains than output-based allocation or exemptions. 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 indirect gains of leakage reduction.

Table 3C. reveals the equity tension of anti-leakage measures in terms of a burden sharing coefficient which is defined as the coalition share in global adjustment cost over the non-coalition share in global adjustment cost. First of all, we see that even for the reference scenario non-coalition countries on average face non-negligible economic cost due to adverse terms-of-trade effects. In other words, the economic burden of domestic emission pricing 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. Output-based allocation and exemptions hardly change the burden sharing ratio of the reference policy. In contrast, border tax adjustments come along with a drastic 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.

Table 3: Cost-effectiveness and burden sharing

Coalition	EUR			A1xR			A1xR_CHN		
Target	10%	20%	30%	10%	20%	30%	10%	20%	30%
A.	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
B.	Cost savings of anti-leakage measures compaared to the reference scenario (in % from *ref* cost)								
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
C.	Burden sharing ratio 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

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 of the x-axis 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 (see Table 1: 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 (A1xR) – and vary the reduction target. 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 more important, border tax adjustments quickly lose in attractiveness and perform much worse than output-based allocation, exemptions or the reference policy design without complementary anti-leakage measure at all. The poor "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.[9]

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

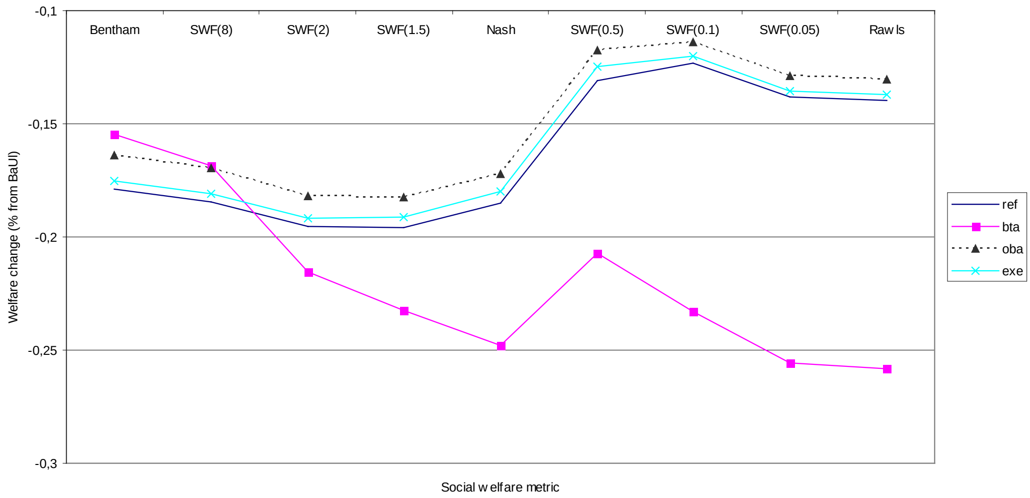
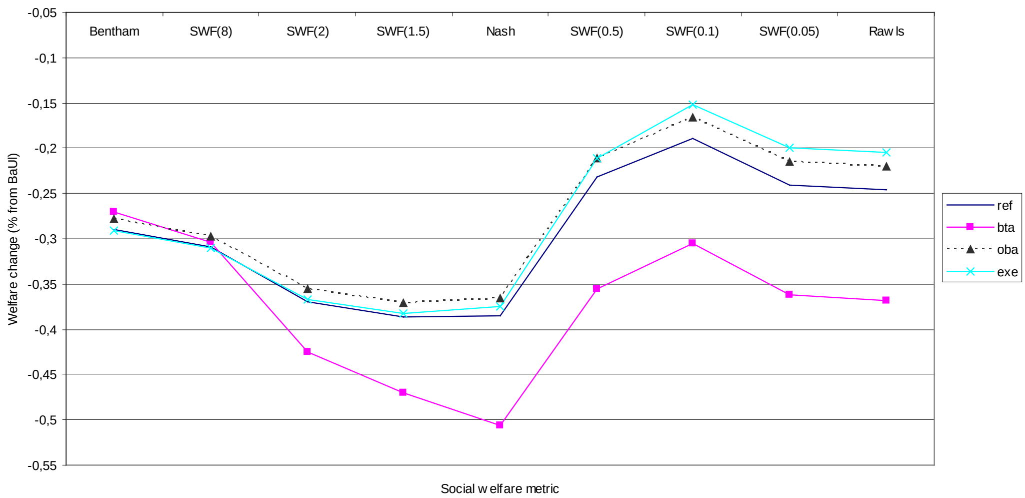


Figure 2: Global welfare changes for 20% emission reduction and coalition size A1xR



[9] Note that the ranking of policy measures can become quite sensitive to the regional decomposition of the data set as the inequality parameter 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 3: Global welfare changes for 20% emission reduction and coalition size A1xR_CHN

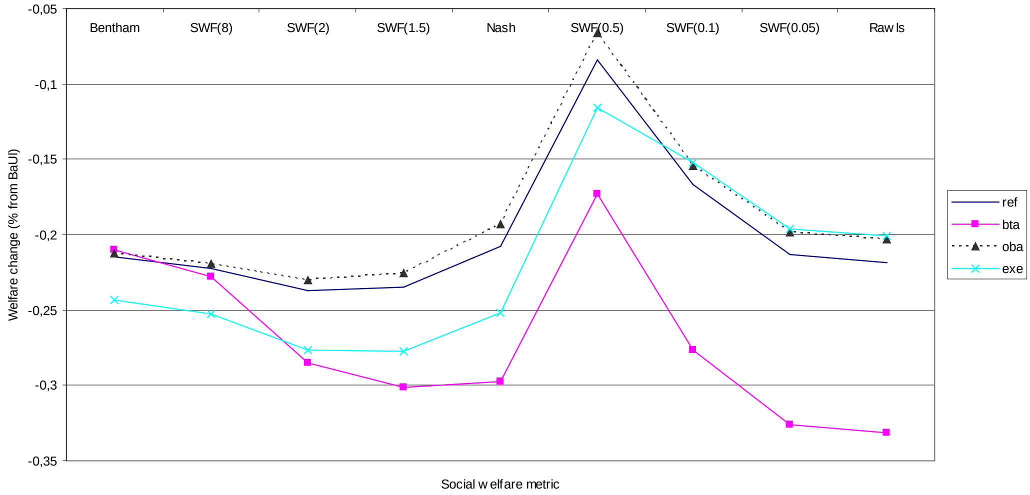


Figure 4: Global welfare changes for 10% emission reduction and coalition size A1xR

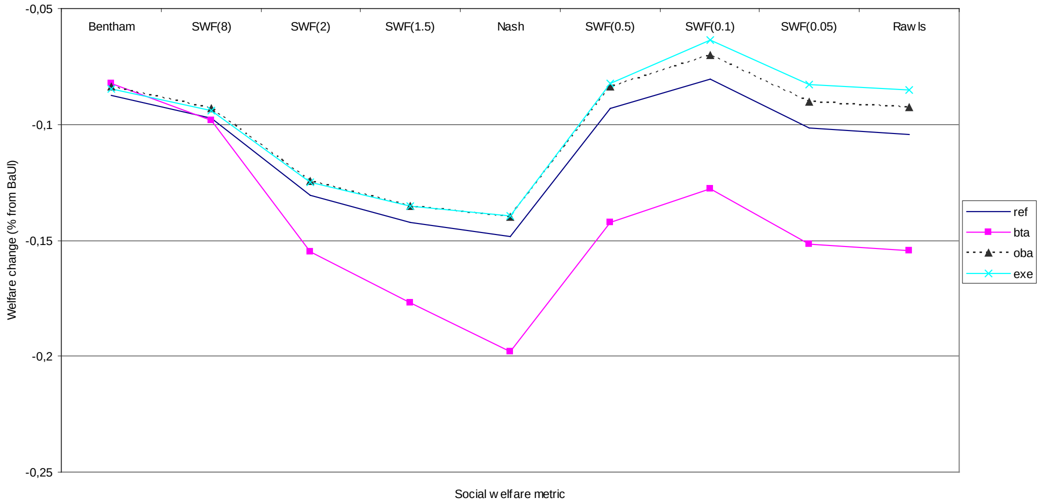
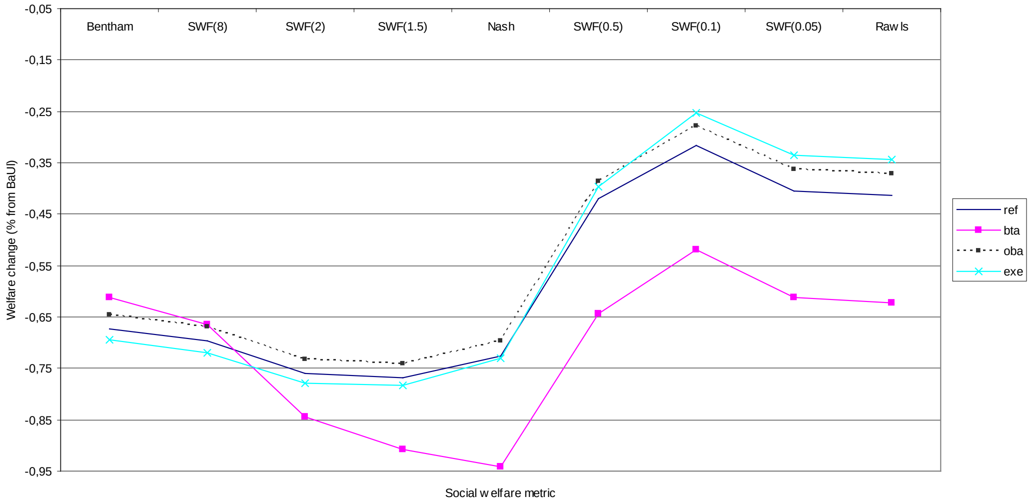


Figure 5: Global welfare changes for 30% emission reduction and coalition size A1xR



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 relatively 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 economic surplus is maximized under this policy.[10]

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 of emission allowances and industry exemptions – with respect to their efficiency and equity implications. We find that no one instrument emerges as a clear winner when both efficiency and equity criteria matter. 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 adjustment 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.

References

Armington, Paul S. 1969. A Theory of Demand for Producers Distinguished by Place of Production. IMF Staff Papers 16(1): 159–78.

Babiker, M.H. and T.F. Rutherford 2005. The Economic Effects of Border Measures in Subglobal Climate Agreements, *The Energy Journal*, 26 (4), 99-126.

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

Böhringer, C. 1998. Unilateral Taxation of International Environmental Externalities and Sectoral Exemptions, in: A. Fossati and J.Hutton (eds.): Policy Simulations in the European Union, Routledge, London, 140-155.

Böhringer, C. and V. Alexeeva-Talebi 2012. Unilateral Climate Policy and Competitiveness: Economic Implications of Differential Emission Pricing, *The World Economy*, DOI: 10.1111/j.1467-9701.2012.01470.x

Böhringer, C. and T. F. Rutherford 2002. Carbon Abatement and International Spillovers, *Environmental and Resource Economics*, 22 (3), 391–417.

[10] 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.

Böhringer, C. and T.F. Rutherford 2011. The Cost of Compliance: A CGE Assessment of Canada's Policy Options under the Kyoto Protocol, *The World Economy*, 2010, 33 (2), 177–211.

Böhringer, C., M. Ferris, and T.F. Rutherford 1998. Alternative CO_2 Abatement Strategies for the European Union. In Climate Change, Transport and Environmental Policy, edited by J.B. Braden and S. Proost. Northampton, Massachusetts: Edward Elgar Publishing, 16–47.

Böhringer, C., A. Lange and T.F. Rutherford 2010. Optimal Emission Pricing in the Presence of International Spillovers: Decomposing Leakage and Terms-of-Trade Motives. NBER working paper 15899, Cambridge.

Böhringer, C., Carbone, J. and T.F. Rutherford 2011a. Embodied carbon tariffs, NBER working paper, 17376, Cambridge.

Böhringer, C., Fischer, C. and K.E: Rosendahl 2011b. Cost-Effective Unilateral Climate Policy Design: Size Matters, RFF Discussion Paper 11-34, Washington, D.C., Resources for the Future.

Brooke, A., Kendrick, B., and A. Meeraus 1996. GAMS: A User's Guide, GAMS Development Corporation, Washington, DC.

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

Dissou, Y. and T. Eyland 2011. Carbon Control Policies, Competitiveness, and Border Tax, *Energy Economics*, 33 (3), 556-564.

EU (2008), European Commission, The EU climate and energy package, available at: http://ec.europa.eu/clima/policies/package/index_en.htm

Fischer, C. 2001. Rebating Environmental Policy Revenues: Output-Based Allocations and Tradable Performance Standards, RFF Discussion Paper 01-22, Washington, D.C., Resources for the Future.

Fischer, C. and A.K. Fox (2009), Comparing Policies to Combat Emissions Leakage: Border Tax Adjustments versus Rebates, Discussion Paper 09-02, Resources for the Future.

Hoel, M. 1991. Global Environmental Problems: The Effects of Unilateral Actions Taken by One Country, *Journal of Environmental Economics and Management*, 20, 55–70.

Hoel, M. 1996. Should a carbon tax be differentiated across sectors?, *Journal of Public Economics*, 59, 17–32.

Markusen, J.R. 1975. International Externalities and Optimal Tax Structures, *Journal of International Economics*, 5, 15–29.

Mattoo, A., A. Subramanian, D. van der Mensbrugghe, and J.He 2009. Reconciling Climate Change and Trade Policy, Peterson Institute Working Paper 09-15.

McKibben, W. and P.J. Wilcoxen 2009. The Economic and Environmental Effects of Border Tax Adjustments for Climate Policy, Lowy Institute Working Paper No. 1.09.

Winchester, Niven, Sergey Paltsev, and John Reilly (2010). Will Border Carbon Adjustments Work? MIT Joint Program on the Science and Policy of Global Change Report no. 184.

Zhang, Z.X. forthcoming. Competitiveness and Leakage Concerns and Border Carbon Adjustments, *International Review of Environmental Economics and Policy*.

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:

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

7. Aggregate imports across import regions:

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

<u>*Market Clearance Conditions:*</u>

8. Labor:

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

9. Capital:

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

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

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

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:

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

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 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

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

Table A3. Price Variables

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