A look inwards: carbon tariffs versus internal improvements in emissions-trading systems

Marco Springmann[a,b]

[a]German Institute for Economic Research (DIW), Mohrenstrasse 58, 10117 Berlin, Germany E-mail: mspringmann@diw.de; [b]Present address: Department of Economics, University of Oldenburg, 26111 Oldenburg, Germany.

Abstract:
Subglobal climate policies will be the norm for some years to come. However, several options exist for improving the efficiency of domestic emissions regulation. A prominent but contentious policy option for improving the external efficiency is the implementation of carbon tariffs on non-regulating regions. This is thought to reduce carbon leakage and increase domestic production, albeit at the cost of non-regulating countries. In contrast, internal efficiency improvements can be more collaborative in type. Among others, they include extending and linking of domestic emissions-trading systems. This study compares the relative economic impacts of those policy options if Annex I countries would follow one or the other. The study uses a computable-general-equilibrium model of the global world economy and develops a set of emissions-trading and carbon-tariff scenarios with various degrees of sectoral and regional coverage. The results indicate that linking Annex I countries' domestic emissions-trading systems and expanding their sectoral coverage could yield greater global welfare improvements than implementing carbon tariffs on energy-intensive goods imported from non-Annex I countries. While non-Annex I countries would be significantly better off without facing carbon tariffs on their exports, Annex I countries could gain from either policy. The relative gains from linking and extending the sectoral coverage of domestic emissions-trading systems are greater for early policy implementation within a large Annex I coalition of climate-regulating countries, while late implementation within a small coalition would yield greater relative welfare gains from imposing carbon tariffs. The results suggest that, in addition to the political benefits, there exists an economic rationale for substituting the external efficiency improvements associated with implementing carbon tariffs with internal ones associated with extending Annex I countries' emissions-trading systems.

Keywords:
Climate policy; Carbon tariffs; Emissions trading; Computable general equilibrium

JEL Classification:
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1. Introduction

Current climate policies are fragmented and subglobal. Emissions abatement efforts are dichotomously divided between industrialized Annex I countries with legal emissions reduction commitments and developing non-Annex I countries without such commitments. The subglobal implementation of carbon pricing and the resulting price differentials between implementing and non-implementing countries have raised several concerns in the implementing countries. Some worry that domestic industries might suffer competitive disadvantages vis-à-vis international imports from non-abating countries. Others stress the risk of carbon leakage, i.e., increases in emissions in non-implementing countries through shifts in consumption demand and production, which could undermine the effectiveness of domestic emissions-reductions efforts (Dröge et al., 2009).

In this context, some Annex I countries have proposed to implement carbon tariffs on imports from non-Annex I countries that have not agreed to adopt binding emissions-reduction commitments. Levying an import tariff in proportion to the carbon content of the imported good is thought to reduce carbon leakage and to preserve the competitiveness of domestic industries vis-à-vis international imports from non-abating countries (van Asselt and Biermann, 2007).

From a theoretical perspective, implementing carbon tariffs is thought to increase the cost-efficiency of subglobal climate policies, to the benefit of Annex I countries, by compensating carbon leakage through comparatively cheaper emissions reductions in the exporting non-Annex I countries (Markusen, 1975; Hoel, 1996).[1] However, while some numerical economic analyses indicate that implementing carbon tariffs could partially reduce carbon leakage and increase domestic consumption in the tariff-implementing regions (Böhringer et al., 2011; Burniaux et al., 2010; Winchester et al., 2011), their distributional effects make them politically contentious. They are likely to place considerable burden with significant welfare losses on developing countries on whose exports the tariffs are imposed (Babiker and Rutherford, 2005; Dröge and Kemfert, 2005; Mattoo et al., 2009; Springmann, 2012). This could have significant political and legal repercussions. For example, China denounced plans for carbon tariffs as trade protectionism for domestic industries, illegal under WTO law and threatened with trade war should carbon tariffs be adopted (Voituriez and Wang, 2011). More broadly, the political tensions arising from the adoption of carbon tariffs could further impede negotiations for a global climate agreement within the United Nations Framework Convention on Climate Change (UNFCCC).

[1] Inducing leakage-compensating emissions reductions in the exporting non-Annex I countries is, in most cases, considered more cost-effective (globally and for Annex I countries) than pursuing additional emissions reductions in Annex I countries which have already exhausted several (comparable) low-cost abatement options.

Politically, carbon tariffs divide countries into potentially tariff-imposing Annex I countries with legal emissions-reduction commitments and potentially targeted non-Annex I countries without legal commitments. However, this distinction is not as clear-cut as it may seem. For example, several non-Annex I countries, such as China and South Korea are considering implementing emissions-trading schemes within this decade (Hood, 2010). On the other hand, many Annex I countries have not yet adopted comprehensive carbon-pricing policies and the emissions-trading schemes that exist, such as the European Union Emissions Trading Scheme (EU ETS) and the Regional Greenhouse Gas Initiative (RGGI) in the US are plagued by problems of overallocation of emissions permits (World Bank, 2011).

Before extending domestic emissions regulation through the implementation of carbon tariffs, it might therefore be more appropriate for Annex I countries to further the improvement of domestic climate policies and the linking of existing and planned emissions-trading schemes. While each of the two policy trajectories may have different political goals[2], either trajectory could be used from an economic perspective to increase the cost-efficiency of domestic abatement efforts in Annex I countries. Carbon tariffs induce *external* efficiency improvements by indirectly regulating those non-Annex I emissions that are associated with the production of export goods, whereas the expansion and linking of emissions-trading systems in Annex I countries induce *internal* efficiency improvements by enabling a more efficient sectoral and regional distribution of abatement efforts across Annex I countries.

Pursuing the linking and extending emissions-trading systems in Annex I countries for economic efficiency gains would circumvent the political and legal problems associated with carbon tariffs and be more in line with the UNFCCC principle of common but differentiated responsibility.[3] Although extending the coverage of emissions-trading systems in Annex I countries and implementing carbon tariffs on exports from non-Annex I countries could, in principle, be pursued in parallel, they are likely to preclude one another politically. The main reason is the incompatibility of incentive structures between the two policies. Carbon tariffs are perceived as politically confrontational which is inconsistent with those cooperative initiatives that are aimed at linking different emissions-trading systems, but also with general economic relationships between countries.[4] Because provisions for carbon tariffs are crucial ETS design choices, the divergent opinions that exist across Annex I countries on the desirability of carbon tariffs would likely hamper the ETS-design harmonization that is

[2] The direct political reason for expanding and linking emissions-trading systems is to increase the cost-efficiency of abatement efforts. On the other hand, the stated political reason for implementing carbon tariffs is to achieve a reduction in carbon leakage and to preserve the competitiveness of domestic (in particular energy-intensive and trade-exposed) industries. However, both of those reasons are connected to the economic rationale of increasing the cost-efficiency of domestic abatement efforts, since leakage reductions and better terms of trade associated with increased competitiveness can be seen as constituting an increase in the cost-efficiency of domestic abatement efforts.

[3] Within the UNFCCC, Annex I countries have pledged to technically and financially support developing countries in their abatement efforts, which can be considered inconsistent with raising new emissions-related tariff barriers.

[4] In that regard, it might be considered unlikely that all Annex I countries would levy carbon tariffs on imports from non-Annex I countries and thereby risk potential trade wars (see, e.g., the contribution in this Special Issue, as well as Böhringer et al., 2011).

needed for different emissions-trading systems to be linked. On the other hand, initiatives aimed at linking emissions-trading systems across Annex I countries can be interpreted as a first step towards pursuing further linkages with those emissions-trading systems that are emerging in non-Annex I countries[5], something which would remove the basis for carbon tariffs being implemented.

This study analyzes whether beside the political appeal, there exist also an economic rationale for pursuing internal efficiency improvements from linking emissions-trading systems in Annex I countries over the external efficiency improvements following from imposing carbon tariffs on non-Annex I countries. Theoretically, the linking and extending of emissions-trading schemes equalizes marginal-abatement costs between the regions and sectors covered. This leads to gains from trade in emissions allowances and associated increases in consumption and welfare in those regions and sectors (see, e.g., Tietenberg, 2006). While the outcome could, in principle, be different in second-best (real-world) settings (Babiker et al., 2004), several model studies have indicated the benefits from extending the coverage of emissions trading systems. For example, Weyant and Hill (1999) indicate significant benefits from emissions-trading across all Annex I countries for a cost-efficient fulfillment of their emissions-reduction obligations under the Kyoto Protocol, whereas Böhringer et al. (2005, 2009) and Klepper and Peterson (2004) highlight the cost-saving potential of extending the sectoral coverage of the EU ETS.

This study builds on those earlier assessments and analyses the potential gains from extending the sectoral and regional coverage of emissions-trading systems within Annex I regions vis-à-vis the implementation of carbon tariffs by Annex I countries on energy-intensive imports from non-Annex I countries. While each of those policies has been assessed before separately, no strict comparison of the policies' relative effects and their respective trade-offs has been made in a numerical setting. This study intends to fill this gap. For that purpose, it uses a computable general equilibrium model of the global world economy which tracks changes in trade flows, carbon-dioxide (CO_2) emissions, as well as economic output and prices. The study develops a set of indicative emissions-trading and carbon-tariff scenarios, and it analyzes the trade-offs along each policy trajectory in terms of a cost-effectiveness analysis of attaining a specified (global) emissions level. Although the focus of this study is on the policies' economic impacts, in particular on welfare, it also assesses their effects on GDP, the production and exports of energy-intensive goods, and carbon leakage.

The analysis is structured as follows. Section 2 describes the structure of the computable-general-equilibrium model, as well as the database and aggregation used in this study. Section 3 highlights the model scenarios and policy trajectories defined for the analysis. Section 4 presents the results of the main scenarios, while Section 5 includes a comprehensive sensitivity analysis that evaluated some of the key abstractions made in study's main scenarios. Section 6 concludes.

[5] For example, the EU is supporting the creation of an OECD-wide emissions-trading system within this decade and envisions the possibility of linking it with emerging emissions-trading systems in developing countries by 2020 (EU Commission, 2009).

2. Model description

This paper utilizes an energy-economic model of the global economy. It is based on the GTAP7inGAMS package developed by Thomas Rutherford (2010) and extended by an explicit representation of the energy sector and a carbon market in line with Rutherford and Paltsev (2000) and Böhringer et al. (2011). A detailed description of the basic framework and its energy extension can be found in the references above. In short, the model is a computable general equilibrium model based on optimizing behaviour of economic agents. Consumers maximize welfare subject to budget constraints and producers combine intermediate inputs and primary factors at least cost to produce output. Energy resources are included as primary factors whose use is associated with the emission of carbon dioxide (CO_2).

2.1. Model structure

The basic energy-economic model includes five energy goods (crude oil (CRU), refined oil (OIL), coal (COL), gas (GAS), and electricity (ELE)) and three aggregated commodities (energy-intensive goods (EIT), transport services (TRN), all other goods (AOG)). Those are produced with inputs of intermediate goods and primary factors (skilled labor, unskilled labor, capital, resources, and land). Secondary energy inputs (refined oil, electricity) are produced with constant returns to scale, whereas primary energy goods (crude oil, natural gas, and coal) exhibit decreasing returns to scale with resource input. Capital and labor are intersectorally mobile, but crude oil, natural gas and coal resources are sector-specific.

The production of energy and other goods is described by nested constant-elasticity-of-substitution (CES) production functions which specify the input composition and substitution possibilities between inputs (see Figure 1). For all goods except fossil fuels, the CES production functions are arranged in three levels. The top-level nest combines an aggregate of capital, labor, and material inputs (KLM) with aggregate energy inputs (E); the second-level nest combines non-energy material inputs (M) in fixed proportions with a value-added composite of capital and labor inputs (VA) in the KLM-nest, as well as electricity inputs (P(ELE)) with final-energy inputs (FE) in the energy nest; and the third-level nest captures the composition of the different material inputs (P(1) to P(N)), the substitution possibilities between capital (PK) and labor (PL) in the VA-nest, and the composition of the different final-energy inputs (coal, refined oil, gas) (P(FE)) and their associated CO_2 emissions (PCARB) in the FE-nest. The production of fossil fuels combines sector-specific fossil-fuel resources with an aggregate of all other inputs which enter in fixed proportions.[6]

[6] This description allows calibrating the elasticities of substitution between resources and other fossil-fuel inputs to match assumed price elasticities of supply with resource rental shares from the database (see, e.g., Balistreri and Rutherford, 2011). The elasticities of supply used in the model are listed in Table A1 in the appendix.

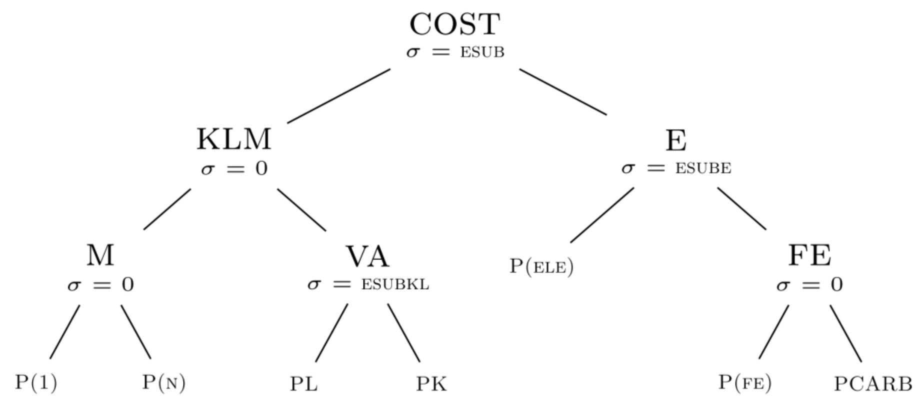

Figure 1. Nesting structure of CES production functions (except for fossil fuels).

The modeling of international trade follows Armington's (1969) approach of differentiating goods by country of origin. Thus, goods within a sector and region are represented as a CES aggregate of domestic goods and imported ones with associated transport services. Final consumption in each region is determined by a representative agent who maximizes consumptions subject to its budget constraint. Consumption is represented as a CES aggregate of non-energy goods and energy inputs and the budget constraint is determined by factor and tax incomes with fixed investment and public expenditure.

2.2. Database and aggregation

The energy-economic model is calibrated to the database version 7.1 of the Global Trade Analysis Project (GTAP). This database represents global production and trade for 113 countries/regions, 57 commodities and 5 primary factors for the benchmark year 2004 (Narayanan and Walmsley, 2008). The data include information on bilateral trade, intermediate demand, direct and indirect taxes on imports and exports, elasticities of substitution, as well as CO_2 emissions from the combustion of fossil fuels. Elasticities of substitution across energy inputs and between energy and other inputs which are not represented in the database are adopted from Böhringer et al. (2011).[7]

For this study, the full GTAP database is aggregated such that it enables a concise but comprehensive analysis of the economic impacts that Annex I climate policies have both domestically and internationally. Table 1 lists the regional aggregation used for this study which explicitly resolves seven Annex I regions and five non-Annex I regions. With respect to commodities, the model's aggregation includes five energy commodities (coal, natural gas, crude oil, refined oil, and electricity) and further differentiates between energy-intensive goods, transport services, and a composite of all other goods. The differentiation between

[7] The GTAP consortium states that in order to construct a consistent global data set for a given year base, significant adjustments have been made to ensure that national input-output tables match external macroeconomic, trade, protection, and energy data (Narayanan and Walmsley, 2008, Chapters 7-8). While this ensures overall consistency, it also poses limits to accuracy, in particular of sectoral national details, which the reader should be aware of. The results should therefore be seen as indicative in nature.

energy-intensive goods and all other goods allows for levying carbon tariffs only on the former as envisioned by most current policy proposals in the EU and US (van Asselt and Brewer, 2010; Monjon and Quirion, 2010). Energy-intensive goods include iron and steel; chemicals, including plastics and petrochemical products; non-ferrous metals, including copper and aluminium; non-metallic minerals, including cement; and refined-oil products.

Table 1. Model regions

Annex I			
EUR	Europe (EU 27 + EFTA)	CAN	Canada
USA	United States	RUS	Russia
JPN	Japan	RA1	Rest of Annex I
ANZ	Australia and New Zealand		
non-Annex I			
CHN	China	MIC	Other middle-income countries
IND	India	LIC	Other low-income countries
EEX	Energy-exporting countries		

3. Model scenarios

This study considers a set of indicative ETS and carbon-tariff scenarios to analyze the potential gains from extending the sectoral and regional coverage of emissions-trading systems in Annex I countries and to compare those gains with the impacts from implementing carbon tariffs on energy-intensive imports from non-Annex I countries. The scenarios are informed by current climate policy proposals in the EU and other Annex I regions which are reviewed below. A comprehensive sensitivity analysis assesses the impacts of alternative scenario specifications.

The study is designed as a cost-effectiveness analysis which assesses the policies' cost-efficiency of attaining a given (global) emissions level. This allows for a rigorous comparison of the policies' effects on carbon leakage, GDP, and welfare with respect to a common emissions basis and therefore without having to quantify the benefits of emissions reductions. The global emissions target is composed of all business-as-usual emissions in 2004, minus those emissions that are associated with a 20% emissions reduction in Annex I countries.

3.1. Emissions-trading scenarios

Current climate policies are highly fragmented (World Bank, 2011). Emissions-trading systems exist in Europe (European Union Emissions Trading System, EU ETS), New Zealand (New Zealand Emissions Trading Scheme, NZ ETS), several US regions (Global Warming

Solutions Act denoted as Assembly Bill 32 (AB32) in California, Regional Greenhouse Gas Initiative (RGGI) in northeastern and mid-Atlantic states), and in the city of Tokyo (Japan). Elsewhere, such as in other western US states (Western Climate Initiative, WCI) and in Australia (Carbon Price Mechanism contained in the Clean Energy Future Package), they are in the planning process or foreseen for implementation within the next few years. The current and proposed emissions-trading systems vary widely with respect to their regional and sectoral coverage (Hood, 2010). On the regional level, they range from subnational ETS (Tokyo, RGGI, AB32) to multinational schemes (EU ETS); the sectoral coverage varies from coverage of the electricity-sector only (RGGI) to ETS intended to cover the whole economy (AB32, NZ ETS).[8]

Despite their heterogeneity, several emissions-trading systems foresee the linking to other ETS in the future. For example, the EU ETS has already been extended to Norway, Iceland, and Liechtenstein, and negotiations on linking the Swiss ETS to the EU ETS were opened in late 2010. The possibilities of linking the EU ETS to future ETS in the USA, Australia, and New Zealand are regularly explored in economic and political analyses (see, e.g., Alexeeva-Talebi and Anger, 2007; Flachsland et al., 2009; Jotzo and Betz, 2009). The stated aim of the EU is to establish an OECD-wide carbon market by 2015 through the bottom-up linking of compatible domestic emissions-trading systems, with further prospects for linking by 2020 to those emissions-trading systems that are emerging in the economically advanced developing countries (EU Commission, 2009). At the same time, the EU intends to harmonize its ETS to facilitate the linking to other emissions-trading systems, e.g., by extending sectoral coverage.

Based on this background, the study considers four indicative emissions-trading scenarios which are described in Table 2. The ETS scenarios are meant to capture different potential routes for linking and extending the emerging domestic emissions-trading systems in Annex I countries across regions and economic sectors. The regional coverage distinguishes between regional emissions-trading schemes in each Annex I region, something that can be envisioned to be put in place within the next 5 years; and internationally schemes linked across all Annex I regions, something which has been envisioned to be implemented within the next 10 years (EU Commission, 2009; Tuerk et al., 2009). With respect to sectoral coverage, the scenarios differentiate between hybrid emissions-trading schemes with partial sectoral coverage, as it is currently found in the EU ETS; and economy-wide emissions trading across all sectors, as to be implemented in the NZ ETS and potentially aimed for in future (more harmonized) trading phases of the EU ETS (Hood, 2010). This wide spectrum of ETS scenarios allows for an assessment of policy trajectories with different degrees of inter-regional linking and sectoral coverage which is intended to reflect the high fragmentation of current climate policies.

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[8] Another point of difference across the current and planned ETS is the coverage of greenhouse gases. While the RGGI and EU ETS (in its second trading phase) cover only CO2, the NZ ETS covers all six greenhouse gases regulated under the Kyoto Protocol (Hood, 2010). This study abstracts from those differences in "what-flexibility" and focuses solely on CO2 as greenhouse gas. Including more greenhouse gases would increase the cost-efficiency of abatement in the ETS scenarios (see, e.g., Böhringer et al., 2006), but also the efficiency of carbon tariffs (Burniaux et al., 2010).

Table 2. Emissions-trading scenarios.

Scenario	Comment
reg_hybrid_ets	The regional-hybrid-ETS scenario represents the most fragmented carbon-pricing scenario. It models individual emissions-trading systems with partial (hybrid) sectoral coverage in each Annex I region. Carbon prices are equalized across ETS sectors, but differentiated by region.
reg_full_ets	The regional-full-ETS scenario models economy-wide emissions-trading schemes in each Annex I region. Carbon prices are equalized across all sectors, but differentiated by region.
int_hybrid_ets	The international-hybrid-ETS scenario models an international emissions-trading scheme with partial sectoral coverage across all Annex I regions. Carbon prices are equalized across countries and across ETS sectors.
int_full_ets	The international-full-ETS scenario is the most integrated carbon-pricing scenario. It models an economy-wide international emissions-trading scheme that covers all Annex I regions and all economic sectors. Carbon prices are equalized across all countries and sectors.[9]

The policy scenarios include two emissions-trading systems with partial (hybrid) sectoral coverage.[10] In hybrid emissions-trading systems, there are two design parameters that influence the potential benefits from extending the hybrid ETS. Those indicate which sectors are initially covered by the ETS and how the emissions reduction burden is distributed between the ETS and non-ETS sectors. This study's parameter choices for its hybrid-ETS scenarios are informed primarily by the design choices made in the EU ETS, since the EU ETS can be considered the forerunner in terms of ETS implementation. The EU ETS is also currently the largest ETS and by far the most well developed one in place (Hood, 2010), so that emerging schemes may choose to (or be expected to) harmonize its design choices with those of the EU ETS during a potential linking procedure (Ellis and Tirpak, 2006). Following the EU ETS, the sectoral coverage of the hybrid-ETS scenarios encompasses electricity, refineries, and energy-intensive industries. Taken together, those sectors cover about half of all sectoral emissions in Annex I regions in 2004.

Although the distribution of emissions-reduction burden between the ETS and non-ETS

[9] This scenario is labelled REF in the model comparison contained in this Special Issue.
[10] Reasons for not including all sectors in an ETS can be practical in nature, i.e., emissions in certain sectors, such as agriculture, are hard to monitor; economic in nature, as building monitoring and reporting infrastructure would be costly for such sectors; and political, as the inclusion of some sectors, such as transport, may face strong political opposition (Hood, 2010). However, countries with hybrid emissions-trading systems typically foresee the regulation of non-ETS sectors by means other than emissions-trading, such as sectoral taxes or quotas.

sectors is informed by the EU ETS, this study adopts an adjusted value for its broader Annex I scope. The EU has split their emissions-reduction commitment of 20% below 1990-levels into a 21% emissions-reduction requirement for the ETS sectors and a 10% emissions-reduction requirement for the non-ETS sectors with 2005 as the reference year (EU Commission, 2008). However, Böhringer et al. (2009) find a split of abatement burden of 30% for ETS sectors and 0% (i.e., business-as-usual emissions) for non-ETS sectors more efficient in terms of equalizing marginal abatement costs. This study chooses the middle value of a 5% emissions-reduction burden for non-ETS sectors for its extrapolation to all Annex I countries. This split was found more ideal, i.e., to yield lower welfare losses for the implementing Annex I countries in aggregate than prescribing non-ETS abatement targets of 10% and 0% respectively. However, a sensitivity analysis considers changes in both directions and implements emissions-reduction targets for the non-ETS sectors of 10% and 0% respectively. In each case, the emissions-reduction constraint for the ETS sectors is scaled endogenously in each Annex I region to achieve the overall Annex I emissions-reduction target of 20%.[11]

3.2. Carbon-tariff scenarios

The carbon-tariff scenarios are adopted on top of the emissions-trading ones. They follow common elements in the current proposals for carbon tariffs made in the EU and the USA (van Asselt and Brewer, 2010; Monjon and Quirion, 2010), but scaled up to all Annex I countries in line with the global scope of this study. In particular, carbon tariffs are imposed by Annex I countries on energy-intensive imports from non-Annex I countries. For each region, the tariff level is determined endogenously in proportion to the carbon content of imports and the price of carbon in the importing Annex I country's ETS sectors. The carbon content of imports is computed from all direct and electricity-related CO_2 emissions used for producing the imported good in the country of origin. This practice of calculating embodied emissions requires less information and is closer to practical implementation than using all direct and indirect emissions for calculating embodied emissions (see, e.g., Winchester, 2011).

Despite this, the carbon-tariff scenarios are idealized scenarios in political terms. In particular, the scenarios do not consider possible tariff exemptions for least-developed countries as included in several US proposals (van Asselt and Brewer, 2010) or export rebates for trade-exposed sectors as discussed for the EU ETS (Monjon and Quirion, 2010). They also abstract from some of the legal hurdles that may influence design details (Ismer and Neuhoff, 2007).[12] The sensitivity analysis chooses to preserve the policy design, but instead varies some of the key parameters governing its model impacts. Those pertain in particular to

[11] The ETS emissions-reduction targets differ by region due to different emissions distributions between ETS and non-ETS sectors across Annex I countries. They range from 28-32% for Russia, Australia, New Zealand, and the Rest of Annex I countries; over 35-36% for the USA and Japan; to 49% for Canada.

[12] Sensitivity analysis conducted within this Special Issue suggests that especially the former two omissions do not significantly affect the results, whereas the influence of different designs of carbon-tariff policies is the topic of a separate paper in this Special Issue.

the elasticities governing international trade responses and the fossil-fuel supply, as well as to the method for accounting for emissions embodied in trade, something which has a great effect on the tariff level and therefore the effectiveness of implementing carbon tariffs (see, e.g., Martins and Burniaux, 2000; Babiker and Rutherford, 2005; Burniaux et al., 2010).

3.3. Scenario trajectories

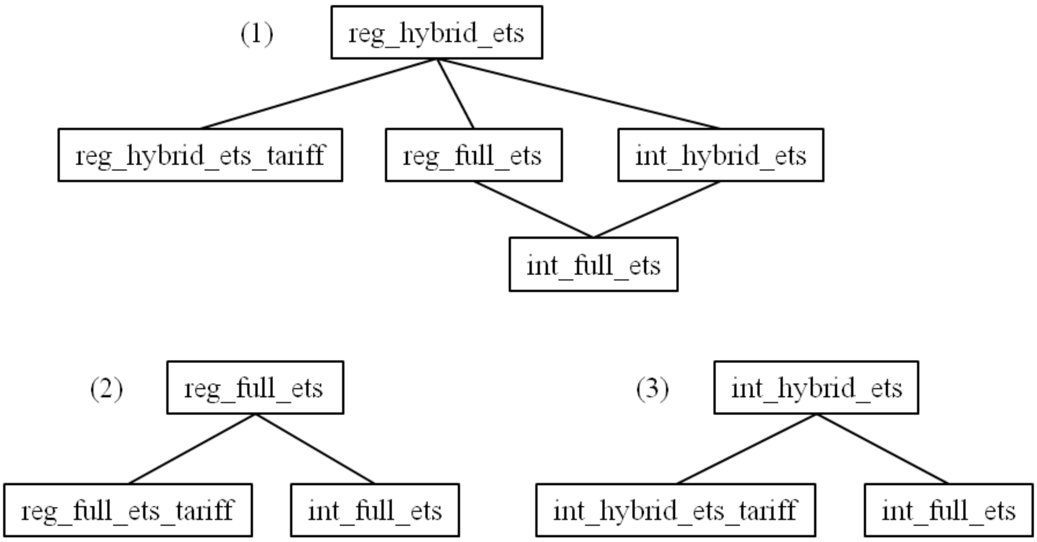

Figure 2. Policy trajectories defining the choice for Annex I countries between extending the coverage of emissions-trading schemes and implementing carbon tariffs on energy-intensive goods imported from non-Annex I countries.

Based on the four emissions-trading scenarios and their associated carbon-tariff scenarios, this study considers three policy trajectories to assess the trade-offs between implementing carbon tariffs and extending the sectoral and regional coverage of emissions-trading systems. The policy trajectories differ with respect to their reference ETS scenario and are illustrated in Figure 2. In each trajectory, Annex I countries can choose between implementing carbon tariffs on top of the reference ETS scenario or extending the sectoral and/or regional coverage of the reference ETS. For example, taking the regional-hybrid-ETS scenario as starting point, Annex I countries have the option to implement carbon tariffs (reg-hybrid-ets-tariff) or to extend the regional-hybrid ETS, either to a regional-full ETS and potentially further to an international-full one, or to an international-hybrid ETS and potentially further to an international-full one. Taking the regional-full ETS and the international-hybrid ETS as starting points again offers Annex I countries the choice between implementing carbon tariffs or regionally and sectorally extending their ETS.[13]

[13] Implementing carbon tariffs on top of a fully integrated international emissions-trading system is not an option considered here as there is no choice possible between implementing carbon tariffs and further extending the coverage of the emissions-trading system. This follows the rationale that the policy trajectories of

The policy trajectories illustrated in Figure 2 have different political interpretations. Trajectories (1) and (2) are especially relevant politically, because they start from indicative representations of those regionally differentiated emissions-trading systems in Annex I countries that are currently emerging and expected to be implemented within the next few years (EU Commission, 2009; Tuerk et al., 2009; Hood, 2010). On the other hand, trajectory (3) is of strategic interest as it indicates whether the decision of linking/extending emissions-trading systems with partial sectoral coverage could be abandoned for economic reasons in favor of implementing carbon tariffs after one linking step. However, the latter consideration is of more of academic interest, since it was argued in Section 1 and above that an ETS-extension strategy would likely preclude a carbon-tariff strategy on political grounds.

4. Results

This study assesses the impacts of extending the coverage of emissions-trading systems in Annex I countries compared to implementing carbon tariffs on energy-intensive imports from non-Annex I countries on several economic and environmental indicators. Those include global and regional welfare, GDP, carbon leakage, and the distribution of emissions burden between Annex I countries and non-Annex I countries. The reference scenario in each case is the 2004 business-as-usual scenario without climate policies implemented.

4.1. Welfare impacts

Changes in welfare are measured in terms of percentage change of Hicksian equivalent variation of income. Implementing carbon-pricing policies leads to reductions in consumption and welfare, since the benefits of emissions reductions are not included in the welfare metric. As global emissions are held constant across all policy scenarios (except for the business-as-usual scenario), the results can be interpreted in terms of a cost-effectiveness analysis in which the least negative carbon-pricing scenario can be considered the most cost-effective one in attaining the global emissions target.

Table 3 (left column) lists the central welfare results of this study. It indicates that extending the coverage of emissions-trading systems in Annex I countries can be more beneficial for Annex I countries than implementing carbon tariffs on energy-intensive imports from non-Annex I countries. In particular, fully extending emissions-trading systems in Annex I countries improves welfare in those countries by 0.01% to 0.07% more, depending on the reference scenario, than implementing carbon tariffs. However, partial extensions from a regional-hybrid ETS to a regional-full one (sectoral extension) or to an international-hybrid one (regional extension) yield lower welfare gains than implementing carbon tariffs.

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implementing carbon tariffs and of extending the sectoral and regional coverage of emissions-trading systems preclude one another politically, in particular due to the incompatibility of incentive structures (see Section 1).

There are also distinct differences between the different ETS expansion paths. In particular, a sectoral expansion of emissions-trading systems from a regional-hybrid ETS to a regional-full ETS is preferred by most Annex I countries over a regional expansion from a regional-hybrid ETS to an international-hybrid ETS. This order of ETS scenarios suggests that it is more beneficial for Annex I countries to first extend the sectoral coverage of their domestic ETS and then to extend the regional coverage as a second step.

Table 3. Changes in welfare and GDP in Annex I countries (A1), non-Annex I countries (nA1), and globally (ALL); welfare is measured in terms of percentage change of Hicksian equivalent variation of income.

Scenario trajectory	Δ EV (%)			Δ GDP (%)		
	ALL	A1	nA1	ALL	A1	nA1
reg_hybrid_ets	-0.53	-0.54	-0.46	-0.61	-0.53	-0.93
> carbon tariffs	-0.50	-0.42	-0.81	-0.57	-0.35	-1.46
> sectoral expansion	-0.48	-0.44	-0.65	-0.58	-0.41	-1.24
> regional expansion	-0.47	-0.47	-0.46	-0.56	-0.47	-0.92
> full expansion	-0.40	-0.35	-0.61	-0.50	-0.34	-1.14
reg_full_ets	-0.48	-0.44	-0.65	-0.58	-0.41	-1.24
> carbon tariffs	-0.46	-0.36	-0.92	-0.56	-0.28	-1.67
> regional expansion	-0.40	-0.35	-0.61	-0.50	-0.34	-1.14
int_hybrid_ets	-0.53	-0.54	-0.46	-0.61	-0.53	-0.93
> carbon tariffs	-0.44	-0.38	-0.75	-0.53	-0.32	-1.36
> sectoral expansion	-0.40	-0.35	-0.61	-0.50	-0.34	-1.14

Table 3 indicates that non-Annex I countries have a clear preference against carbon tariffs. Facing carbon tariffs on non-Annex I countries' energy-intensive exports leads to welfare losses that are 0.20-0.35% greater than those associated with changes in Annex I countries' emissions-trading systems. For example, implementing carbon tariffs on top of a regional-full ETS would reduce non-Annex I countries' welfare by 0.27%, while extending the ETS to an international-full one would result in a welfare gain of 0.04%. Although sectorally extending Annex I countries' emissions-trading systems can lead to welfare losses in non-Annex I countries, those losses are smaller compared to facing carbon tariffs being implemented in addition to the corresponding emissions-trading system. However, welfare in non-Annex I countries differs significantly across the different ETS scenarios. In particular, the hybrid-ETS scenarios are associated with 0.15-0.19% less negative welfare impacts than the corresponding full-ETS ones. In contrast to Annex I countries, most non-Annex I countries would therefore prefer Annex I countries to implement hybrid emissions-trading systems instead of economy-wide ones.

On the global level, extending the sectoral and regional coverage of emissions-trading systems in Annex I countries improves global welfare two to four times more than implementing carbon tariffs on energy-intensive goods imported from non-Annex I countries. Taking the regional-hybrid ETS as a starting point, Table 3 indicates that extending the sectoral and regional coverage of the ETS yields global welfare gains of 0.05% and 0.06% respectively and a two-step extension to an international-full ETS yields total welfare gains of 0.13%. This contrasts with global welfare gains of 0.03% from implementing carbon tariffs on top of regional-hybrid ETS. Taking the regional-full ETS and the international-hybrid ETS as starting points, welfare gains of 0.08% and 0.07%, respectively, can be achieved by one-step regional and sectoral extensions of Annex I countries' ETS, while implementing carbon tariffs would improve global welfare by 0.02% and 0.03% respectively.[14]

4.2. Impacts on GDP

In principle, changes in GDP can differ from changes in equivalent variation as GDP focuses solely on the production side of the economy. Table 3 (right column) lists the changes in GDP for the policy scenarios considered.[15] The changes in GDP broadly follow the changes in equivalent variation discussed above. Globally, the regional and sectoral extension of emissions-trading systems in Annex I countries yields greater increases in GDP than implementing carbon tariffs on energy-intensive goods imported from non-Annex I countries. Similarly, the implementation of carbon tariffs leads to greater GDP losses in non-Annex I countries than the GDP losses associated with changes in Annex I countries' emissions-trading systems.

However, in contrast to the changes in global welfare, Annex I countries increase their GDP more by implementing carbon tariffs than by extending the coverage of their emissions-trading systems. For example, implementing carbon tariffs on top of a regional-full ETS yields GDP increases of 0.13%, while regionally extending the ETS to an international-full one yields GDP increases of 0.07%. This indicates that overall production in the carbon-tariff scenarios is higher than in the corresponding ETS ones.

4.3. Effects on energy-intensive sectors

[14] Only when carbon tariffs are implemented on top of an international ETS with economy-wide coverage do they yield further global welfare gains (-0.39% compared to -0.40% in the international-full-ETS scenario) as all efficiency improvements from sectoral or regional expansion of emissions-trading systems in Annex I countries are realized already. However, this option is not discussed further, since it does not allow for a strict comparison between carbon tariffs and sectoral or regional extensions of coverage of emissions-trading systems along the policy trajectories described in the previous section.

[15] Prices are expressed in terms of a weighted global consumption price index expressed as an arithmetic mean: $P_{num} = \sum_r P(\mathrm{c},r)Y(c,r)\,vom(c,r)/\sum_s Y(c,s)vom(c,s)$, where $vom(c,r)$denotes base-year consumption, $Y(c,s)$ is the activity level of production, and $P(\mathrm{c},r)$ is the consumption price; r and s both denote the set of regions.

Underlying those changes in welfare and GDP levels are, among others, changes in output and prices, in particular of energy-intensive industries. The energy-intensive (EIT) sectors are affected differently in Annex I countries than in non-Annex I countries. The former is regulated within Annex I countries' emissions-trading systems, while the latter is subjected to carbon tariffs imposed by Annex I countries. However, each policy will, in general, affect both regions through spillover effects.

Table 4 lists changes in EIT output and exports for the different policy scenarios. The implementation of carbon-pricing policies in Annex I countries reduces EIT output in those countries by 1.8-2.3% and correspondingly their exports by 6.4-7.8% depending on the emissions-trading scenario implemented. As domestic EIT production decreases in Annex I countries, more EIT products are imported from non-Annex I countries. Table 4 indicates that EIT production in non-Annex I countries increases by 3.3-4.1% and EIT exports by 10-12%.

Table 4. Changes in energy-intensive production and exports in Annex I countries (A1), non-Annex I countries (nA1), and globally (ALL).

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Scenario trajectory	Δ Output (%)			Δ Exports (%)		
	ALL	A1	nA1	ALL	A1	nA1
reg_hybrid_ets	-0.04	-2.31	4.14	-0.98	-7.78	12.44
> carbon tariffs	-0.01	-0.23	0.41	-6.22	-5.75	-7.15
> sectoral expansion	-0.02	-1.96	3.55	-0.68	-6.44	10.68
> regional expansion	0.01	-2.00	3.73	-1.21	-7.36	10.94
> full expansion	0.02	-1.77	3.32	-1.01	-6.56	9.96
reg_full_ets	-0.02	-1.96	3.55	-0.68	-6.44	10.68
> carbon tariffs	0.00	-0.27	0.52	-4.94	-4.83	-5.16
> regional expansion	0.02	-1.77	3.32	-1.01	-6.56	9.96
int_hybrid_ets	0.01	-2.00	3.73	-1.21	-7.36	10.94
> carbon tariffs	0.03	-0.30	0.66	-5.39	-5.48	-5.22
> sectoral expansion	0.02	-1.77	3.32	-1.01	-6.56	9.96

The changes in EIT output between the different emissions-trading scenarios is in line with the changes in GDP and welfare discussed above. Annex I countries' EIT output is greater in the regional-full-ETS scenario than in the international-hybrid one, which supports Annex I countries' relative preference for the regional-full ETS. Complementarily, non-Annex I countries' EIT output and exports are greater in the international-hybrid-ETS scenario than in the regional-full one, which supports non-Annex I countries' relative preference for the international-hybrid ETS.

Implementing carbon tariffs on energy-intensive imports from non-Annex I countries has a significant trade-depressing effect in that sector. EIT exports from non-Annex I countries decreases by 16-20% and overall EIT exports by 4-5% depending on the underlying emissions-trading scenario. As a result, EIT production decreases by 3-4% in non-Annex I countries, but increases by about 2% in Annex I countries. The effects of implementing carbon tariffs on EIT output and exports dwarf those resulting from changes in the Annex I countries' emissions-trading systems by an order of magnitude and are the dominant channel for determining the welfare impacts of the policies considered on non-Annex I countries.

Although not shown in Table 4, prices for EIT goods increase by 0.2% following the implementation of carbon tariffs. This explains part of the divergence of impacts between welfare and GDP in Annex I countries (see previous section). In particular, the increases in EIT prices negatively affect consumer spending which leads to decreases in welfare despite higher EIT output when compared to the emissions-trading scenarios without carbon tariffs.[16]

4.4. Carbon-permit prices

Contributing to the changes in output and exports of energy-intensive goods, in particular in Annex I countries, are the marginal-abatement costs the energy-intensive sector is facing. Table 5 shows the carbon-permit prices which correspond to the marginal-abatement costs of the sectors included in the ETS, i.e. energy-intensive sectors, electricity-generation, and oil refining in the hybrid-ETS scenarios, and all sectors in the full-ETS ones. Extending the coverage of emissions-trading systems equalizes marginal-abatement costs across the sectors and regions included. This leads to gains from trade in emissions permits and to a more efficient burden sharing between sectors and regions. Consequently, carbon-permit prices decrease in most regions when emissions-trading systems are extended sectorally, from 22-120 USD/tCO_2 to 25-61 USD/tCO2 in the regional ETS and from 50 USD/tCO2 to 41 USD/tCO2 in the international ETS; and regionally, from 22-120 USD/tCO2 to 50 USD/tCO2 in the hybrid ETS and from 25-61 USD/tCO2 to 41 USD/tCO2 in the full ETS.

Comparing the carbon-permit prices resulting from regional and sectoral extensions suggests that a sectoral extension from a regional-hybrid ETS to a regional-full ETS is more cost-efficient (for the given parameter values) than a regional extension from a regional-hybrid ETS to an international-hybrid ETS. In particular, the carbon-permit prices in a regional-full ETS are lower in most regions than in an international-hybrid ETS. Behind this finding are large intersectoral differences in marginal-abatement costs. Sectors with low marginal-abatement costs, such as the production sector of All Other Goods (AOG), the transport sector (TRN), and final demand (C) bring down permit prices more than equalizing the relatively higher marginal-abatement costs in the ETS sectors across regions. This also helps explain the differences in EIT output between the emissions-trading scenarios discussed above. In the regional-full-ETS scenario, the EIT sector is less burdened than in the international-hybrid-ETS scenario due to larger gains from trade in emissions permits. Consequently, the regional-full-ETS scenario is preferred over the international-hybrid one by Annex I countries (and disfavored more by non-Annex I countries).

[16] Prices are expressed in terms of a weighted global consumption price index (see previous footnote).

Implementing carbon tariffs on energy-intensive imports from non-Annex I countries has little impact on carbon-permit prices in Annex I countries, which illustrates the gains from trade in emissions permits foregone compared to extending the sectoral and/or regional coverage of Annex I countries' emissions-trading systems.

Table 5. Carbon-permit prices (USD/tCO_2) in the emissions-trading sectors in Annex I countries; regional abbreviations are given in Table 1.

Scenario trajectory	Carbon-permit price (USD/tCO_2)						
	EUR	USA	JPN	ANZ	CAN	RUS	RA1
reg_hybrid_ets	73.4	46.0	79.3	21.9	118.1	33.4	51.0
reg_hybrid_ets_tariff	73.4	45.1	78.1	21.5	119.1	32.9	50.5
reg_full_ets	59.9	37.6	59.2	24.4	47.2	25.7	40.0
reg_full_ets_tariff	57.8	36.1	56.6	23.5	45.6	25.0	38.9
int_hybrid_ets	50.3	50.3	50.3	50.3	50.3	50.3	50.3
int_hybrid_ets_tariff	49.7	49.7	49.7	49.7	49.7	49.7	49.7
int_full_ets	40.9	40.9	40.9	40.9	40.9	40.9	40.9

4.5. Carbon leakage and distribution of emissions reductions

The small effect that carbon tariffs have on the carbon-permit price results from their modest effect on carbon leakage. Carbon leakage can undermine emissions-reduction efforts of Annex I countries by increasing emissions in non-Annex I countries (Felder and Rutherford, 1993). There are two major channels through which this can happen (see, e.g., Martins and Burniaux, 2000). For one, carbon pricing introduced in the coalition of emissions-abating countries raises production costs. This affects, in particular, the competitiveness of energy-intensive industries which may loose international market shares to industries in non-coalition countries. Emissions could increase in those non-coalition countries as a result of increased energy-intensive production. Second, unilateral emissions abatement in a large coalition of countries can depress the world prices for the most carbon-intensive fossil fuels through decreases in demand. This, in turn, could increase fossil-fuel demand non-coalition countries and thereby also increase emissions. Carbon tariffs predominantly affect the former competitiveness (non-energy) channel through shifts in energy-intensive production.

Table 6 indicates that implementing carbon tariffs on energy-intensive imports from non-Annex I countries has a modest effect on carbon leakage. It reduces carbon leakage by about 3% from 14-15% to 11-12% depending on the ETS scenario. The small effects that carbon tariffs have on leakage indicate that, for the given parameter constellation, most leakage results from changes in fossil-fuel prices.[17] Changes in Annex I countries' emissions-trading systems affect carbon leakage even less. Extending ETS coverage from a regional-hybrid ETS to an international-full one reduces leakage by about 1%; partial extension yield leakage reductions below 1%.

Table 6. Carbon leakage and change in emissions in Annex I countries (A1), non-Annex I countries (nA1), and globally (ALL).

Scenario	Carbon leakage (%)	Δ Emissions (%)		
		ALL	A1	nA1
reg_hybrid_ets	14.74	-11.16	-23.46	4.36
reg_full_ets	14.48	-11.16	-23.39	4.27
int_hybrid_ets	13.97	-11.16	-23.25	4.10
int_full_ets	13.59	-11.16	-23.14	3.97
reg_hybrid_ets_tariff	11.38	-11.16	-22.57	3.24
reg_full_ets_tariff	11.64	-11.16	-22.64	3.33
int_hybrid_ets_tariff	11.10	-11.16	-22.50	3.15

The magnitude of carbon leakage affects the distribution of emissions reductions between Annex I countries and non-Annex I ones. In particular, Annex I countries have to compensate carbon leakage by additional emissions reductions, because global emissions are held constant across the policy scenarios and non-Annex I countries face no direct emissions-reduction commitments. Table 6 indicates that the 14-15% of carbon leakage in the ETS scenarios would require Annex I countries to reduce their emissions by an additional 3%, i.e. 23% in total, to achieve the global reduction target. This value does not change much across the different ETS scenarios. Carbon tariffs reduce the additional reduction requirement in Annex I countries by less than 1%. Hence, neither extending the coverage of emissions-trading systems in Annex I countries, nor the implementation of carbon tariffs on energy-intensive imports from non-Annex I countries has a significant effect on the distribution of emissions-reduction burden under a fixed global carbon budget.

5. Sensitivity analysis

The results obtained above evidently hold for specific parameter values only. Specifically, the welfare effects of sectoral and regional expansions of Annex I emissions-trading systems are governed by differences in marginal-abatement costs, the magnitude of emissions-reduction

[17] This is underlined by a sensitivity analysis (described, in detail, in the overview article of this Special Issue) in which fossil-fuel prices are held constant, which effectively reduces leakage rates to a few percent in total. The sensitivity analysis in Section 5 assesses the effects of different parameter constellation which are relevant for leakage.

and, given a particular emission-reduction objective, by the emissions-reduction split between sectors covered by the ETS and those which are not. On the other hand, the welfare effects that result from implementing carbon tariffs are influenced, among others, by the tariff level and consequently by the way the carbon content of imports is assessed. Given a particular tariff level, the effectiveness of carbon tariffs further hinges on the assumptions governing trade and fossil-fuel supply responses. Important for either policy's effects are assumptions on the coalition size of emissions-abating countries, as well as on the temporal evolution of economic activity and emissions.

This section analyzes the robustness of the results with respect to changes in some of the key parameters and abstractions made in the main policy scenarios. First, it varies the emissions-reduction objective and the allocation between ETS and non-ETS sectors in the hybrid-ETS scenarios. Second, it considers different tariff bases for calculating carbon tariffs and changes in trade and fossil-fuel supply elasticities. Third, it analyzes recent changes in the composition of Annex I countries; and fourth, it employs a forward projection to analyze the policy impact in the years 2010 and 2020. To keep the analysis tractable, the sensitivity analysis focuses solely on the trade-off between implementing carbon tariffs and extending emissions-trading systems from the welfare perspective of policy-implementing Annex I countries.[18]

5.1. Effect of different ETS hybridization

The first sensitivity study assesses the impacts of laxer and more stringent regulation of the ETS sectors vis-à-vis non-ETS ones[19] and of changes in the overall emissions-reduction target. Both specifications are critical determinants of the effectiveness of extending the sectoral and regional coverage of emissions-trading systems. With regards to sector regulation, the sensitivity analysis changes the emissions-reduction burden of non-ETS sectors from 5% in the main scenarios to 10% (laxer regulation of ETS sectors) and 0% (more stringent regulation of ETS sectors) respectively. The emissions-reduction burden of the ETS sectors scales endogenously to achieve the (main scenario's) overall emissions reductions of 20% in each region. With regards to the overall emissions target, the analysis adopts overall targets of 10% and 30% respectively without changing the emissions-reduction allocation between ETS and non-ETS sectors.

Figure 3 illustrates the effects of those changes in parameter specification in terms of the relative Annex I welfare benefit associated with ETS extending compared to those accruing from implementing carbon tariffs. The figure focuses on the greatest changes from the main

[18] The directions of welfare effects for non-Annex I countries, as well as the global ones, are robust under the parameter changes considered below. The only exception occurs for a significant reduction in the coalition size of emissions-abating countries (to A1_s, see Section 5.3) which reverses the direction of global welfare benefits.
[19] The fear of suffering negative competitiveness effects could induce laxer regulation of ETS sectors at the expense of imposing tighter emissions constraints on non-ETS sectors. Also the opposite is possible when sectors not covered by an ETS are deemed to hard to regulate, e.g., due to difficulties of monitoring. In that case, the ETS would be the main mechanism to achieve a region's emissions reductions.

scenario which, in this analysis, occur along the policy trajectory (1).[20] The results indicate that both a too stringent (nETS_0%) and a too lax (nETS_10%) regulation of the ETS sectors yield greater relative benefits of pursuing a full or sectoral ETS extension to an international-full ETS and a regional-full ETS respectively. Especially the relative benefit of a sectoral ETS expansion constitutes a reversal of the main scenario's welfare ordering in which implementing carbon tariffs yield relative greater welfare gains. Underlying those increases in relative ETS benefits are absolute welfare losses associated with the too lax and too stringent regulation of the ETS sectors. As a result, implementing carbon tariffs on top of the regional-hybrid ETS of policy trajectory (1) is less welfare improving than expanding the hybrid ETS to a full one which covers all sectors and which is therefore not subject to those absolute welfare losses.

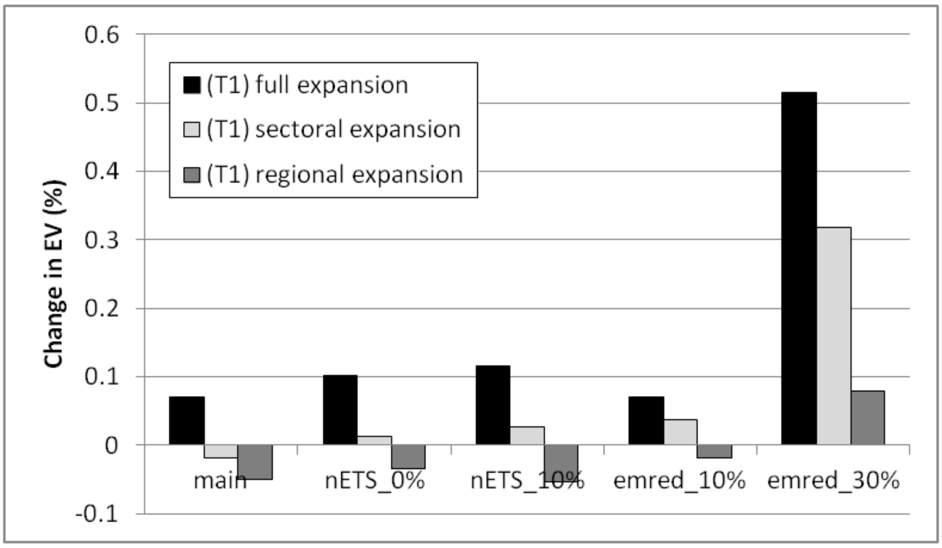

Figure 3. Annex I countries' welfare benefits resulting from the expansion of regional-hybrid emissions-trading systems along policy trajectory (1) (denoted as T1) relative to the welfare benefits resulting from implementing carbon tariffs. The scenarios consider changes from the main with respect to the split of emissions-reduction targets between ETS and non-ETS sectors and to the overall emissions-reduction target (details are given in the main text).

Similar results hold for less and more stringent overall emission reduction objectives (emred_10%, emred_30%). Compared to the main scenario, sectoral and full ETS extensions increase their relative welfare benefits over implementing carbon tariffs under each alternative emissions target. The relative benefits of ETS extension increase most in the more

[20] The results are unaffected if start and endpoints of policy trajectories do not include hybrid-ETS scenarios. In particular the relative welfare ordering of extending a regional-full ETS and implementing carbon tariffs in that scenario are preserved and therefore not shown in Figure 3. The positive relative welfare benefits of extending an international-hybrid ETS along policy trajectory (3) are preserved throughout the sensitivity scenarios and omitted in Figure 3 to keep the graphical analysis tractable.

stringent 30% emissions-reduction scenario due to higher absolute welfare costs which also enable higher efficiency gains from extending the scope of regional emissions-trading systems compared to the main scenario.

5.2. Effect of carbon-tariff base and elasticities

The second sensitivity analysis considers changes in the carbon-tariff level and in the elasticities governing trade and fossil-fuel supply responses. Both of those parameters are critical in determining the effectiveness of carbon tariffs (see, e.g., Martins and Burniaux, 2000; Babiker and Rutherford, 2005; and Section 4.5). In general, a higher tariff level will induce greater trade responses and leakage reductions which, through better terms of trade in energy-intensive goods, results in larger welfare gains for Annex I countries. Given a particular reference scenario, greater leakage rates and welfare losses result from higher trade-substitution (Armington) elasticities and lower fossil-fuel supply elasticities. Higher Armington elasticities increase the trade response to changes in prices and therefore accentuates the competitive disadvantages of energy-intensive industries which operate in carbon-pricing Annex I countries. Lower fossil-fuel supply elasticities decrease the responsiveness of the fossil-fuel supply to demand reductions in the emissions-abating Annex I countries, with non-Annex I countries absorbing the excess supply as a result.

The sensitivity analysis adopts parameter constellations that go into either direction of the main scenario's ones. Regarding changes in elasticities, the sensitivity analysis considers a doubling and halving of both the trade-subsitution (Armington) elasticities (e_Arm) and the oil supply elasticities (e_oil). Regarding the tariff level, the sensitivity analysis considers two alternative bases for carbon accounting which lead to lower and higher tariff rates respectively. In the first, tariff levels are calculated in proportion to the carbon intensity of domestic Annex I industries (CC_ele_d). In practice, this might ease the information and administrative burden of implementing carbon tariffs[21] and be less likely challenged under regulations of the World Trade Organization (WTO), since it does not discriminate imported goods vis-à-vis domestically produced ones (Monjon and Quirion, 2010). The second tariff scenario goes into the other direction and assesses the effect of a comprehensive accounting of all emissions embodied in imports (CC_full) which results in higher tariff levels.[22] The calculation of the total carbon content follows a recursive diagonalization algorithm described in Böhringer et al. (2011). As this scenario is associated with greater administrative and informational challenges of measuring emissions embodied in the global supply chain (see, e.g., Izard et al., 2010; Moore, 2011), a third scenario is considered in which the carbon content of imports is based on domestic emissions intensities (CC_full_d).

Figure 4 illustrates the effects of those changes for the relative Annex I welfare benefits of

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[21] Unlike many non-Annex I countries, Annex I countries have already put measurement, reporting and verification practices in place.

[22] For calculating the carbon content of imports and consequently the tariff level, this scenario of the sensitivity analysis accounts for all direct and indirect emissions used for producing the goods in the country of origin plus the transportation services needed for exporting them to Annex I countries.

full ETS extensions compared to those of carbon tariffs along the three policy trajectories (see Figure 2).[23] The results indicate that higher tariff levels increase Annex I countries' relative preference for implementing carbon tariffs over ETS extensions and vice versa. Under a full accounting of the carbon content of Annex I countries' imports (CC_full), it becomes more welfare improving to implement carbon tariffs in the policy trajectories (1) and (2) than to pursue ETS expansions. However, expanding Annex I countries' regional-hybrid ETS to international-full ones along trajectory (1) is still more welfare improving than implementing carbon tariffs on the reference scenario. The lower tariff rates associated with using domestic Annex I emissions intensities for calculating the carbon content of its imports result in a lower efficiency gains from carbon tariffs and, correspondingly, in greater relative benefits of pursuing ETS expansions. The latter double when the main scenario's accounting of the carbon content of imports is based on domestic emissions intensities (CC_ele_d) instead of those from the countries of production, and they increase by 30% and more if a full carbon accounting of domestic emissions intensities is used (CC_full_d).

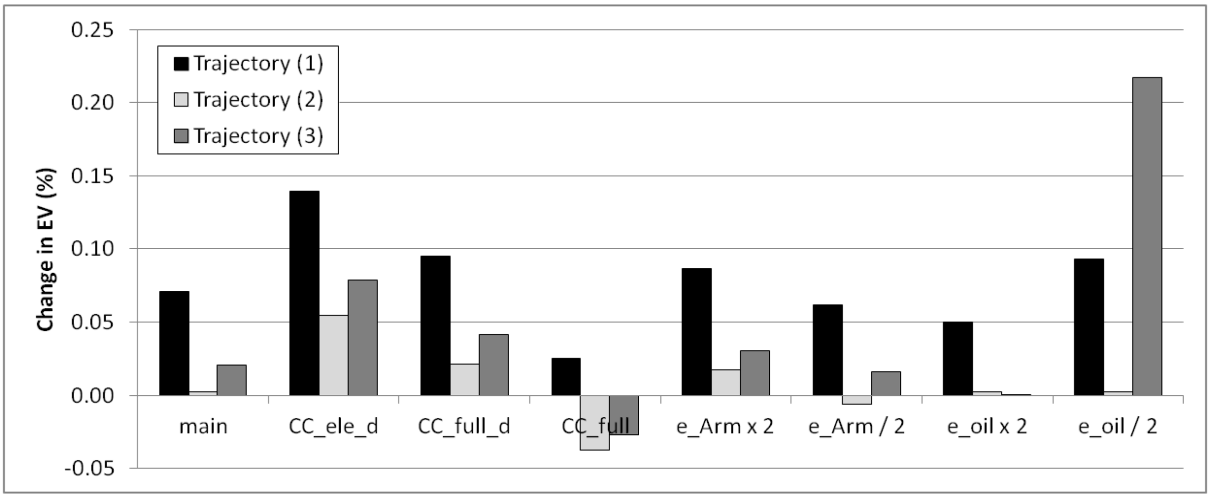

Figure 4. Annex I countries' welfare benefits resulting from the expansion of emissions-trading systems relative to the welfare benefits resulting from implementing carbon tariffs along the three policy trajectories defined in Figure 2. The scenarios consider changes from the main scenario with respect to calculating emissions embodied in imports and to the Armington and oil-supply elasticities.

Regarding changes in elasticities, Figure 4 indicates that leakage-increasing changes in elasticities (doubling of Armington elasticities, halving of oil-supply elasticities) are associated with increases in the relative welfare benefits of extending emissions-trading systems, while leakage-decreasing constellations (halving of Armington elasticities; doubling

[23] The preference for implementing carbon tariffs compared to one-step sectoral or regional extension in the regional-hybrid-ETS scenario (see Figure 3) are preserved under most parameter changes (except for calculating the carbon content of imports from domestic emissions intensities and for a halving of the oil-supply elasticities). They are not shown in Figure 4 to keep the graphical analysis tractable.

of oil-supply elasticities) increase the relative benefit of implementing carbon tariffs. However, the relative preference for extending ETS coverage along the three policy trajectories is largely preserved. The only partial exception occurs under a halving of Armington elasticities for trajectory (2) in which implementing carbon tariffs on top of the regional-full-ETS scenario is preferred over linking the regional ETS across Annex I countries.

5.3. Effect of coalition size

The third sensitivity study considers changes in the size of the coalition of emissions-abating countries. While all (mainly industrialized) countries listed in Annex I of the Kyoto Protocol have agreed to binding emissions-reduction targets, not all of those countries have yet implemented concrete action towards reducing emissions, nor indicated that they would do so. The USA has not ratified the Kyoto Protocol and Canada, Russia, and Japan have announced in 2010 that they would not take on further Kyoto targets. Canada has formally withdrawn from the Kyoto Protocol in 2011. In general, it can be expected that implementing carbon tariffs becomes relatively more attractive with decreasing coalition size. First, the revenue base from carbon tariffs increases as carbon tariffs can be levied on more imports from non-coalition countries; and second, a smaller coalition size means for coalition countries less potential for cost-efficiency improvements through regional ETS expansion.

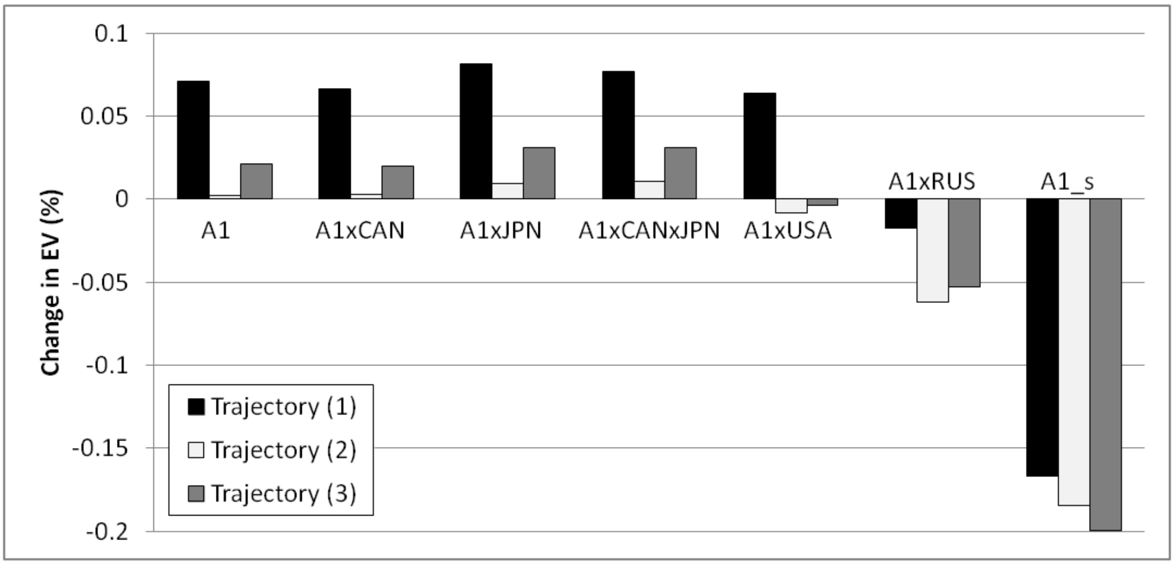

Figure 5. Annex I countries' welfare benefits resulting from the expansion of emissions-trading systems relative to the welfare benefits resulting from implementing carbon tariffs along the three policy trajectories defined in Figure 2. The scenarios consider changes in the coalition size of emissions-abating countries.

Figure 5 analyzes the numerical effects of the gradual withdrawal from the coalition of emissions-abating countries.[24] It indicates that a withdrawal of Canada and Japan, whether individually (A1xCAN, A1xJPN) or jointly (A1xCANxJPN), does not change the remaining coalition's welfare ordering along the three policy trajectories, i.e., full ETS extensions are preferred over implementing carbon tariffs. [FN: although sec ext and reg ext in pj 1 are not shown in the figure, they also do not change]. However, a withdrawal of the USA reverses the welfare ordering in policy trajectory (2) and (3), while a withdrawal from Russia and a joint withdrawal from USA, Russia, Japan, and Canada (A1_s) reverse the welfare ordering for all policy trajectories, i.e., the small coalitions that remain in those cases prefer implementing carbon tariffs over extending the scope of their emissions-trading systems.

5.4. Effect of target year

The last sensitivity analysis projects forward the target year of policy implementation from 2004 to 2010 and 2020 respectively to account for the changes in CO_2 emissions and marginal-abatement costs occurring through time. The forward calibration is based on data contained in the U.S. Department of Energy's International Energy Outlook (IEO) 2009.[25] It follows three steps (see, e.g., Böhringer and Vogt, 2003; Böhringer et al., 2009). First, labor and capital endowments (as well as government expenditure and investment) are scaled by region-specific GDP growth rates that are calculated from the IEO forecast for the years 2010 and 2020; resource supplies are scaled by projected increases in energy demand; and fossil-fuel prices are set to their projected 2010 and 2020 levels respectively. It is assumed that the price of natural gas follows that of crude oil and that coal prices remain constant. Second, fossil-fuel inputs are scaled by autonomous energy efficiency improvements (AEEI) to match the exogenous CO_2 emissions profiles of the IEO forecast.[26] Finally, the fossil-fuel supply functions are recalibrated to assure the consistency of responses to changes in energy prices with the resource value shares and substitution elasticities adapted to the projected baseline. Given the great uncertainties associated with economic projections, the forward calibration primarily serves illustrative purposes to provide ballpark guesses about potential economic pathways.[27]

[24] The relative welfare benefits of implementing carbon tariffs over one-step regional or sectoral expansions in policy trajectory (1) are preserved in all sensitivity analysis considered here (see Figure 3). They are not shown in Figure 5 to keep the graphical analysis tractable.

[25] The International Energy Outlook provides data on future GDP levels by region, CO_2 emissions and energy demand by region and sector, as well as crude-oil prices for several growth scenarios. The sensitivity analysis adopts the forecasts for the reference growth scenario for the years 2010 and 2020.

[26] The AEEI represent the change in energy intensity, i.e. the ratio of changes in energy consumption to GDP. The final AEEI values are adjusted iteratively to match the projected CO_2 emissions levels by sector and region.

[27] The allocation of emissions-reduction burden between ETS and non-ETS sectors is adjusted to preserve the close-to-optimal split of emissions-reduction burden in order to isolate the effects of the forward calibration from the effects of hybridization of emissions-trading scenarios. For that purpose, non-ETS sectors have been allocated their 2010 and 2020 business-as-usual emissions respectively (instead of being subjected to a 5% decrease in emissions as in 2004). The emissions constraint for the ETS sectors is adjusted endogenously to fulfil the global emissions constraint composed of a 20% emissions reduction in Annex I countries compared to their 2010 and 2020 business-as-usual emissions respectively.

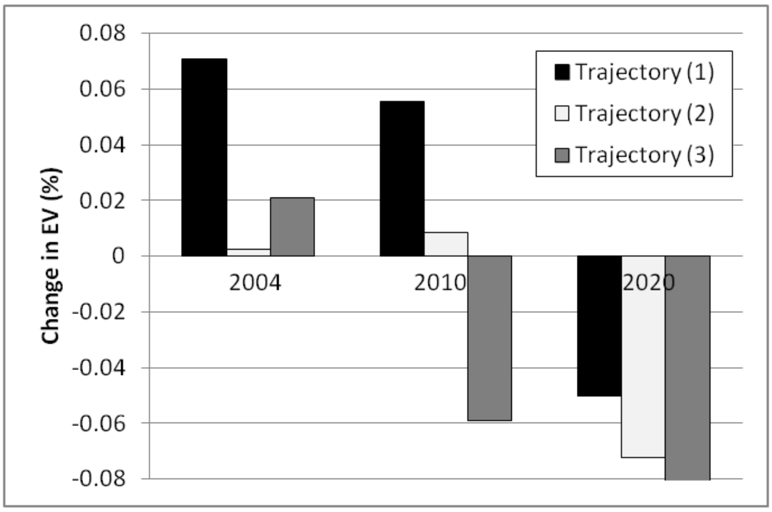

Figure 6. Annex I countries' welfare benefits resulting from the expansion of emissions-trading systems relative to the welfare benefits resulting from implementing carbon tariffs along the three policy trajectories defined in Figure 2. The scenarios consider changes in the target year of policy implementation.

Figure 6 displays the relative welfare benefits of ETS extension along the three policy trajectories for the years 2004, 2010, and 2020.[28] Implementing the policy trajectories in 2010 preserves the relative Annex I welfare preference for ETS extensions in the policy trajectories (1) and (2), but it reverses the preference in trajectory (3). In contrast, implementing the policy trajectories in 2020 reverses the welfare preference in all trajectories, i.e., implementing carbon tariffs is preferred in that target year above extending the coverage of Annex I emissions-trading systems. Underlying the reversal of preference for Annex I countries are projected increases in marginal-abatement costs. Those occur as cheap abatement options, such as intra-fuel substitution, are increasingly exhausted along the reference trajectory to 2020. Higher marginal-abatement costs reduce the relative efficiency improvements that can be achieved by extending emissions-trading systems and, at the same time, increase the potential revenue stream from implementing carbon tariffs as tariff levels are set in proportion to carbon-permit prices, i.e. to the marginal-abatement costs in the ETS sectors.

6. Conclusion

Subglobal climate policies will be the norm for some years to come. However, several options exist for improving the efficiency of domestic emissions regulation. A prominent but contentious policy option for improving the external efficiency is the implementation of

[28] The relative welfare benefits for Annex I countries of implementing carbon tariffs over one-step regional or sectoral ETS expansions in policy trajectory (1) (see Figure 3) are preserved in the sensitivity analysis considered here. They are not shown in Figure 6 to keep the graphical analysis tractable.

carbon tariffs on non-regulating regions. This is thought to reduce carbon leakage and increase domestic production, albeit at the cost of non-regulating countries. In contrast, internal efficiency improvements are inward looking and can be more collaborative in type. Among others, they include extending and linking of domestic emissions-trading systems. This study compares the relative economic impacts of those policy options.

This study's main results indicate that extending the sectoral and regional coverage of Annex I countries' emissions-trading systems could yield greater global welfare improvements than implementing carbon tariffs on energy-intensive goods imported from non-Annex I countries. While non-Annex I countries would be significantly better off without facing carbon tariffs on their exports, Annex I countries could gain from either policy.[29] For the latter, extending the coverage of emissions-trading systems generates welfare improvements primarily by equalizing marginal-abatement costs and the associated gains from trade in emissions permit, whereas implementing carbon tariffs on energy-intensive imports generates welfare improvements through increases in domestic production and terms-of-trade effects in that sector.

Under the main scenarios' parameter constellation, the welfare benefits for Annex I countries that result from extending the sectoral and regional coverage of their emissions-trading systems exceeds those that result from implementing carbon tariffs on energy-intensive goods imported from non-Annex I countries. This result holds strictly for extending Annex I countries' regional emissions-trading systems to international ones covering all sectors. For extensions to international ones with partial sectoral coverage the welfare benefits are comparable but exceeded by those following from implementing carbon tariffs.

The results are robust with respect to several changes in the key parameters governing the efficiency of extending emissions-trading systems and implementing carbon tariffs. In particular, the welfare ordering is preserved under changes in the overall emissions-reduction objective and the emissions-reduction allocation between sectors covered under the ETS and those which are not. While changes in some scenarios can occur, the results for a full ETS extension from regional emissions-trading systems with partial sectoral coverage to economy-wide international ETS are also robust with respect to changes in the elasticities governing trade substitution and fossil-fuel supply, as well as to changes in the tariff level associated with different methods to calculate the emissions embodied in non-Annex I countries' imports.

However, the welfare ordering for Annex I countries could reverse for changes in the year of policy implementation and the coalition size of emissions-abating countries. An indicative forward calibration to 2020 suggests that the welfare benefits for Annex I countries that result from implementing carbon tariffs could exceed those that result from extending the sectoral or regional coverage of their emissions-trading systems when implemented in 2020. The

[29] The directional effects of each policy are in line with findings from previous studies that have assessed each policy separately, but without considering their trade-offs (see Section 1).

prime reason for this reversal is the projected increase in marginal-abatement costs in the future which, on the one side, reduces the efficiency improvements that can be achieved by extending emissions-trading systems, and on the other side, increases the potential revenue stream from implementing carbon tariffs on non-regulating countries. Reducing the coalition size from all Annex I countries to the current nucleus of emissions-regulating countries results in a reversal of the original welfare ordering for similar reasons. Thus, early implementation and enlarging the coalition of emissions-regulating countries would increase the relative benefits of internal efficiency improvements through extensions of emissions-trading systems, while late implementation and a small coalition of climate-regulating countries would increase the relative benefits of external efficiency improvements through implementing carbon tariffs on imports from non-regulating countries.

Albeit tacitly, current negotiations within the UNFCCC clearly move towards the conditions for increasing the relative benefits of collaborative action and internal efficiency improvements. The Durban Platform established in 2011 at the 17th Conference of the Parties is tasked to develop a universal legal agreement on climate change and emissions-reduction commitments by 2015 which should be implemented by 2020. Such an agreement, together with the climate policies already emerging in developing countries, would make the policy of imposing carbon tariffs on exports from non-regulating countries obsolete. A more politically sustainable policy option compared to implementing carbon tariffs could therefore be to support the UNFCCC process by concentrating on internal efficiency improvements, such as those from extending and linking of domestic emissions-trading systems. The EU Commission's (2009) policy vision of a linked OECD carbon market within this decade clearly points in that direction. The results obtained in this study suggest that in addition to the political appeal, there exist also an economic rationale for pursuing internal efficiency improvements from extending and linking of emissions-trading systems over external ones from implementing carbon tariffs.

Notwithstanding, this study's analysis is far from complete and subject to several caveats. In particular, the computable-general-equilibrium model and the model scenarios devised for this study are highly indicative and abstract from many legal, political, and regulatory issues. For example, considerable efforts would be necessary to overcome current barriers to pursuing the extending and linking of emissions-trading systems. In particular, critical design elements, such as sectoral coverage and the inclusion of cost-containing measures would need to be harmonized (see, e.g., Tuerk et al., 2009). Although this study's sensitivity analysis indicates a certain robustness of general impact directions, additional and more detailed assessments that would include such political and regulatory externalities would be beneficial.

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Appendix

Elasticities of substitution and elasticities of supply

Table A.1 Elasticities of substitution and elasticities of supply.

	OIL	GAS	ELE	COL	CRU	EIT	TRN	AOG
esub	0.50	r	0.50	r	r	0.50	0.50	0.50
etaen	x	0.25	x	1.00	0.50	x	x	x
esubkl	1.26	0.65	0.50	0.20	0.20	1.26	1.68	1.27
esube	0.00	0.00	0.50	0.00	0.00	1.00	1.00	1.00
esubd	2.10	5.00	2.80	3.05	5.00	3.28	1.90	2.54
esubm	4.20	10.00	5.60	6.10	10.00	6.69	3.80	6.54

esub: top-level elasticity of substitution
etaen: elasticity of supply
esubkl: capital-labour elasticity
esube: elasticity of substitution between energy inputs
esubd: elasticity of substitution between domestic goods and imports
esubm: intra-import elasticity of substitution
r: region-specific, concrete value depends on resource rental share and etaen
Sources: GTAP database 7.1 (Narayanan and Walmsley, 2008) and Böhringer et al. (2011).