The Global Trade and Environmental Effects of Carbon Border Tariffs

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Abstract

The European Union just added a carbon border adjustment mechanism (CBAM) to its carbon emission trading system (EU ETS) to protect industries covered by the ETS from imports lacking equivalent carbon prices and mitigate carbon leakage. Other developed countries are also contemplating carbon border adjustments, and thus their impacts on global trade and economic growth become a critical concern for many countries. We develop a dynamic recursive global model with 10 world regions and 29 sectors to simulate the impacts of the EU CBAM on trade and output. We find that the EU ETS without a CBAM causes significant carbon leakage due to increased fuel consumption and energy-intensive manufacturing activities outside the EU. Adding CBAM tariffs only marginally reduces this leakage, from 59.4% to 54.6%, due to a shift to imports from cleaner regions. The carbon tariffs adversely affect China and India, as they reduce exports covered by the CBAM, while countries like the US and other countries with lower carbon intensities, experience minimal aggregate economic impacts. However, the CBAM hurts non-CBAM sectors within the EU, leading to a lower EU GDP.

JEL codes: C68, F18, Q48, Q56, Q58

Keywords: Carbon Price, Carbon Tariff, Carbon Leakage, Dynamic Global Economic model

Introduction

Carbon pricing policies are widely advocated as a cost-effective and flexible strategy to mitigate greenhouse gases (GHG) emissions. According to the World Bank Report on States and Trends of Carbon Pricing (2023)[1], there are currently 37 carbon tax initiatives and 36 emissions trading systems (ETS) globally, collectively accounting for 23% of global GHG emissions. Carbon price policies are predominantly concentrated in high-income European and North American nations where they often feature higher carbon tax rates or ETS prices. For instance, the current average global carbon price is only US$3 per ton, while the ETS in the European Union (EU ETS) reached an average price of USD 85 per ton in 2022.

In the absence of uniform carbon prices, two risks emerge: free-riding and carbon leakage[2]. Carbon leakage occurs when emitters relocate to places with less strict, or no, greenhouse gas regulations, or when those regions increase their fossil fuel consumption due to lower global fuel prices driven by reduction in demand in policy-compliant countries[3]. Additionally, a pressing political-economy challenge for governments adopting unilateral policies comes from complaints by domestic producers about unfair competition from imports from countries not subject to comparable regulations.

The European Union has the world's first Carbon Border Adjustment Mechanism (CBAM), with a transitional reporting-only phase that started on October 1, 2023, and carbon tariffs collected starting in January 2026[4]. It complements the current EU ETS, aiming to mitigate carbon leakage and preserve the competitiveness of domestic industries. Under the CBAM, importers must acquire carbon certificates based on the carbon content of the product, the price of which mirrors the market price of permits in the ETS. This raises the cost of exporting to the EU. The initial part of the plan targets high-carbon-intensity, high-leakage-risk products such as cement, iron and steel, electricity, aluminum, fertilizers, and hydrogen. The current CBAM policy only covers direct CO_2 emissions for steel, aluminum, and hydrogen, while requiring certificates for both direct and indirect emissions embodied in electricity use for cement, fertilizer, and electricity.

Looking ahead, there are discussions for the CBAM to expand its scope to include all sectors currently covered, or will be covered, by the EU ETS (for example, the EU has considered extending the CBAM to the entire chemical sector instead of just fertilizers by 2030, which is projected to cover only 50-60% of production-related emissions, leaving substantial upstream emissions unpriced; Minten et al., 2025[5]). In parallel, carbon tariffs may eventually cover embedded carbon emissions in more inputs, not just direct emissions and those indirectly embodied in electricity use. Concurrently, other developed countries, including the United States, Japan, and the United Kingdom, are actively exploring some form of carbon tariffs[6,7].

Against this backdrop of rapid policy diffusion and deepening regulatory ambition, research is converging on several interrelated topics – multilateral rule-making and strategic interactions, North-South coordination, the integration of climate justice considerations into global trade and climate governance frameworks, and the role of AI-driven innovations in carbon pricing and policy design[8].

The implementation of the EU CBAM will have significant impacts on the economy and environment, both within the EU and internationally. Domestically, the CBAM shields local industries from imports when free ETS permit allocations are gradually phased out, and it generates additional revenue. However, the mechanism's efficacy hinges on specific design choices, such as coverage of downstream products, the scope of emissions covered (embodied and upstream emissions), and whether export rebates are included. For the EU trade partners, the CBAM imposes tariff rates based on each exporter's carbon intensity and posing a disadvantage to countries with older, more carbon intensive technologies. Concerns also arise over the fairness and measurement of carbon intensity calculations, which may not be calculated based on actual country data and could result in unfair tariffs. With the shock from the EU carbon tariffs, as well as changes of the relative prices of energy-intensive products from different regions, the global ripple effects could fundamentally reshape global trade flows and value chains, and affect world GDP, employment and welfare.

Indeed, CBAM measures pose special challenges for developing countries. First, many middle-income and low-income countries which are significant exporters to the EU are not expected to have comparable carbon policies in the near-to-medium term that would exempt them from such tariffs. Second, these developing countries often exhibit higher carbon intensities due to less energy-saving production techniques or specific energy structures. Moreover, they tend to lack the financial resources not only to mitigate or adapt to climate change, but also to invest substantially in green energy and technological transformation like the EU and US. Consequently, these countries are poised to face dual pressures from rising carbon prices and ongoing disparities in carbon intensities. Despite the limited impact expected of the initial EU CBAM, once this mechanism is spread to more sectors or countries, it could pose significant challenges to global trade flows and economic development.

In light of these complexities and potential ripple effects on international trade and production, this paper aims to examine the distributional effects of the EU CBAM on exports and economic structure. To accomplish these objectives, we develop a dynamic global economic model (GEM), featuring 10 regions and 29 sectors, using the GTAP Data version 11[9]. We simulate the impacts on trade patterns, output, emissions and GDP. This research contributes to the existing literature by: 1) employing a dynamic model to explore both short-term and long-term effects, 2) providing a comprehensive assessment of the nexus between trade and carbon emissions, and 3) comparing the effects of different scopes of emission.

In this work, we find that a unilateral EU ETS without a CBAM will lead to lower EU CO_2 emissions but only a small reduction in global emissions, that is, there is a high leakage rate. The second conclusion is that the carbon tariffs provide only a modest protection for the EU producers; while there is a big reduction in imports from the high carbon intensity countries, these are offset by higher imports from the cleaner countries. The CBAM generates only a small reduction in leakage.

Results

We simulate the effects of the EU ETS and carbon border tariffs using a global economic model that encompasses 10 regions and 29 sectors (Supplementary Tables 1 and 2), based on the GTAP database version 11. In this classification, Russia, Canada and Other oil-exporters (XOI) are the major energy exporters. First, we model a hypothetical scenario (S.no-ETS) over the 2014-2040 period, where no carbon prices are imposed in any of the 10 regions throughout the simulation horizon beyond the taxes that exist in the base year. We calibrate changes in total factor productivity to hit GDP growth baselines in the S.no-ETS case. The growth rates of key variables are shown in Supplementary Table 4 and sources of imports into the EU in Supplementary Fig.2. China, USA, Annex I countries, and Russia are the largest exporters to the EU in 2026, with aggregate export values of 760, 467, 822, and 162 billion dollars, respectively. CBAM products account for only 9% of total exports of China and Russia to the EU, while this ratio for USA and ANNEX I countries is around 21%. For China, US, Annex I countries and Russia, the highest exports are electronic products, services, chemicals, and oil. This scenario serves as a dynamic baseline for comparison with a ETS policy (S.ETS) scenario, allowing us to highlight carbon leakage and competitiveness challenges under the EU's unilateral carbon policy. We then simulate an ETS with various CBAM policies (S.CBAM) to assess how these policies alter output and emissions across regions compared to the ETS-only case.

Effects of Unilateral Carbon Price Policy in EU (scenario S.ETS)

The ETS covers 7 sectors – paper, petroleum, chemicals, non-metallic products, ferrous metals, non-ferrous metals and electricity (Supplementary Table 5). These sectors are required to pay the emission permit price for each ton of CO_2 produced but are also allocated free permits to help them adjust to the higher costs which we represent as an output subsidy in our model. In the ETS-only scenario (S.ETS), we impose rising emission permit prices to reflect tightening emission caps on these 7 sectors (from \$3/ton in 2017 to \$120/ton in 2040, Supplementary Fig.1).

The impacts of the ETS on key variables in 2040, compared to the no-ETS case, are given in Fig. 1. EU GDP in 2040 is slightly lower by 0.19% while CO_2 emissions fall by 14%, compared to the S.no-ETS case. There is a fall in aggregate exports and consumption; aggregate EU imports fall by 1.0%. There are shifts in the composition of fuel use in the EU - coal (-39%), oil (-4.8%) and gas (-10%) - due in part to the structure of electricity production in the EU and the heavy use of gas in the ETS sectors.

CO_2 emissions fall in countries with the ETS but rise in some of the non-ETS regions and so global emissions do not fall by the amount that it falls in the EU; we compute a leakage rate to indicate the size of this offsetting rise. The global leakage rate is 47.6% in 2026 and rising to 59.4% in 2040 because of the rising carbon price and changes in GDP. India and China benefit from the unilateral carbon price policy of the EU from two sources; one due to the higher costs of energy-intensive products raising EU imports from India and China, and the second due to lower world energy price benefitting energy importers. Their GDP rise by more than 0.47% and 0.18% and exports rise by 1.7% and 0.69%, respectively, leading to increases of CO_2 emissions by 0.87% and 0.34%. Energy exporters, like Russia, Canada, and Other Oil exporters suffer because of lower fuel prices. The higher 2040 GDP in China and India contributes to the high leakage rate.

The EU ETS has a marked impact on output, exports, and imports across regions and sectors. The higher costs of production raise prices of the ETS sectors in the EU even after including output subsidies representing the limited free permits. This cuts demand and ETS sector output falls the most (Supplementary Table 5, Petroleum -5.5%, Chemicals -1.8%, Non-metallic minerals -1.8%, Ferrous metals -3.2%, Non-ferrous metals -4.2%). EU electricity output fall by a large 11% in 2040 since it does not receive free permits. The loss of competitiveness leads to an increase in imports of ETS goods into the EU by 0.3% to 4.6%, except for Petroleum Products, which fall slightly due to a reduction in overall demand. The carbon price reduces fuel demands and the output of coal falls by 15% and Gas Utilities by 7.1% (Supplementary Table 6).

The exports of ETS goods from India, USA, and China to the EU rise significantly (Supplementary Fig.5. (a)) while Canada, Russia and XOI see a small fall in exports in some goods despite an overall increase in their exports due to a depreciated exchange rate. These changes in exports and imports leads to corresponding changes in sector output, e.g., Chemicals in India (+2.8%), in China (-0.98%), in Canada (-0.20%) (Supplementary Table 5). Further details of the sector impacts are in the Supplementary Discussion.

The effects just discussed for 2040 reflect the cumulative impact of the ETS on investment prices and capital accumulation. The immediate impact is milder with a low carbon price. There are only small reductions in EU GDP and emissions in the first year, but the CO_2 impact rises to -14% by 2040 (Supplementary Fig.4). The reduction in global emissions, however, rises steadily for the first 9 years but then diminishes; this reflects the opposing changes in fuel use - a reduction in the EU due to the carbon price, but an increase in fuel use from higher exports to the EU.

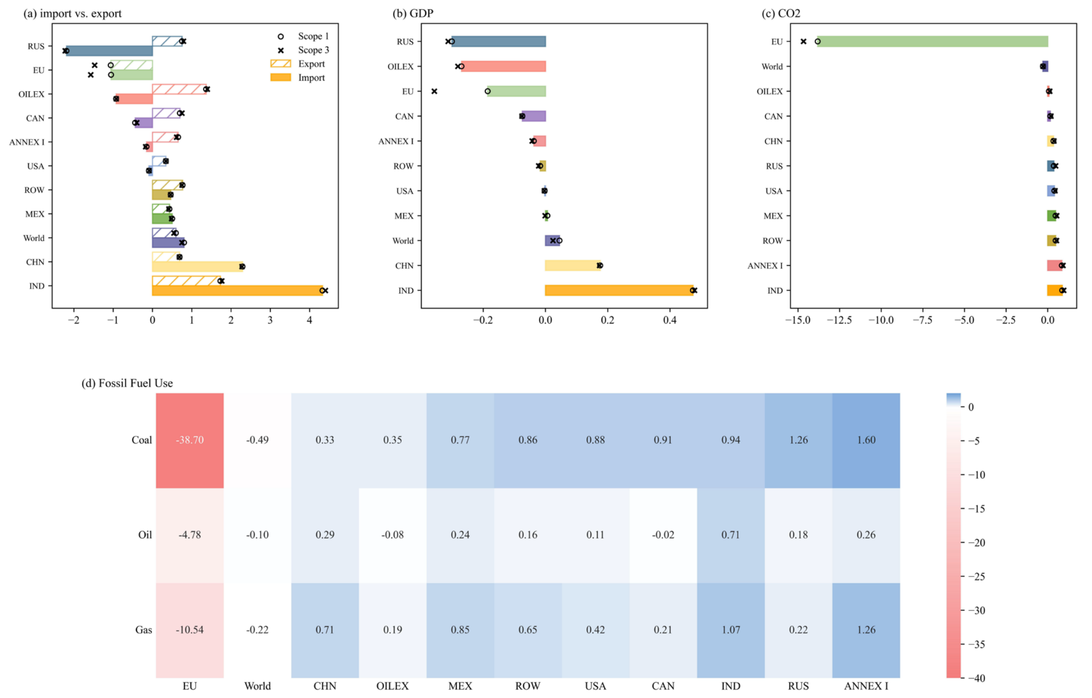

Fig. 1 | Economic and emissions impacts of the ETS-only scenario across regions in 2040 (unit: %). Changes in imports and exports (a), GDP (b), carbon emissions (c) under alternative carbon-accounting scopes, and fossil fuel use (coal, oil, and gas) across all regions in the CGE model. The bars in (a)-(c) are for Scope 2 policy and “x” and “o” marks are for Scopes 1 and 3.

Effects of Carbon Border Adjustments in EU (scenario S.CBAM)

We analyze how the CBAM changes the effects of the ETS by imposing border tariffs at rates that differ by exporting region depending on their sectoral carbon content (eq.4 in Methods). These tariffs are imposed in addition to the ETS rules. The current CBAM covers only 5 of the 7 sectors in the ETS, paper and petroleum products are not given carbon tariff protection. In this section, we discuss the results of the scope 2 scenario, S.CBAM2, where permits are required for direct emissions and those embodied in electricity. We compare this with scopes 1 (direct emissions only) and 3 (all embodied emissions) options later. The ETS does not provide free allocations of permits to electricity producers, and free allowances for other ETS sectors are gradually phased out to zero by 2036, meanwhile CBAM fees are phased in at the same rate.

Fig. 2 shows the effects on the main variables in 2040 compared to the ETS-only case. There is a trivial additional fall in GDP in the EU, -0.017% after CBAM on top of the -0.19% change in the S.ETS case. Furthermore, the introduction of CBAM, combined with the phasing out of free allowances by 2036, results in a transient increase followed by a decrease in EU GDP (Supplementary Fig.4(b)). This pattern is due to two effects; one is the negative impact of carbon prices on domestic production and the other is the change in international trade from the tariffs. The CBAM has very limited effects on the aggregate economy of other regions; the GDP of India changes by -0.011%, China by -0.007%, Oil exporters by -0.015%, and Rest-of-Annex1 by -0.002%. The aggregate exports of India and China change by -0.18% and -0.07%, respectively.

With protection from imports, ETS sector outputs are higher, leading to a 0.33% increase in CO_2 emissions within the EU, compared to the initial 13.8% reduction under the ETS alone. There is a tiny 0.03% reduction in global CO_2, primarily driven by decreases in Russia, India, and other Annex I countries while other regions see a small rise. Consequently, the reduction in leakage rates is small, from 59.4% under the ETS to 54.5% with the CBAM.

The imports of most of the ETS goods in the EU are lower with the CBAM tariff protection – Chemicals -5.5%, Non-metallic minerals -13%, Ferrous metals -18%, Non-ferrous metals -7.4% (Supplementary Table 7). This leads to a higher level of domestic output for these sectors, e.g., Ferrous metals output is 1.3% higher after falling 3.2% due to the ETS; Non-metallic minerals are 0.64% higher after falling 1.8%; Electricity output, which does not get free allocations, is only 0.86% higher after falling by 11%. However, the protective effects of the border carbon adjustments are not uniform across sectors due to the different tariff rates and elasticities of substitution. Paper is not protected by carbon tariffs and imports into the EU rises, but exports fall by more, resulting in EU output falling another 0.11%, after falling by 1.1% due to the ETS. The outputs of the other ETS sectors in the EU are higher than in the ETS-only case, Chemicals by 0.51% and Petroleum by 0.06%. Supplementary Table 7 also shows large reductions in 2040 CBAM goods exports from India, Russia, and China compared to their increase under the ETS-only scenario given their high carbon intensities. Although the CBAM has only modest effects on the total exports of the CBAM sectors in all non-EU countries, it has a large effect on CBAM exports to the EU. For example, there are large reductions, more than 30%, in the exports of these four goods from India to the EU (Supplementary Fig.5. (b)), and a reduction of about 10% from Russia, China and Oil-exporters. There are small offsets by higher exports from low-carbon intensity regions - Canada, US and Rest-of-Annex1 countries.

Using a general equilibrium model allows us to capture the economy-wide effects across all sectors and understand the broader economic effects after the implementation of a policy targeting only the carbon-intensive industries. In the EU, output in non-CBAM sectors and some services declines by up to 0.96% relative to the ETS-only scenario (Supplementary Table 8), as resources are shifted to the protected CBAM sectors; the carbon tariffs further raise prices of inputs and exacerbating the negative impact on aggregate GDP. For countries exporting to the EU, the reduction in output of CBAM sectors is small and the impact on the non-CBAM sectors, positive or negative, is small. For instance, in China, the output and exports of most non-CBAM goods, such as Machinery and Electronic products, increase, partially offsetting the decline in ETS sector exports (Supplementary Table 8).

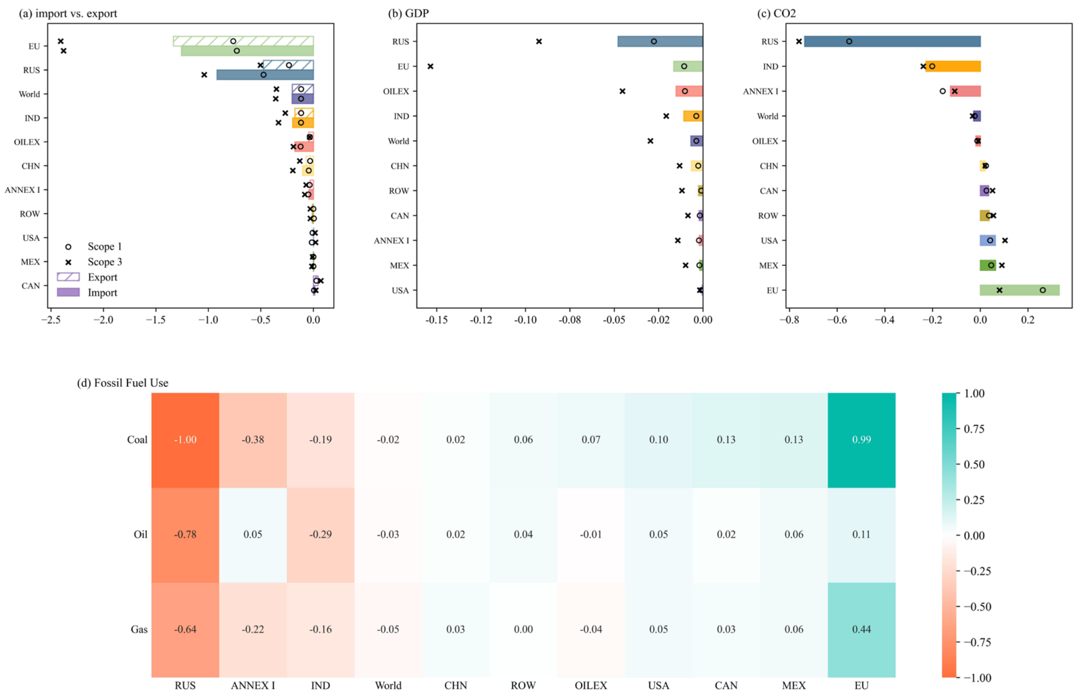

Fig. 2 | Economic and emissions impacts of the CBAM+ETS scenario across regions in 2040 (unit: %). Changes in imports and exports (a), GDP (b), carbon emissions (c) under alternative carbon-accounting scopes, and fossil fuel use (coal, oil, and gas) across all regions in the CGE model, relative to the ETS-only scenario. The bars in (a)-(c) are for Scope 2 policy and "x" and "o" marks are for Scopes 1 and 3.

CBAM effects under different scopes of emission coverage

We consider three scopes of calculating sector emissions to illustrate how implementation rules affect the impacts – scope 1 covers direct emissions, scope 2 covers direct and indirect emissions from electricity, and scope 3 includes emissions embedded in all intermediate inputs. First, we calculate three carbon intensities (total emissions per unit output) in region *s* according to the three scopes of coverage. These intensities are then used to calculate the carbon tariff rates (eq.4), assuming a long-run \$100/ton CO_2 price, and these vary significantly across commodities and regions, as shown in Supplementary Fig. 3. Developing countries face notably higher tariff rates than developed regions (per billion \$ of imports). Across products, nonmetallic mineral products and ferrous metals have higher intensities and face higher tariff rates than the other products. The scope of covered emissions changes the rates significantly, particularly for ferrous and non-ferrous metals. This variation in carbon intensity reflects the diverse manufacturing processes and electric power structures. Developing regions often employ extended steel processes which uses more energy. In contrast, developed regions use more energy efficient techniques like electric arc furnaces that require fewer intermediate steps.

Aluminum production hinges on electricity, with high embodied (scope 2) emissions - China's aluminum products see carbon tariff rates of 1%, 10%, and 18% under the 3 scopes.

In the scope 1 case the CBAM only covers direct emissions while the ETS covers electricity emissions, and thus the competitiveness protection is reduced. In the scope 2 case, the CBAM and ETS coverage is the same for domestic goods and imports. To implement scope 3, we run a different S.ETS3 case so that we are comparing CBAM3 to ETS3 with the same coverage. The scope 1 results are thus asymmetrical. Fig. 2 shows the effects of the CBAM, compared to the ETS-only case, under the three scopes of coverage. Across various metrics, the impact is consistently smaller under narrower scopes, though the extent of this reduction varies. Aggregate imports of EU fall 1.3% under scope 2 but fall only 0.73% under scope 1 and 2.4% under scope 3. The exports from the carbon-intensive countries fall under the CBAM, but the reduction under scope 1 is much smaller while the change under scope 3 is large, e.g. the total exports (not just to the EU) of India change by -0.12%, -0.18% and -0.27% under the respective scopes. In parallel, the rise in exports from the low intensity countries increase with the scopes, e.g., the exports from Canada change by 0.03%, 0.04%, 0.07% respectively.

While there is a big reduction in imports into the EU under scope 3, there is also a correspondingly large reduction in exports from the EU, leading to bigger GDP losses. EU GDP fall by 0.009%, 0.016% and 0.15% under the 3 respective scopes. As a result of these changes in imports and GDP there are non-linear changes in CO_2 emissions. EU CO_2 emissions rise under the CBAM protection, but they change by 0.26%, 0.33% and 0.08% under the three scopes. The higher CBAM sector emissions in the EU under bigger scopes are offset by lower GDP effects leading to smaller total CO2 changes. The changes in global CO_2 are minor, -0.023%, -0.028% and -0.032% under the three scopes. Leakage rates remain high under all scopes, with scope 3 slightly worsening the situation (Fig. 3). By 2040, scope 1 reduces leakage to 55.4%, compared to 54.5% in scope 2, while scope 3 marginally improves leakage to 57.5%. Recall that CBAM scope 1 effects are asymmetrical since it is being compared to the actual ETS2 which is scope 2, while CBAM3 is compared to ETS3. Broader coverage under scope 3 results in a slight improvement in leakage rates to 62.0% under ETS-only scenario, but overall, the leakage reduction effect of CBAM remains limited. The changes at the sector level are very different given the differences in carbon intensity and tariff rates (Fig. 3, Supplementary Table 9 and Fig.7).

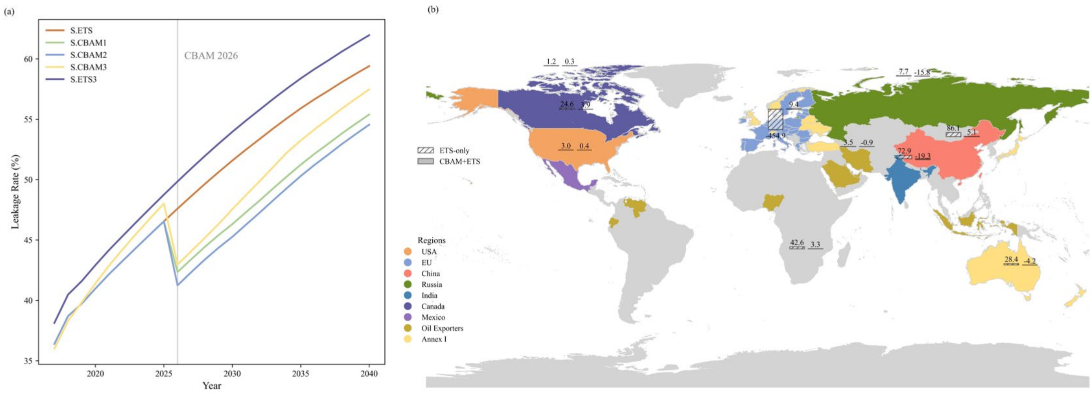

Fig. 3 | Carbon leakage dynamics and emission redistribution under alternative policy scenarios. (a) Simulated carbon leakage rates under the ETS-only scenario and CBAM scenarios with different accounting scopes over 2017-2040; the CBAM policy is introduced in 2026. (b) Carbon emissions (100 million tonnes) under the ETS-only scenario in the first number on the map, and changes in emissions following the introduction of CBAM in the second number.

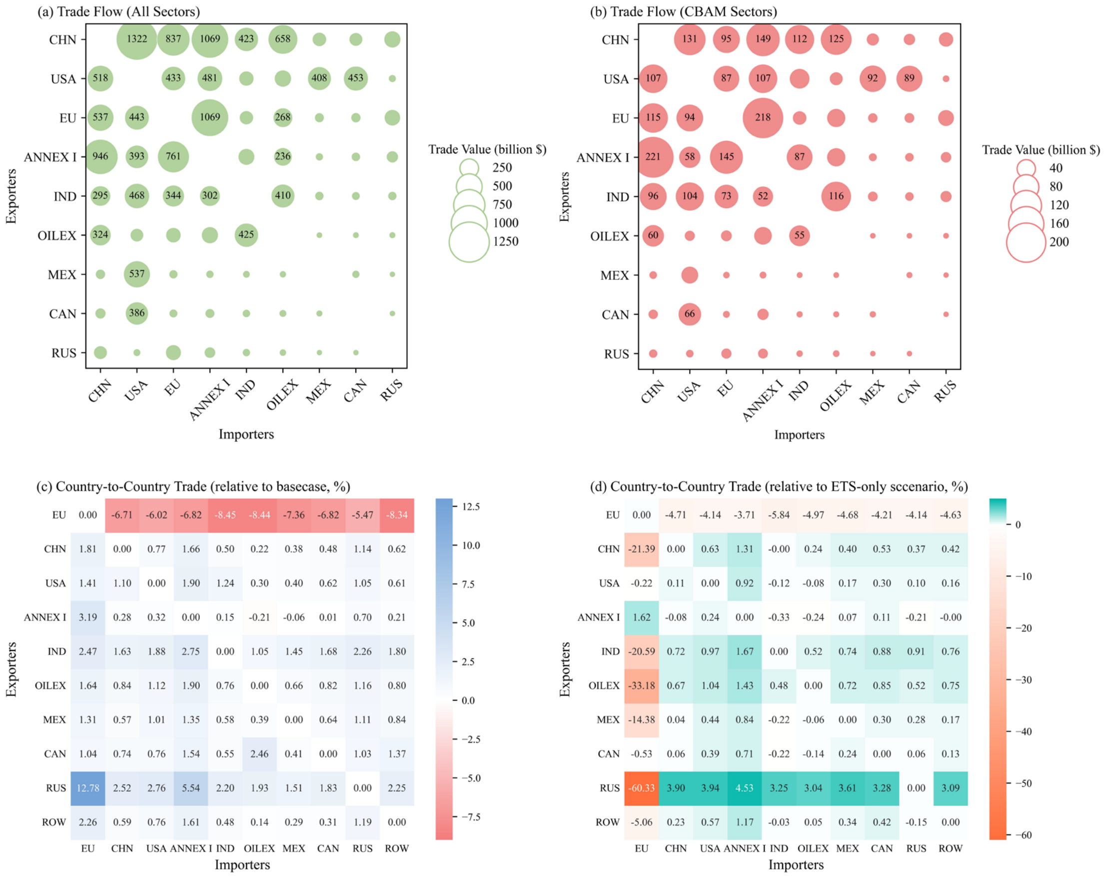

Fig. 4 | Trade effects under alternative policy scenarios. Changes in trade flows across all sectors (a) and in CBAM-affected sectors only (b), and changes in bilateral trade (imports and exports) among the ten CGE regions under the ETS-only scenario relative to the baseline (c) and under the CBAM-ETS scenario relative to the ETS-only scenario (d).

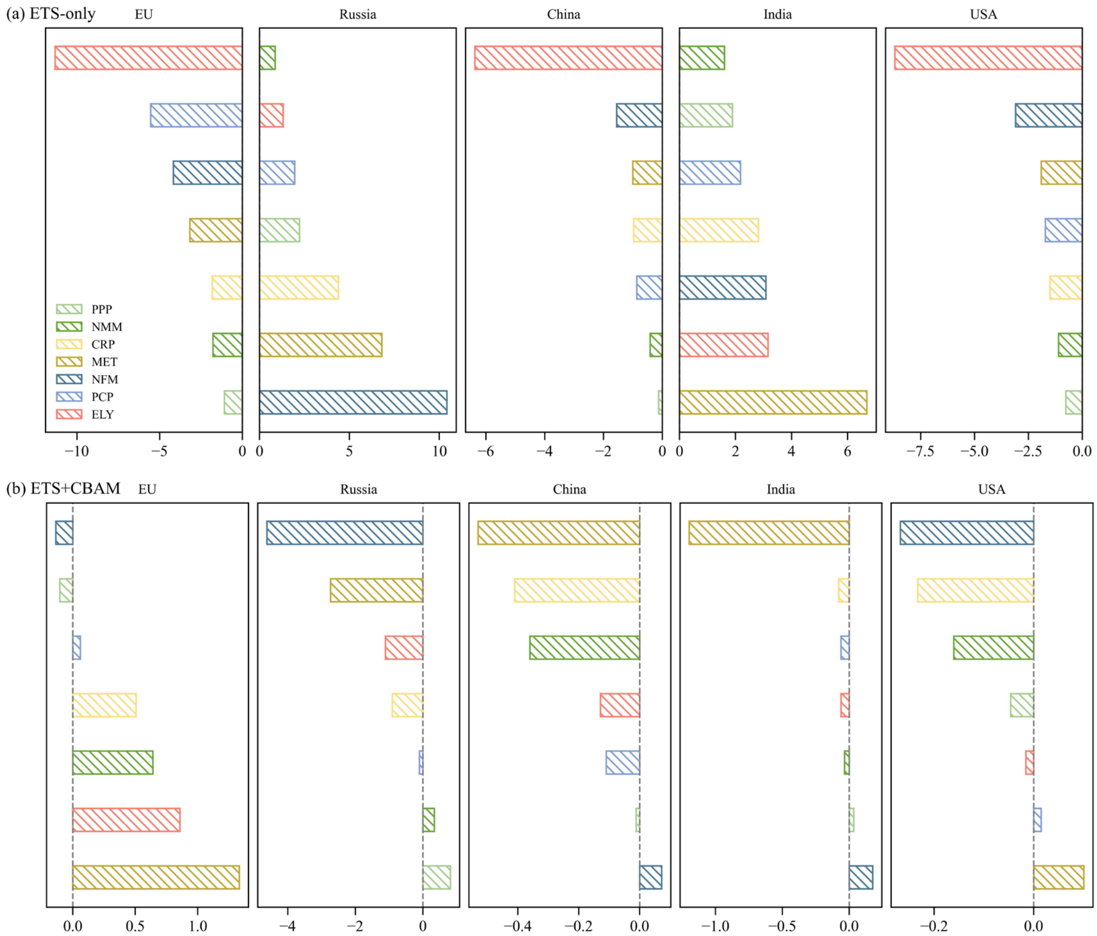

Fig. 5 | Sectoral output effects under alternative policy scenarios. Changes in output for key CBAM-covered sectors under the ETS-only scenario (a) and the ETS+CBAM scenario (b).

Discussion

Our first main conclusion from simulating the EU-ETS and carbon tariffs is that a unilateral ETS without a CBAM will lead to lower EU CO_2 emissions but only a small reduction in global emissions, that is, there is a high leakage rate. The second conclusion is that the carbon tariffs provide only a modest protection for the EU producers; while there is a big reduction in imports from the high carbon intensity countries, these are offset by higher imports from the cleaner countries. The CBAM generates only a small reduction in leakage. Another result that we find in common with previous work is that oil importers benefit noticeably from the EU carbon price while oil exporters suffer losses in GDP.

Estimates in the literature of the leakage from unilateral carbon policy vary quite widely given the different assumptions about the many aspects of modeling choice – substitution elasticities, market structure, mining supply elasticities, factor mobility, etc. Partial equilibrium studies of specific industries tend to estimate high leakage rates, e.g., steel[10] and cement[11] sectors have 50-70% rates. Studies using CGE models report a big range of leakage rates, the earlier paper by Felder and Rutherford[2] estimate 40%, Babiker[12] shows how market structure assumptions may generate a 50-130% range of rates, and Bellora and Fontagné[13] simulation of the EU system reports 76%, while Bohringer et al.,[14] summary of 12 models report a lower range of 5-19%. The important aspect here is the change in the leakage rate due to adding a CBAM to the unilateral carbon price. Studies have shown that implementing a CBAM reduces carbon leakage rates by 2 to 15 percentage points[15-18], depending on the carbon price, scope of coverage, and specific CBAM policy applied. Our estimate of leakage from the ETS-only scenario is in the high end (60%), and we estimate that the CBAM reduces it by only 4.9 percentage points. This small reduction is due in part to the application of lower tariff rates to cleaner sources. A detailed comparison of the modeling choices would be needed to trace the reasons for the wide range of estimates.

There are debates about the coverage of emissions in CBAMs: should it just include direct emissions from fossil fuels used, or include indirect emissions due to electricity and other intermediate inputs at the cost of higher complexity in policy administration. We estimate that if the ETS and border tariffs are extended to include CO_2 embodied in all intermediate inputs (scope 3), the covered sectors in the EU experience very different effects, some enjoy higher protection while others suffer lower output. On net EU emissions and global emissions are higher under scope 3 rules, with very minor differences in GDP.

There are two limitations in our current analysis. First are the common caveats of CGE methods. Analyses based on data from GTAP or other multi-regional databases do not have very detailed sectors. The industry classifications within these databases do not precisely align with the categories in the EU CBAM, e.g. aluminum, and we rely on broader categories like non-ferrous metals. The trade flows in these detailed commodities may be very different from the broader basket, and this should be kept in mind when assessing the sector results. It is important to construct more disaggregated models in future work.

It is also well-known that the simulated policy responses using CGE models depend on the model structure and elasticities of the production and consumption functions. We conducted sensitivity analyses, in the Supplementary Discussion 3.2.1 and Supplementary Table 12, we report how the estimated change in GDP and emissions depend on the elasticities for substitution between domestic and imported goods, between different regional sources of imports, and between different energy inputs. These key parameters affect the estimated size of policy impacts to a noticeable degree. However, the direction of the change in emissions in the EU and global total emissions is not reversed (no changes in the signs of the effect). The sign of the change in emissions in only 1 region is reversed by the different elasticities (Rest of Annex I). The change in GDP due to the CBAM is very small for all regions, and the sign of the change is sensitive to the parameter values, however, the effect on global GDP is not reversed. The change in leakage rates is also not reversed by the different elasticities tested.

The second limitation of the study is the lack of usable estimates of carbon prices in the non-EU regions. The EU CBAM allows the cost of CO_2 emissions paid by exporters to be deducted from the calculation of carbon tariffs. World Bank reports 68 carbon pricing initiatives implemented as of 2022[1] and it is a huge challenge to connect these policies to carbon prices for CBAM purposes due to differences in sector coverage, subnational policies, and offsetting subsidies. To give a sense of how carbon prices in non-EU regions change the impacts estimated here we ran a scenario with a simple representation of such prices in 5 regions (S.ROW). This alternative assumes a carbon price in the US, Canada and Annex I countries equal to 50% of the EU price, and 20% for China and Mexico. The results reported in the Supplementary Discussion 3.2.2 and Fig.1 show a small negative GDP effect for the 5 regions, consistent with the standard effects of adding commodity taxes. There is a corresponding shift to imports from the 5 regions enjoying lower tariffs in this case. There is a much smaller leakage rate when more countries in the world have carbon prices.

In addition to the complexity of actual carbon prices, some countries argue that implicit carbon costs, due to CO_2 emission standards or renewable standards, should also be counted. Estimating effective carbon prices in exporting countries is a major challenge not just for researchers but also for the EU authorities. Calculating them is an important priority for future work, for now, we merely note that the main results are the upper bound since the scenarios ignore carbon prices in non-EU countries. The alternative scenarios show how illustrative carbon prices change the sources of imports into the EU under the CBAM.

Our simulations indicate that the effects on different regions are not equal: developing countries like India, Russia, China and rest of world with higher carbon intensities will be charged with higher border taxes and suffer larger reductions in exports to the EU, while the effects on aggregate GDP of developed countries and regions are smaller and even positive for some of the rest of Annex I countries. If the EU acts unilaterally to implement uniform carbon pricing for countries with different levels of development, then some might argue that it contradicts the principle of "common but differentiated responsibilities." This has led some papers to propose parallel compensatory policies, for example, recycling the tariff revenues to the poorer countries[19] or exempting least developed countries[20]. Analyzing these compensation schemes would be a subject of future work.

At the same time, the policy environment surrounding CBAM is evolving rapidly. Less than two weeks before the definitive phase of CBAM takes effect on 1 January 2026, the European Commission released a comprehensive legislative package on 17 December 2025, clarifying the legal, technical, and procedural framework for CBAM implementation[21]. Of particular relevance for future economic assessments is the proposal to extend CBAM's scope to a broad range of steel- and aluminum-intensive downstream products from 2028 onward, covering around 180 additional tariff lines and potentially bringing approximately 7,500 new importers into the compliance regime[22]. Together with strengthened anti-circumvention measures, aimed at preventing strategic misreporting of embedded emissions and artificial supply-chain restructuring, and the introduction of a Temporary Decarbonization Fund (TDF) to support energy-intensive industries at risk of carbon leakage, these revisions signal a transition of CBAM from a relatively narrow border instrument to a more comprehensive and administratively sophisticated climate policy tool[23]. These late-2025 developments highlight that CBAM is best understood as a dynamic and evolving policy framework rather than a static trade instrument. Future research should move beyond stylized CGE settings to incorporate the increasing regulatory granularity of CBAM as well as its interaction with revenue recycling and newly introduced support mechanisms.

Methods

Dynamic model of the world economy

To model how the EU CBAM policies affect world output, trade, emissions, and consumption, we construct a dynamic multi-region, multi-sector CGE model. The inter-industry general equilibrium approach allows us to describe the comprehensive economy-wide impacts of these carbon policies on the major economies and all industries, including those not covered by the carbon price. The incorporation of capital accumulation allows us to track the impact of these policies on economic growth spanning the time frame to 2040. The model has a dynamic recursive structure, i.e., an exogenous investment rate assumption. Details are given in a Supplementary Model (SM) available online, we summarize the main features here.

There are 10 countries/regions, including Canada, China, the European Union, India, Mexico, the Russian Federation (RUS), United States (US), other oil exporters (XOI), rest of Annex I countries, and rest of world (XRW). 29 industries are identified and listed in Supplementary Table 2. The model follows neoclassical competitive assumptions. Production is represented by constant elasticity of substitution (CES) functions where an energy-value-added bundle substitutes against a non-energy intermediate bundle. Energy is an aggregate of coal, oil, gas mining, petroleum products, electricity, and gas utilities. For trade flows, total imports of a commodity in each region are an aggregate over the supply from all other regions, and imports are imperfect substitutes for domestically produced commodities. Economic growth is driven by population growth, capital accumulation, and total factor productivity growth.

Households receive wages, returns to capital, and government transfers. Income is allocated to consumption and savings according to an Extended Linear Expenditure System. The utility function includes leisure and generates an endogenous labor supply in the developed regions of the world. In the other regions we specify exogenous labor supply. A tax cut from recycling carbon revenues will lead to higher consumption and savings. Investment demand is driven by household savings and retained earnings. Government revenues are collected from tariffs, indirect taxes, and direct taxes on labor and capital income, and expenditures include purchases of products, subsidies, and transfer payments.

For each period, given an inherited stock of capital and resources, the general equilibrium model solves for a set of prices that clears all goods and factor markets. The closure rules for the macro balances are as follows: (1) Aggregate investment is set as a fixed proportion of GDP, and household savings adjust endogenously; (2) Government deficits and tax rates are exogenous, with endogenous government purchases in the no-ETS case; (3) The exogenous current account balance is achieved through an endogenous exchange rate. The GDP deflator for each region is set to 1 and sector quantities reported are in constant 2014 U.S. dollars. Real GDP over time, and across policies, is computed as a Laspeyres index over commodity prices in the no-ETS case.

Data

Our model is based on the GTAP 11 dataset[9] which provides input-output accounts and trade flows for 65 sectors in 141 countries/regions for 2014. There is a parallel set of accounts of energy use in physical units (tons of coal or MWh of electricity) together with CO_2 emissions. We aggregated these accounts to 10 regions and 29 sectors for model analysis.

Elasticities of substitution between factors of production, between domestic and imported goods, and between goods from different regions are provided by the GTAP 10 dataset. In the utility function, the Frisch parameter (marginal utility of income/income) is set uniformly across all regions[24]. The share parameters in the production and consumption functions are calibrated to satisfy the equilibrium equations of the 2014 base year. The GTAP provides equivalent import tariffs for non-tariff trade barriers (NTBs), see Supplementary Model.

Real GDP growth, investment rate, population and labor supply all evolve according to projections by CEPII[25,26] given in the EconMap database. Our baseline scenario is calibrated with an endogenous TFP term and running the model constrained to follow CEPII projections of GDP, investment, and population. These investment rates, population and TFP growth rates are then exogenously fixed in policy scenarios.

Modeling the EU Emissions Trading System

We first simulate a no-ETS case path over 2014-2040 using the base year tax parameters and projections, except that we remove the 2014 carbon price in the EU region (scenario S.no-ETS). We then simulate a growth path with the EU-ETS policy but without any border adjustments (scenario S.ETS). This policy covers a few high CO_2-emissions sectors - iron and steel, petroleum refining, cement, and certain chemicals; a set denoted by S^{ETS}. The producers in S^{ETS} are required to have a permit for each ton of CO_2 from the fossil fuels used. They are allocated a quota of permits for free, and we represent this as a subsidy on output. Producers in region *r=EU* are required to buy the remaining permits from the market at price t_r^{ETSco2} (\$ per ton of CO_2). The EU-ETS also covers the electricity sector which are not allocated any free permits, and this means that the electricity prices incorporate the carbon price.

The ETS and carbon tariffs are specified at a fairly fine level of commodity detail such as dyes & pigments, inorganic basic chemicals, flat glass, cement. The GTAP database does not provide such a level of detail. Our model sectors are Chemicals, Non-metallic mineral products, Ferrous metals, etc., for a total of 29 sectors that are chosen given the sector resolution in GTAP. Dyes & pigments, and inorganic basic chemicals are part of our Chemicals industry while glass and cement are part of Non-metallic mineral products. The data only allow us to represent the average ETS price and tariff for the Chemical sector, and not distinct tariffs for dyes and inorganic basic chemicals. We are thus assuming that the ETS rules apply to all commodities in each of these 7 sectors in set SETS = {PPP, PCP, CRP, NMM, MET, NFM, ELY} (abbreviations in Supplementary Table 2).

The ETS covers industrial process emissions, but the CO_2 data in GTAP are all attributed to fuel inputs, there is no separate account of process emissions, such as those from cement production. This means that the carbon price in the current model only incentivizes the reduced use of fossil fuels and not the changes in technology (e.g. reduced use of clinker in cement production). This should be included in future versions of the model. However, we note that this is applied symmetrically to EU and non-EU production and so the carbon tariffs are comparable to EU carbon prices.

The shadow carbon price per unit fuel input e to industry t is the carbon permit price times the emission coefficient:

$$tx_{e,t,r}^{ETS} = t_r^{ETSco2}\theta_{e,t,r} \qquad t1 \in S_{CO2emit}^{ETS} \;; \qquad t \in S^{ETS} \tag{1}$$

The set of inputs that generate CO_2 emissions from their use is $S_{CO2emit}^{ETS} =$ {COA, GAS, PCP, GDT}. Note that electricity is not in this set. Eq. (1) corresponds to (58e) in the SM, and $\theta_{e,t,r}$ is given in eq. (112).

Producers subject to the permit requirement (set S^{ETS}) pay a different shadow price for the inputs of coal, oil, and gas. Let PB_{etr} denote the buyer's price of energy input *e* into industry *t*, inclusive of the permit price:

$$PB_{e,t,r} = PX_{e,r} + tx_{e,t,r}^{ETS} \tag{2}$$

The price of the energy input bundle in industry t is a function of these *PB*'s. Intermediate inputs of quantity IX_{etr} are required to produce output Q_{tr} (production functions in SM eqs. 21-36). The total value of the permits required by sector t is thus $\sum_e tx_{e,r}^{ETS} IX_{e,t,r}$.

Producers in S^{ETS} are given fixed shares of free allocations of the emission permits, $\phi_{free;tr}^{ETS}$. We represent the value of these allocations as a subsidy, s_{tr}^{co2}, on their output. The subsidy rate is chosen endogenously so that total value of subsidy exactly equals the free allocation for sector t:

$$s_{t,r}^{co2} P_{t,r} Q_{t,r} = \phi_{free;tr}^{ETS} \sum_e tx_{e,r}^{ETS} IX_{e,t,r} \tag{3}$$

$\phi_{free;try}^{ETS}$ is the share of permits allocated free to sector *t* in year *y* and $P_{t,r}$ is the price paid by purchasers for the output. The total auction revenue is given by SM eq. 53b. The recycling of this revenue is an important policy choice as discussed by many[24]. In this scenario we cut the factor tax on labor ($tf_{labor,r}$ in SM eq. 51b) so that real government purchases are maintained at no-ETS case levels for each year. Keeping an index of government purchases (SM eq. 44b) the same across scenarios allows a simple comparison of household utility across policies without having to worry about different levels of public goods.

The EU ETS sets an emission cap, and the market determines the permit price. In modeling the effects of future ETS and border tariffs, we find it better to set a carbon price and model the economic responses rather than projecting future emission caps and simulating endogenous future carbon prices. While there are broad EU CO_2 goals, there are no official emission targets for the ETS sectors, nor official price targets for our 2040 horizon, and the political economy of setting targets would likely consider new technologies and actual permit prices. Given the uncertainties of technologies and ambition, we believe it would be most straightforward to represent future policy by an exogenous ETS permit price that is similar to current values and let emissions be endogenous. We can let the indices of technology remain at base year values in this approach, if we had set emission targets in line with the broad goals, we would have to project future technologies that are assumed (implicitly or explicitly) in these ambitious goals. Thus, in the simulations we use actual EU ETS prices for the historical period and a linear forecast of future carbon prices in policy scenarios. We retain all essential features of the ETS including representing the free allowances as output subsidies.

Monthly average EU-ETS permit prices are taken from Online Database TradingEconomics[25] and averaged to annual values. The ETS price jumped to more than \$90 in 2022 from less than \$26 prior to 2021. Since the EU proposals do not discuss targets for future emissions or prices, we simply set the 2040 target at \$100 per ton and interpolated it linearly. Supplementary Fig.1 gives the projected path of carbon prices. We emphasize that this is not an economy-wide carbon price, it is a permit price payable only by the ETS sectors.

Modeling Carbon Border Adjustment under 3 Scopes of Coverage

After simulating scenario S.ETS we then consider the case with the same path of carbon prices but include tariffs on the covered imports into the EU region under the CBAM. Supplementary Table 3 shows the CBAM policy and model characteristic. While the ETS covers the 7 sectors in set S^{ETS}, the tariffs are only imposed on some commodities, they are not put on goods in the PPP and PCP sectors. That is, carbon tariffs are placed only on Chemicals-Rubber-Plastics, Non-metallic Mineral Products, Ferrous Metals, Non-ferrous metals, and Electricity. We denote this CBAM-liable set as S^{CBA} = {CRP, NMM, MET, NFM, ELY}. We also conducted an additional simulation that illustrates the possible scenario where S^{CBA} equals S^{ETS}, meaning that, in addition to the five sectors, PPP and PCP are also incorporated (Supplementary Discussion 3.2.3).

According to the EU CBAM rules[4], tariffs are linked to the permit prices and based on the emissions from fossil fuels used and the CO_2 embodied in electricity used in producing the good exported from any region *s* to the EU. Covering primary emissions and those embodied in electricity is known as Scope 2 coverage and we denote this scenario as S.CBAM2, which is closest to the CBAM policy, representing border adjustments on scope 2 emissions. We also have a Scope 1 scenario, S.CBAM1, with tariffs based only on direct emissions and a Scope 3 scenario, S.CBAM3, which covers the embedded carbon of all intermediate inputs. The S.CBAM3 scenario is compared to a S.ETS3 case where the ETS covers scope 3 emissions.

The rules specify that any carbon price that is in effect in region *s* may be deducted from these border adjustments. Given the narrow nature of the ETS pilots in China, we do not represent them in our model of China, and thus do not implement any exemption for China exports to the EU in the main S.CBAM scenario. The adjustment for carbon prices in the US is likely to be part of a complex negotiation between the two regions and for the S.CBAM case we assume there are no carbon prices in the US eligible for adjustment. We consider an alternative scenario where we impose illustrative carbon prices in the US, Canada, Annex 1, China and Mexico. This is described in the Supplementary Discussion as the “carbon tariffs in the rest-of-world” (S.ROW) scenario.

The EU CBAM proposal[4] has various options to determine the carbon content of imports into the EU, one is to allow verified estimates of actual emission intensity in the exporting country, another is to use an EU default value, and finally, a third country intensity may be used. For simplicity we use the most convenient and transparent method to calculate carbon tariff rates for each exporter using the carbon emissions and input-output data in GTAP11.

Let t_r^{BTAco2} be the tariff rate per ton of CO_2 on imports into r. The tariff on good t exported from s to r (X_{tsr}) is this rate times the carbon intensity:

$$tm_{t,s,r}^{co2} = t_r^{BTAco2} \cdot \theta_{t,s}^{Q} \qquad t \in S^{CBA} \tag{4}$$

With this tariff on imports, the landed value of imports *(MX_{tr})* becomes:

$$PM_{tr} MX_{tr} = \sum\nolimits_s (1 + tn_{tsr} + tm_{tsr}) ERT_r PWM_{tsr} X_{tsr} + tm_{tsr}^{co2} ERT_r X_{tsr} \tag{5}$$

where *PWM* is the price in dollars, *ERT* is the exchange rate, *PM* is the landed price of imports, *tm* is the regular tariff and *tn* is the non-tariff barrier equivalent (SM eq. 63b). *PWM* includes the cost of shipping from *s* to *r*.

EU CBAM[4] also discuss the phasing in of these tariffs in parallel with the rising share of auctioned permits. This reflects the idea that EU producers do not need import protection while they have output subsidies in the form of free permits. We thus set border carbon price equal to the permit price multiplied by the auction share (see eqs. 1 and 3):

$$t_r^{BTAco2} = (1 - \phi_{free;tr}^{ETS}) t_r^{ETSco2} \qquad \text{r=EU} \tag{6}$$

The EU also propose to send revenues raised by the BCA to the European Budget, that is, as general revenues not allocated to a particular purpose. There are other ideas[26-29] suggested using them to help exporting countries maintain the principle of Common but Differentiated Responsibilities or transfer to global south to helping developing countries strengthen climate resilience. To maintain symmetry with the S.ETS1 case, we recycle the border tax revenue in scenario S.CBAM1 by reducing tax rates on factors and keeping government real purchases at no-ETS case levels.

In designing ETS and CBAMs there is a debate about the scope of emissions that are liable for emission permits. Scope 1 refers only to direct emissions due to fossil fuel use in the production process. Scope 2 includes the CO_2 embodied in the electricity used, in addition to the direct emissions. Scope 3 then adds the CO_2 embodied in all intermediate inputs, e.g. those embodied in the iron bars used. The EU-ETS is essentially a Scope 2 system which is used in the main scenarios simulated. To illustrate how future changes to the CBAM rules might alter the policy effects, we also simulated a Scope 1 and Scope 3 system. We calculate three distinct carbon intensities (total emissions per unit output, in constant $ units) in region *s* according to the three scopes of coverage ($\theta_{t,s}^{Q}$, $\theta_{t,s}^{Q\_ELY}$ and $\theta_{t,s}^{Q\_Em}$ in SM eq. 114, 117). These are then used to determine the ETS requirements and carbon tariffs.

For consistent scope 3 analysis, we simulate a new ETS-only scenario, S.ETS3, where the ETS is extended to require permits for scope 3 emissions. In the scope 1 CBAM comparisons, we keep the ETS as implemented in the main scope 2 case, and impose tariffs that are lower than scope 2 tariffs.

In reporting the simulation results we focus on the impacts of output and exports of each of our 29 sectors in the countries of interest. The impacts on aggregate GDP, consumption and capital accumulation are obviously important, as well as the accounting of carbon emissions by region, including calculation of leakage rates. We define the leakage rate as the ratio of the increase in carbon emissions in non-policy regions (set NRL) to the reduction in policy countries (set RL) when they system move from policy P0 to P1:

$$LEAK_{y}^{P1,P0} = \frac{\sum_{r \in NRL} EMR_{ry;P1}^{CO2} - EMR_{ry;P0}^{CO2}}{\sum_{r \in RL} EMR_{ry;P0}^{CO2} - EMR_{ry;P1}^{CO2}} \tag{7}$$

where $EMR_{ry;P1}^{CO2}$ is the regional CO_2 emissions from region *r* in year *y* (SM eq. 119). CBAM terminology and our model details are given in Supplementary Table 3.

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Supplementary Information

For

The Global Trade and Environmental Effects of Carbon Border Tariffs and Climate Clubs

Table of Contents

Supplementary Tables

Supplementary Table 1. Regions in Model

Symbol	Region	Members
USA	United States	
CAN	Canada	
MEX	Mexico	
CHN	China	
IND	India	
RUS	Russian Federation	
EU	European Union	Austria, Belgium, Bulgaria, Croatia, Cyprus, Czech, Republic, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Ireland, Italy, Latvia, Lithuania, Luxembourg, Malta, Netherlands, Poland, Portugal, Romania, Slovakia, Slovenia, Spain, Sweden
RXAN	Rest of Annex I	Australia, New Zealand, Japan, United Kingdom, Switzerland, Norway, Rest of EFTA, Belarus, Ukraine, Turkey
XOI	Oil Exporters	Indonesia, Ecuador, Venezuela, Iran, Islamic, Republic of Kuwait, Qatar, Saudi Arabia, United Arab Emirates, Nigeria
XRW	Rest of the World	Albania, Argentina, Armenia, Azerbaijan, Bahrain, Bangladesh, Benin, Bolivia, Botswana, Brazil, Brunei Darussalam, Burkina Faso, Cambodia, Cameroon, Caribbean, Central Africa, Chile, Colombia, Costa Rica, Cote d'Ivoire, Dominican Republic, Egypt, El Salvador, Ethiopia, Georgia, Ghana, Guatemala, Guinea, Honduras, Israel, Jamaica, Jordan, Kazakhstan, Kenya, Korea, Kyrgyzstan, Lao People's Democratic Rep., Madagascar, Malawi, Malaysia, Mauritius, Mongolia, Morocco, Mozambique, Namibia, Nepal, Nicaragua, Oman, Pakistan, Panama, Paraguay, Peru, Philippines, Puerto Rico, Rest of Central America, Rest of East Asia, Rest of Eastern Africa, Rest of Eastern Europe, Rest of Europe, Rest of Former Soviet Union, Rest of North Africa, Rest of North America, Rest of Oceania, Rest of South African Customs, Rest of South America, Rest of South Asia, Rest of Southeast Asia, Rest of the World, Rest of Western Africa, Rest of Western Asia, Rwanda, Senegal, Singapore, South Africa, South Central Africa, Sri Lanka, Tajikistan, Tanzania, Thailand, Togo, Trinidad and

	Tobago, Tunisia, Uganda, Uruguay, Viet Nam, Zambia, Zimbabwe

Supplementary Table 2. Sectors in Model

Abbreviation	Sector	
AGR	1	Agriculture
COA	2	Coal
OIL	3	Oil
GAS	4	Natural Gas
OMN	5	Other Minerals
FBT	6	Food, Beverages, and Tobacco
TEX	7	Textiles
WAP	8	Wearing Apparel and Leather Products
LUM	9	Wood Products
PPP	10	Paper Products and Publishing
PCP	11	Petroleum and Coal Products
CRP	12	Chemicals, Rubber, and Plastics
NMM	13	Other Non-Metallic Mineral Products
MET	14	Ferrous Metals (Iron and Steel)
NFM	15	Non-Ferrous Metals
FMP	16	Fabricated Metal Products
MVH	17	Motor Vehicles and Transport Equipment
ELE	18	Electronic and Communication Equipment
OME	19	Other Machinery and Equipment
OMF	20	Other Manufacturing and Recycling
ELY	21	Electricity
GDT	22	Gas Manufacture and Distribution
CNS	23	Construction
TRD	24	Trade (Retail and Wholesale Services)
TRN	25	Transport
CMN	26	Communication
FIN	27	Finance and Insurance
SER	28	Other Services
DWE	29	Ownership of Dwellings

Supplementary Table 3. CBAM terminology and model details

Topic	EU CBAM	Model Set Up	If not, Additional features
Time Schedule	**Transition (Report-only) Period: October 2023-December 2025** **Phase-in Period: 10 years from 2026 to 2035, reduce free allowances under the EU-ETS after 2026, to reach zero in 2035, CBAM is to be applied gradually at the same pace with the phasing out of free allowance (2026: 2.5%, 2027: 5%, 2028: 10%, 2029: 22.5%, 2030: 48.5%, 2031: 61%, 2032: 73.5%, 2033: 86%, 2034: 100%)**	**Included in model**	**In accordance with the rules of the ETS Directive for phase 4 of the EU ETS, from 2021, around 57% of the Union-wide cap is auctioned and the rest is provided for free. We choose 57% as auction part in 2026 and gradually increase to 100% in 2036 when modelling EU ETS. For power sector, no free allowance, which in consistent with actual EU-ETS rule.**
Coverage	**Initially apply to cement, iron and steel, aluminum, fertilizers, electricity and hydrogen**	**Included in model**	**The EU CBAM make a detail list based on CN code. Due to the limits of GTAP database and CGE model, we apply CBAM to sector-level but not product level, which may slightly expand the coverage.**
Emission Scopes	**Report both direct and indirect emissions. Cement and fertilizers will be charged both in scope2 emissions while other only scope1.**	**Implemen-ted slightly differently**	**We have three scenarios on one, two and three scopes. In each scenario, we set CBAM fees all on the same scope.**

Embedded emission benchmark	**Based on EU methodology or default reference values**	**Slightly different**	**We calculate embedded emission for each sector based on input-output table**
Country coverage	**Applies to all non-EU countries except those with equivalent carbon pricing mechanisms, such as Switzerland, Iceland, Liechtenstein, and Norway. Low-value consignments (up to €150) and certain military imports are exempt. EU is committed to support developing countries and LDCs.**	**Our implement-ation**	**We exempt countries with ETS or carbon taxes linked with EU ETS, including the UK. Main case S.CBAM ignores carbon fees paid in other countries due to the low price and limited coverage. Case S.ROW includes exemption for carbon prices in main regions.**
CBAM Revenue	**The EU is working towards a decision on the use of CBAM revenues.**	**Our implement-ation**	**The revenue will go to the general budget in EU like other taxes. We impose revenue neutrality by recycling with adjustments to income tax rate.**

Supplementary Table 4. No-ETS case path of key variables; 2026 value and 2026-2040 growth rate (% per year)

		World	Canada	Russia	China	India	Mexico	USA	Oil Exporter	EU	rest of ANNEX I	rest of world
Economy variables												
GDP	**bil.$**	**112749**	**2194**	**2367**	**23092**	**5407**	**1841**	**22038**	**5925**	**18208**	**14351**	**17325**
	%	3.00	1.73	1.79	5.07	7.29	2.51	1.56	3.28	0.68	1.50	3.25
CONSUMOTION	%	3.08	2.00	2.26	5.55	7.28	2.57	1.70	3.82	1.06	1.85	3.40
INVESTMENT	%	2.95	1.15	1.34	4.51	6.76	1.96	1.06	2.81	0.15	0.99	2.86
GOVERNMENT	%	2.77	1.41	1.62	5.64	7.85	2.94	1.44	3.16	0.29	1.04	3.14
EXPORT	%	3.99	1.61	1.98	5.86	9.98	2.44	2.45	3.03	1.64	2.05	3.75
IMPORT	%	3.95	1.52	2.56	6.14	9.58	2.36	2.11	3.54	1.74	2.06	3.69
Emission variables												
CO2 EMISSION	**mil tons**	**40901**	**662**	**1507**	**13801**	**3899**	**508**	**5850**	**2863**	**2938**	**2726**	**6145**
	%	2.21	1.20	1.48	2.76	4.50	1.33	0.95	2.90	-0.10	0.44	1.99
COAL USE	%	2.48	0.24	0.93	2.73	4.29	1.11	0.61	1.91	-0.25	-0.01	1.59
OIL USE	%	1.83	1.21	1.30	2.76	4.34	1.34	0.57	2.72	-0.09	0.55	1.90
GAS USE	%	2.21	1.39	1.71	3.21	7.83	1.39	1.69	3.24	0.03	0.70	2.49

Supplementary Table 5. Effects of EU-ETS without a border adjustment on ETS sectors, 2040 (% change from no-ETS case, GTAP 11)

	Canada	Russia	China	India	Mexico	USA	Oil Exporter	EU	Rest-Annex 1	Rest of World
						Output				
Paper, publishing	-2.84	2.23	-0.13	1.89	0.04	-0.77	0.69	-1.09	-0.62	0.85
Petroleum	-1.80	1.96	-0.87	2.18	-1.22	-1.71	1.07	-5.55	-3.03	1.17
Chemicals	-0.20	4.39	-0.98	2.82	-0.70	-1.50	2.97	-1.82	-0.71	1.49
Non-metallic min.	-0.64	0.87	-0.42	1.60	-1.01	-1.10	-0.23	-1.78	-1.09	1.20
Ferrous metals	-4.32	6.80	-1.01	6.69	0.71	-1.90	1.46	-3.18	-2.61	2.98
Non-ferrous	-4.31	10.42	-1.55	3.09	0.63	-3.10	4.63	-4.18	-0.92	2.90
Electricity	-2.46	1.32	-6.38	3.16	-2.09	-8.70	0.76	-11.33	-5.73	2.05
						Exports				
Paper, publishing	-4.48	9.76	0.08	4.84	-0.06	-2.46	5.06	-4.33	-2.36	3.36
Petroleum	-2.63	3.30	6.92	0.68	-2.73	-2.98	1.42	-7.80	-4.08	-0.47
Chemicals	-0.44	11.57	-2.96	4.97	-1.75	-2.69	7.21	-3.14	-1.19	3.05
Non-metallic min.	-1.21	11.90	-1.31	9.20	-3.78	-3.23	5.90	-8.53	-4.73	7.22
Ferrous metals	-7.39	16.83	-5.85	25.19	2.03	-4.67	7.16	-9.66	-6.57	6.97
Non-ferrous	-4.58	14.56	-5.07	5.03	0.48	-4.15	5.97	-7.27	-0.99	3.80
						Imports				
Paper, publishing	-0.14	-4.79	-0.23	-1.06	-0.82	0.51	-2.46	1.61	0.01	-1.29
Petroleum	-1.56	-1.46	-3.86	2.86	-0.97	0.29	-1.03	-0.39	-1.55	0.63
Chemicals	-0.71	-3.02	1.41	-0.56	-0.39	0.44	-2.20	0.31	-0.48	-0.75
Non-metallic min.	-0.54	-6.18	0.51	-3.45	0.93	0.96	-3.92	3.27	0.66	-3.09
Ferrous metals	0.34	-5.13	2.29	-6.63	-1.71	1.68	-2.77	4.60	0.74	-2.81
Non-ferrous	-1.87	-3.14	1.49	0.10	-1.22	-0.22	-0.28	1.35	-0.60	-0.43

Supplementary Table 6. Sector impacts of EU-ETS in major regions, 2040 (%change from no-ETS case, GTAP 11)

	EU			China			Russia			India			US		
	Output	Imports	Exports	Output	Imports	Exports	Output	Imports	Exports	Output	Imports	Exports	Output	Imports	Exports
Agriculture	-0.20	-0.25	-0.29	0.02	-0.37	0.57	0.48	-1.89	3.57	0.27	2.96	-5.13	-0.22	-0.31	-0.15
Coal	-15.26	-41.16	98.48	-6.08	-26.03	58.67	-5.84	2.03	-11.93	-0.78	20.43	-27.21	-6.18	-41.75	42.67
Oil	-0.96	-4.02	4.83	-0.57	-1.76	2.46	-0.22	0.88	-1.14	-0.13	2.31	-6.16	-0.46	-1.22	0.81
Natural Gas	-2.17	-10.51	12.56	-30.20	-1.29	-41.26	-2.13	-1.64	-3.73	-0.76	6.20	0.00	-1.97	-7.70	12.73
Other Minerals	-0.50	-1.88	1.61	-0.49	-1.18	2.23	0.55	-0.43	1.32	0.58	2.77	-4.44	-0.53	-0.96	-0.02
Food mfg	-0.21	0.07	-0.67	0.12	-0.45	0.93	-0.30	-2.74	4.23	-0.16	2.20	-3.30	-0.20	0.06	-0.54
Textiles	-0.26	-0.26	-0.30	-0.19	0.13	-0.43	2.36	-2.10	8.61	0.20	0.75	-0.59	-1.60	0.30	-3.00
Apparel, leather	0.32	-0.31	0.52	-0.02	-0.30	0.04	1.71	-2.06	7.39	-1.18	1.63	-2.28	0.71	-0.23	1.15
Wood	-1.08	1.17	-3.44	-0.40	-0.29	0.11	2.59	-3.84	7.18	0.92	0.30	1.25	-0.78	0.79	-2.76
Paper, publishing	**-1.09**	**1.61**	**-4.33**	**-0.13**	**-0.23**	**0.08**	**2.23**	**-4.79**	**9.76**	**1.89**	**-1.06**	**4.84**	**-0.77**	**0.51**	**-2.46**
Petroleum	**-5.55**	**-0.39**	**-7.80**	**-0.87**	**-3.86**	**6.92**	**1.96**	**-1.46**	**3.30**	**2.18**	**2.86**	**0.68**	**-1.71**	**0.29**	**-2.98**
Chemicals	**-1.82**	**0.31**	**-3.14**	**-0.98**	**1.41**	**-2.96**	**4.39**	**-3.02**	**11.57**	**2.82**	**-0.56**	**4.97**	**-1.50**	**0.44**	**-2.69**
Non-metallic min.	**-1.78**	**3.27**	**-8.53**	**-0.42**	**0.51**	**-1.31**	**0.87**	**-6.18**	**11.90**	**1.60**	**-3.45**	**9.20**	**-1.10**	**0.96**	**-3.23**
Ferrous metals	**-3.18**	**4.60**	**-9.66**	**-1.01**	**2.29**	**-5.85**	**6.80**	**-5.13**	**16.83**	**6.69**	**-6.63**	**25.19**	**-1.90**	**1.68**	**-4.67**
Non-ferrous	**-4.18**	**1.35**	**-7.27**	**-1.55**	**1.49**	**-5.07**	**10.42**	**-3.14**	**14.56**	**3.09**	**0.10**	**5.03**	**-3.10**	**-0.22**	**-4.15**
Fabricated metal	-0.49	-0.86	-0.45	-1.01	1.30	-3.21	2.15	-4.06	11.44	1.42	-0.50	2.34	-0.36	-0.73	-0.41

Transportation equip	-0.38	-0.22	-0.58	-0.39	0.04	-1.27	0.33	-2.98	5.78	1.23	0.23	1.35	-0.40	-0.33	-0.46
Electronic, Comm eq	-0.28	-0.41	-0.26	-0.78	-0.16	-1.02	2.34	-2.58	9.12	1.41	0.39	1.25	0.84	-0.55	1.19
Machinery	-0.34	-0.57	-0.23	-0.81	0.12	-1.67	2.68	-2.42	9.54	1.67	-0.07	2.14	-0.27	-0.50	-0.16
Other mfg, recycling	-0.32	0.14	-0.95	-0.20	-0.32	-0.16	0.31	-2.84	6.06	0.60	0.99	-0.12	0.17	-0.64	1.18
Electricity	-11.33	34.64	-47.09	-6.38	22.09	-37.43	1.32	-1.20	104.26	3.16	-2.07	42.04	-8.70	20.64	-40.77
Gas utilities	-7.06	-5.53	-5.63	0.67	-4.20	9.45	0.57	-1.46	1.51	1.92	2.33	-4.02	-7.18	-7.02	-3.12
Construction	-0.03	-0.07	-0.47	-0.24	0.24	-1.19	-1.05	-2.81	3.46	0.78	1.34	-1.58	-0.10	-0.31	0.18
Trade	-0.13	-0.30	0.18	-0.13	-0.71	0.68	-0.94	-2.48	3.27	1.10	1.64	-1.02	-0.25	0.08	-0.39
Transport	-0.59	0.02	-1.05	-0.08	-0.64	0.86	-0.40	-2.59	3.65	1.06	1.26	-0.34	-0.53	-0.03	-0.97
Communication	0.05	-0.22	0.25	-0.03	0.02	-0.23	-0.78	-2.27	2.96	0.69	1.14	-0.21	-0.09	-0.22	0.08
Finance, Insurance	0.00	-0.40	0.47	-0.11	-0.51	0.50	-0.72	-2.05	2.70	0.80	1.64	-1.42	-0.05	-0.45	0.26
Other Services	-0.05	-0.42	0.24	0.02	-0.30	0.35	-0.66	-2.45	3.47	0.42	1.95	-2.68	-0.10	-0.33	0.12
Own dwellings	0.42			0.49			-1.65			1.06			0.08		

Supplementary Table 7. Sector impacts of carbon tariffs on ETS sectors in 2040 (%change from ETS-only case, GTAP 11)

	Canada	Russia	China	India	Mexico	USA	Oil Exporter	EU	Rest-Annex 1	Rest of World
Output										
Paper, publishing	0.18	0.82	-0.01	0.03	-0.06	-0.05	0.01	-0.11	0.00	-0.05
Petroleum	-0.08	-0.10	-0.11	-0.06	-0.06	0.02	-0.03	0.06	0.07	0.09
Chemicals	-0.36	-0.91	-0.41	-0.08	-0.56	-0.23	-0.21	0.51	0.46	0.33
Non-metallic min.	-0.63	0.34	-0.36	-0.04	-0.42	-0.16	0.26	0.64	-0.28	0.34
Ferrous metals	-3.18	-2.74	-0.53	-1.20	0.22	0.10	0.95	1.33	0.16	1.17
Non-ferrous	0.05	-4.62	0.07	0.18	0.57	-0.27	-0.31	-0.14	0.10	0.08
Electricity	-0.04	-1.11	-0.13	-0.06	-0.06	-0.02	0.00	0.86	-0.07	0.00
Exports										
Paper, publishing	0.28	2.96	0.15	0.26	-0.06	-0.11	0.16	-0.55	-0.04	-0.18
Petroleum	-0.05	0.53	0.18	0.04	-0.09	0.04	-0.06	-0.04	0.03	-0.08
Chemicals	-0.51	-10.48	-1.87	-0.51	-1.42	-0.24	-1.16	-2.18	1.15	0.52
Non-metallic min.	-1.55	-5.27	-2.14	-4.30	-1.73	-0.14	1.19	-4.02	-1.12	0.63
Ferrous metals	-4.92	-9.99	-4.34	-12.94	0.58	0.56	3.02	-5.40	1.08	2.23
Non-ferrous	0.06	-7.41	0.01	-0.32	0.71	-0.28	-0.45	-5.26	0.15	-0.03
Imports										
Paper, publishing	-0.11	-1.11	-0.12	-0.09	-0.09	0.05	-0.12	0.20	-0.05	0.07
Petroleum	-0.06	-0.74	-0.19	-0.08	-0.01	0.03	0.02	0.20	0.07	0.13
Chemicals	-0.13	-1.20	0.09	-0.70	-0.10	0.15	-0.49	-5.53	-0.01	-0.37
Non-metallic min.	0.21	-3.06	0.36	-1.80	0.17	0.23	-1.58	-12.74	0.26	-1.50
Ferrous metals	0.49	-3.09	1.57	-1.65	-0.25	0.16	-1.26	-17.89	0.41	-1.51
Non-ferrous	-0.08	-2.50	-0.53	-0.11	-0.25	0.22	-0.11	-7.41	-0.05	-0.11

Supplementary Table 8. Sector impacts of EU-ETS and CBAM in 2040 (%change from ETS-only case, GTAP 11)

	EU/2040			China/2040			Russia/2040			India/2040			US/2040		
	Output	Imports	Exports	Output	Imports	Exports	Output	Imports	Exports	Output	Imports	Exports	Output	Imports	Exports
Agriculture	-0.04	0.02	-0.16	0.00	-0.12	0.17	0.42	-0.56	1.49	0.00	0.02	-0.07	-0.04	-0.03	-0.06
Coal	-0.01	1.21	-2.11	-0.09	-0.29	0.50	0.09	-1.04	0.52	-0.02	-0.20	0.49	-0.07	0.03	-0.16
Oil	-0.05	0.09	-0.12	-0.02	-0.15	0.37	0.11	-0.33	0.25	-0.01	-0.06	0.18	-0.03	0.05	-0.20
Natural Gas	-0.02	0.42	-0.65	0.10	-0.18	0.47	0.22	-1.13	0.54	-0.01	-0.10	0.00	-0.02	0.01	0.01
Other Minerals	-0.04	0.40	-0.34	-0.16	-0.50	0.91	-0.02	-0.59	0.63	-0.01	0.04	-0.41	-0.05	0.09	-0.31
Food mfg	-0.03	0.14	-0.28	0.03	-0.16	0.31	0.19	-1.00	2.08	0.01	-0.06	0.09	-0.01	0.02	-0.06
Textiles	-0.53	0.36	-1.49	0.08	-0.19	0.24	0.97	-0.50	2.85	0.03	0.02	0.11	-0.31	0.11	-0.59
Apparel, leather	-0.27	0.14	-0.65	0.10	-0.23	0.22	1.13	-0.52	3.28	0.01	0.05	0.03	-0.04	0.01	-0.06
Wood	-0.32	0.22	-0.81	-0.07	-0.08	0.15	1.34	-1.24	3.02	0.03	-0.05	0.08	-0.07	0.04	-0.23
Paper, publishing	-0.11	0.20	-0.55	-0.01	-0.12	0.15	0.82	-1.11	2.96	0.03	-0.09	0.26	-0.05	0.05	-0.11
Petroleum	0.06	0.20	-0.04	-0.11	-0.19	0.18	-0.10	-0.74	0.53	-0.06	-0.08	0.04	0.02	0.03	0.04
Chemicals	**0.51**	**-5.53**	**-2.18**	**-0.41**	**0.09**	**-1.87**	**-0.91**	**-1.20**	**-10.48**	**-0.08**	**-0.70**	**-0.51**	**-0.23**	**0.15**	**-0.24**

Non-metallic min.	**0.64**	**-12.74**	**-4.02**	**-0.36**	**0.36**	**-2.14**	**0.34**	**-3.06**	**-5.27**	**-0.04**	**-1.80**	**-4.30**	**-0.16**	**0.23**	**-0.14**
Ferrous metals	**1.33**	**-17.89**	**-5.40**	**-0.53**	**1.57**	**-4.34**	**-2.74**	**-3.09**	**-9.99**	**-1.20**	**-1.65**	**-12.94**	**0.10**	**0.16**	**0.56**
Non-ferrous	**-0.14**	**-7.41**	**-5.26**	**0.07**	**-0.53**	**0.01**	**-4.62**	**-2.50**	**-7.41**	**0.18**	**-0.11**	**-0.32**	**-0.27**	**0.22**	**-0.28**
Fabricated metal	-0.80	0.72	-2.58	-0.21	-0.08	-0.55	1.19	-1.69	4.84	0.13	-0.99	1.89	0.08	-0.36	0.47
Transportation eq	-0.73	0.13	-1.14	-0.03	-0.35	0.10	0.58	-1.15	2.87	0.10	-0.51	0.74	0.02	-0.13	0.11
Elect, Comm eq	-0.96	0.17	-1.69	0.05	-0.14	0.11	1.34	-0.90	4.08	0.20	-0.16	0.50	0.09	-0.05	0.13
Machinery	-0.90	0.52	-1.87	-0.08	-0.28	0.01	1.49	-0.96	4.26	0.37	-0.56	1.11	0.08	-0.18	0.25
Other mfg, recycling	-0.53	0.49	-1.57	0.05	-0.24	0.21	0.79	-0.98	3.38	0.15	-0.09	0.28	0.00	-0.01	0.09
Electricity	0.86	-40.38	-0.45	-0.13	-0.22	0.39	-1.11	-1.65	-54.35	-0.06	-0.26	0.32	-0.02	0.15	-0.18
Gas utilities	0.15	0.29	-0.36	0.07	-0.22	0.55	-0.68	-2.17	2.92	-0.11	-0.07	-0.22	-0.02	-0.07	-0.05
Construction	-0.13	0.22	-0.77	-0.23	0.06	-0.59	-0.09	-1.30	2.16	0.00	-0.29	0.43	-0.03	-0.14	0.15
Trade	0.00	0.03	-0.06	-0.02	-0.21	0.27	-0.12	-1.17	2.08	0.00	0.05	-0.03	0.00	0.08	-0.04
Transport	-0.06	0.02	-0.10	-0.04	-0.13	0.18	0.03	-0.97	1.76	0.01	-0.01	0.02	-0.02	-0.02	-0.01
Communication	0.04	0.03	-0.03	0.02	-0.12	0.23	0.09	-0.96	2.04	0.00	-0.02	0.02	0.00	0.02	-0.03
Finance, Insurance	0.05	-0.03	0.07	-0.01	-0.18	0.29	0.00	-1.10	2.22	-0.01	0.02	-0.05	0.00	-0.02	-0.03
Other Services	0.02	0.03	-0.08	0.01	-0.14	0.23	0.01	-1.10	2.15	-0.01	-0.04	0.02	0.00	-0.01	0.00
Own dwellings	0.14			0.09			-0.05			-0.02			0.01		

Supplementary Table 9. Sector impacts of carbon tariffs on output under coverage scopes 1,2 and 3, in 2040 (%change from ETS-only case, GTAP 11)

	Scope	**Canada**	**Russia**	**China**	**India**	**Mexico**	**USA**	**Oil Exporter**	**EU**	**Rest-Annex 1**	**Rest of World**
	1	0.12	-0.10	-0.04	0.02	-0.07	0.01	-0.40	-0.21	0.31	0.10
Chemicals	**2**	0.26	-1.09	-0.18	-0.26	-0.07	0.09	-0.45	0.40	0.52	0.09
	3	0.43	-0.55	-0.27	-0.73	-0.08	0.50	-0.27	-0.37	1.28	0.21
	1	0.14	0.08	-0.04	-0.19	0.04	0.12	0.03	0.28	0.15	-0.01
Non-metallic min.	**2**	0.15	0.07	-0.07	-0.21	0.00	0.10	0.02	0.67	0.07	-0.03
	3	0.25	0.11	-0.14	-0.21	0.02	0.25	0.02	0.56	0.32	-0.01
	1	0.42	-3.12	-0.02	-1.51	0.23	0.34	0.21	0.24	0.76	0.33
Ferrous metals	**2**	0.47	-3.63	-0.02	-1.59	0.25	0.33	0.18	0.85	0.79	0.11
	3	0.92	-3.50	0.02	-1.44	0.47	0.61	0.31	-0.25	0.75	0.20
	1	0.19	2.05	0.06	0.20	0.05	0.11	0.03	-1.07	-0.02	0.02
Non-ferrous	**2**	0.26	-4.41	0.07	0.18	0.11	0.29	-0.12	0.09	0.19	0.00
	3	0.91	-3.55	0.18	0.41	0.34	0.58	0.49	-3.07	0.32	0.28
	1	0.02	-0.68	0.01	-0.08	0.03	0.02	0.00	1.14	-0.63	-0.03
Electricity	**2**	0.02	-0.88	0.00	-0.10	0.04	0.03	-0.01	1.22	-0.60	-0.04
	3	0.07	-0.92	0.00	-0.11	0.07	0.07	-0.01	1.01	-0.62	-0.02

Supplementary Table 10. Aggregate impacts of carbon tariffs in 2040 in S.ROW (scenario with carbon prices in US, Canada, Annex I, China and Mexico, GTAP 11)

Panel A. Effects of different carbon prices without a border adjustment in 2040 (% change from no-ETS case)											
	2040										
	World	**Canada**	**Russia**	**China**	**India**	**Mexico**	**USA**	**Oil Exporter**	**EU**	**Rest-Annex 1**	**Rest of World**
GDP	-0.041	-0.191	-0.552	-0.032	0.603	-0.001	-0.101	-0.509	-0.147	-0.127	-0.022
Consumption	-0.043	-0.839	-1.939	0.375	1.222	0.147	-0.240	-1.476	-0.110	-0.454	0.005
Investment	0.227	-0.763	-1.924	0.376	2.117	-0.010	-0.122	-1.386	0.063	-0.371	-0.060
Government	-0.107	-0.314	-1.053	0.102	0.855	-0.163	-0.028	-1.736	-0.064	-0.182	-0.355
Export	0.281	0.569	1.216	-0.606	2.284	-0.182	0.214	1.751	-1.174	0.223	0.752
Import	0.594	-1.282	-4.263	1.509	6.224	0.018	-0.409	-2.145	-0.875	-0.865	0.578
Utility		-9.124	-0.793	0.091	0.584	1.734	-1.458	1.593	0.270	0.187	1.934
Exchange rate		0.490	1.527	-0.148	-0.572	-0.209		0.729	-0.298	0.106	-0.167
CO2 Emissions	-4.325	-5.215	1.935	-8.980	5.676	-3.015	-10.334	1.195	-12.728	-7.610	3.251
Coal use	-8.393	-29.024	7.921	-12.742	7.700	-16.954	-27.918	6.979	-37.130	-19.689	8.145
Oil use	-0.998	-1.521	1.074	-2.958	2.636	-1.122	-0.931	0.350	-4.155	-3.027	1.078
Gas use	-2.039	-4.886	0.797	-0.133	2.928	-2.676	-9.975	1.213	-8.887	-5.362	2.256
Leakage rate (%)	23.897										

Panel B. Effects of adding a border carbon tariff to the ETS in 2040 (% change from ETS-only case)											
	2040										
	World	**Canada**	**Russia**	**China**	**India**	**Mexico**	**USA**	**Oil Exporter**	**EU**	**Rest-Annex 1**	**Rest of World**
GDP	-0.020	-0.013	-0.058	-0.041	-0.012	-0.021	-0.003	-0.025	-0.017	-0.006	-0.012

Consumption	0.015	-0.033	-0.144	0.077	-0.006	-0.026	0.003	-0.059	0.074	0.008	-0.020
Investment	-0.093	-0.098	-0.205	-0.149	-0.019	-0.089	-0.029	-0.082	-0.090	-0.072	-0.053
Government	-0.008	0.000	-0.091	0.000	-0.031	0.000	0.000	-0.069	0.000	0.000	-0.006
Export	-0.222	0.000	-0.542	-0.249	-0.199	-0.032	-0.007	-0.052	-1.080	0.003	-0.037
Import	-0.219	-0.094	-1.093	-0.184	-0.196	-0.077	-0.012	-0.228	-1.006	-0.022	-0.088
Utility		-0.010	-0.044	0.013	-0.001	-0.008	-0.004	-0.013	0.017	0.000	-0.004
Exchange rate		0.085	0.524	-0.040	0.021	0.012		0.051	-0.121	-0.014	-0.027
CO2 Emissions	-0.073	-0.088	-0.817	-0.143	-0.136	-0.044	0.008	0.016	0.266	0.014	0.102
Coal use	-0.084	-0.081	-1.201	-0.135	-0.111	0.008	0.000	0.148	0.711	-0.015	0.167
Oil use	-0.069	-0.090	-0.715	-0.184	-0.185	-0.013	0.030	0.009	0.111	0.038	0.090
Gas use	-0.059	-0.088	-0.763	-0.009	-0.109	-0.123	-0.021	0.001	0.338	-0.010	0.056
Leakage rate (%)	23.200										

Supplementary Table 11(a). Effects of adding a border carbon tariff to the ETS in 2040 in scenario S.7sec (where CBAM covers all ETS sectors; % change from ETS-only case, GTAP 11)

	2040										
	World	**Canada**	**Russia**	**China**	**India**	**Mexico**	**USA**	**Oil Exporter**	**EU**	**Rest-Annex 1**	**Rest of World**
GDP	-0.007	-0.003	-0.061	-0.005	-0.006	-0.003	-0.001	-0.024	-0.016	-0.003	-0.004
Consumption	0.003	-0.019	-0.180	-0.001	0.003	-0.004	0.000	-0.076	0.107	-0.008	-0.004
Investment	-0.022	-0.026	-0.224	-0.013	-0.015	-0.017	-0.008	-0.085	-0.034	-0.025	-0.020
Government	-0.010	-0.006	-0.099	-0.013	-0.018	0.004	0.000	-0.071	0.001	0.007	-0.003
Export	-0.239	0.058	-0.483	-0.068	-0.155	0.008	0.007	-0.040	-1.669	-0.048	-0.011
Import	-0.234	0.007	-1.112	-0.086	-0.146	0.001	0.000	-0.263	-1.515	-0.073	-0.022
Utility		-0.006	-0.054	0.000	0.000	-0.001	0.000	-0.017	0.024	-0.002	-0.001
Exchange rate		0.025	0.605	0.033	0.075	0.002		0.143	-0.156	0.002	0.020
CO2 Emissions	-0.038	0.049	-0.748	0.040	-0.196	0.093	0.084	-0.024	-0.285	-0.112	0.056
Coal use	-0.013	0.137	-1.032	0.024	-0.181	0.144	0.112	0.062	0.965	-0.368	0.073
Oil use	-0.058	0.043	-0.761	0.072	-0.229	0.095	0.087	-0.020	-0.920	0.065	0.071
Gas use	-0.052	0.036	-0.665	0.051	-0.141	0.071	0.057	-0.042	0.401	-0.211	0.008
Leakage rate (%)	54.874										

Supplementary Table 11(b). Sector impacts of carbon tariffs on ETS sectors in 2040 in scenario S.7sec (% change from ETS-only case, GTAP 11)

	Canada	Russia	China	India	Mexico	USA	Oil Exporter	EU	Rest-Annex 1	Rest of World
					Output					
Paper, publishing	-0.06	0.29	-0.01	-0.05	0.02	-0.03	0.07	0.18	-0.08	-0.14
Petroleum	0.10	-1.05	0.08	0.00	0.12	0.14	0.04	-1.28	0.15	0.18
Chemicals	0.32	-0.80	-0.16	-0.23	-0.04	0.12	-0.38	0.15	0.57	0.12
Non-metallic min.	0.16	0.11	-0.07	-0.19	0.02	0.10	0.01	0.63	0.07	-0.03
Ferrous metals	0.49	-3.40	-0.01	-1.56	0.26	0.33	0.19	0.76	0.79	0.11
Non-ferrous	0.27	-3.95	0.07	0.18	0.11	0.28	-0.01	-0.02	0.19	0.00
Electricity	0.02	-0.90	0.00	-0.09	0.05	0.04	-0.02	1.16	-0.60	-0.03
					Exports					
Paper, publishing	-0.15	-1.68	-0.20	-1.07	-0.01	-0.31	0.20	-2.22	-1.14	-1.13
Petroleum	0.22	-1.83	0.30	0.73	0.11	0.11	-0.02	-6.07	-0.90	0.08
Chemicals	0.47	-10.47	-1.36	-0.80	-0.35	0.15	-1.53	-3.85	0.94	0.17
Non-metallic min.	0.55	-6.51	-1.11	-6.03	-0.43	0.14	-0.43	-6.85	-0.54	-1.36
Ferrous metals	0.73	-12.26	-1.14	-15.52	0.56	0.80	0.32	-8.67	1.79	-0.03
Non-ferrous	0.28	-6.68	-1.00	-0.10	0.17	0.34	-0.09	-6.05	0.18	-0.08
					Imports					
Paper, publishing	-0.06	-1.61	-0.17	-0.29	-0.06	-0.05	-0.34	-7.83	-0.34	-0.15
Petroleum	-0.02	-1.91	0.02	-0.18	0.07	-0.14	-0.75	-4.90	-0.35	-0.17
Chemicals	0.01	-1.18	-0.38	-0.38	-0.06	-0.20	-0.38	-6.66	-0.23	-0.12
Non-metallic min.	-0.10	-2.10	-0.53	-0.43	-0.23	-0.26	-0.55	-15.47	-0.75	-0.25

Ferrous metals	0.04	-2.32	-0.57	-0.68	-0.10	-0.31	-0.40	-18.76	-0.99	-0.14
Non-ferrous	0.18	-2.48	-0.15	-0.09	0.06	0.04	-0.16	-9.03	-0.01	-0.06

Supplementary Table 12. Sensitivity Analysis of 3 key elasticities (% change from ETS-only case, 2040, GTAP 11)

Panel A: GDP effect

	Canada	Russia	China	India	Mexico	USA	Oil Exporter	EU	Rest-Annex 1	Rest of World
Base	-0.002	-0.048	-0.007	-0.011	-0.002	-0.001	-0.015	-0.017	-0.002	-0.003
0.5SGT	-0.005	-0.062	-0.005	-0.016	-0.006	-0.003	-0.020	0.011	-0.013	-0.008
1.5SGT	-0.002	-0.045	-0.007	-0.009	-0.001	0.001	-0.012	-0.028	0.003	-0.001
0.5SEN	-0.002	-0.047	-0.007	-0.010	-0.002	-0.001	-0.016	-0.016	-0.002	-0.003
1.5SEN	-0.002	-0.048	-0.007	-0.011	-0.002	-0.001	-0.015	-0.017	-0.002	-0.002
0.55SGM	-0.002	-0.038	-0.008	-0.009	-0.002	0.001	-0.013	-0.025	0.005	0.001
1.5SGM	-0.003	-0.058	-0.006	-0.012	-0.002	-0.002	-0.018	-0.009	-0.008	-0.005

Panel B: CO2 effect

	Canada	Russia	China	India	Mexico	USA	Oil Exporter	EU	Rest-Annex 1	Rest of World
Base	0.035	-0.737	0.020	-0.228	0.064	0.063	-0.018	0.331	-0.125	0.037
0.5SGT	0.026	-0.692	0.040	-0.300	0.066	0.048	-0.019	0.501	-0.257	0.012
1.5SGT	0.037	-0.975	0.004	-0.155	0.055	0.068	-0.021	0.264	0.009	0.041
0.5SEN	0.033	-0.701	0.020	-0.206	0.064	0.064	-0.014	0.309	-0.130	0.037

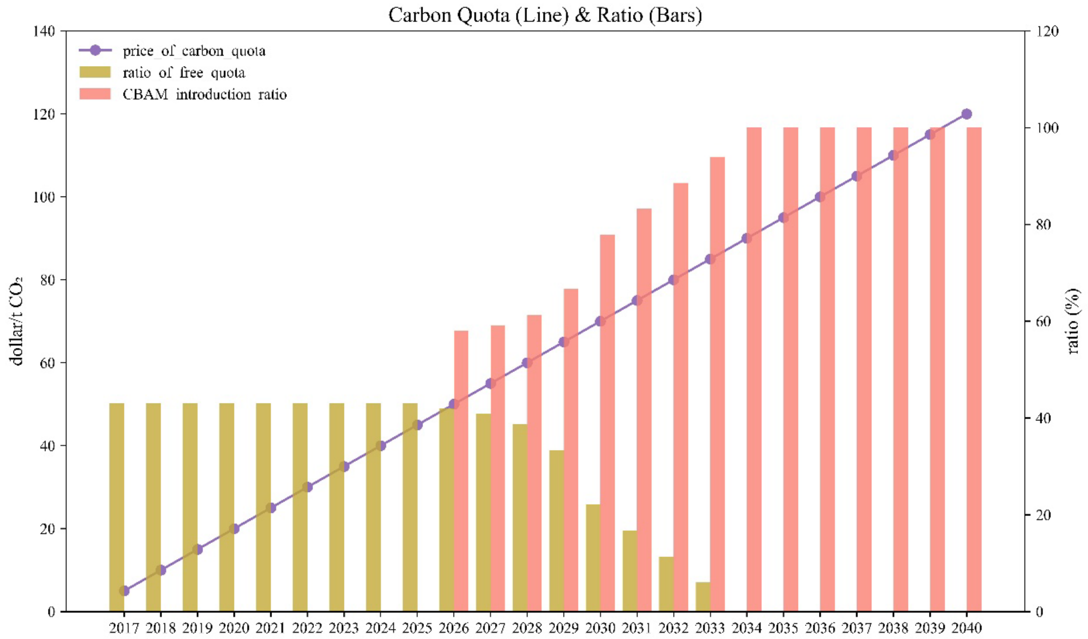
1.5SEN	0.036	-0.772	0.020	-0.246	0.063	0.061	-0.023	0.353	-0.122	0.036
0.55SGM	0.038	-0.462	0.006	-0.257	0.056	0.070	-0.017	0.059	0.071	0.061
1.5SGM	0.029	-1.109	0.033	-0.196	0.071	0.056	-0.017	0.703	-0.401	0.012

Panel C: Global effect

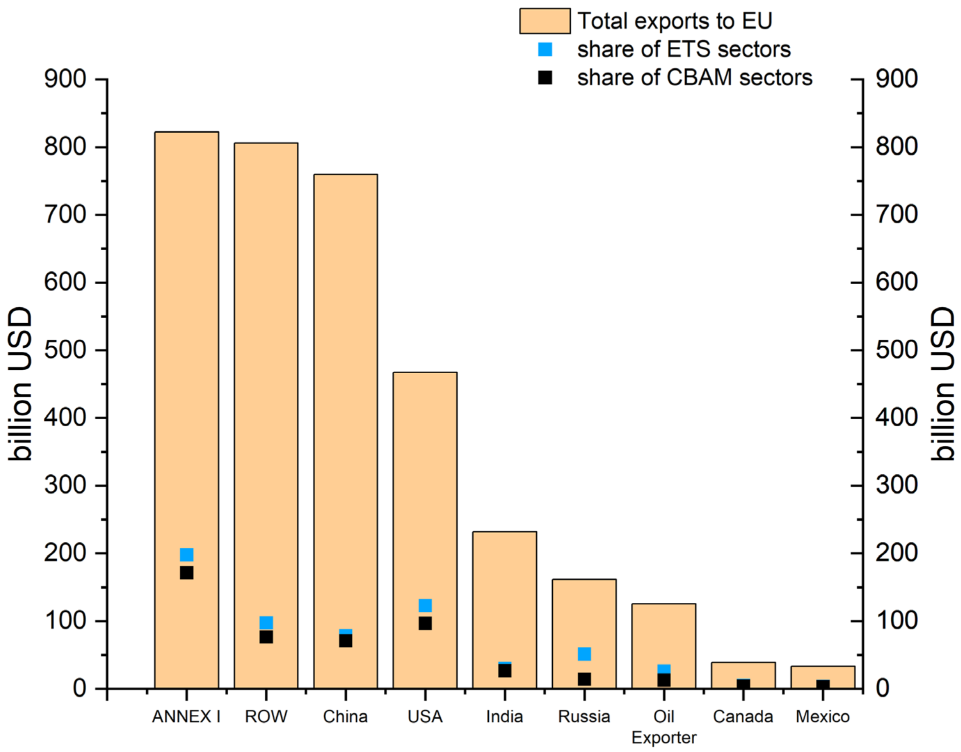
	world GDP	world CO2	leakage (ETS)	leakage (CBAM)	leakage reduction
Base	-0.007	-0.028	59.407	54.551	4.855
0.5SGT	-0.007	-0.031	55.470	49.809	5.661
1.5SGT	-0.007	-0.027	64.505	59.924	4.580
0.5SEN	-0.007	-0.024	65.439	60.867	4.572
1.5SEN	-0.007	-0.031	54.125	49.090	5.035
0.55SGM	-0.006	-0.025	56.035	52.395	3.640
1.5SGM	-0.008	-0.034	63.151	56.541	6.610

Note: SGT: elasticity of imports from different countries; SGM: Armington elasticity between domestic and imports; SEN: energy composite elasticity.

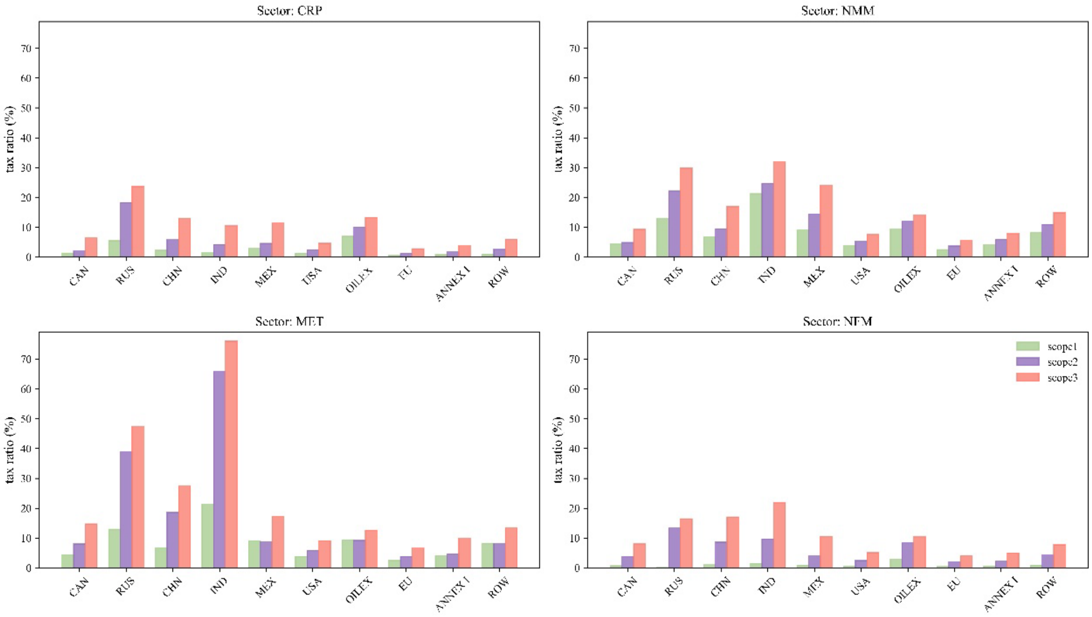
Supplementary Figures



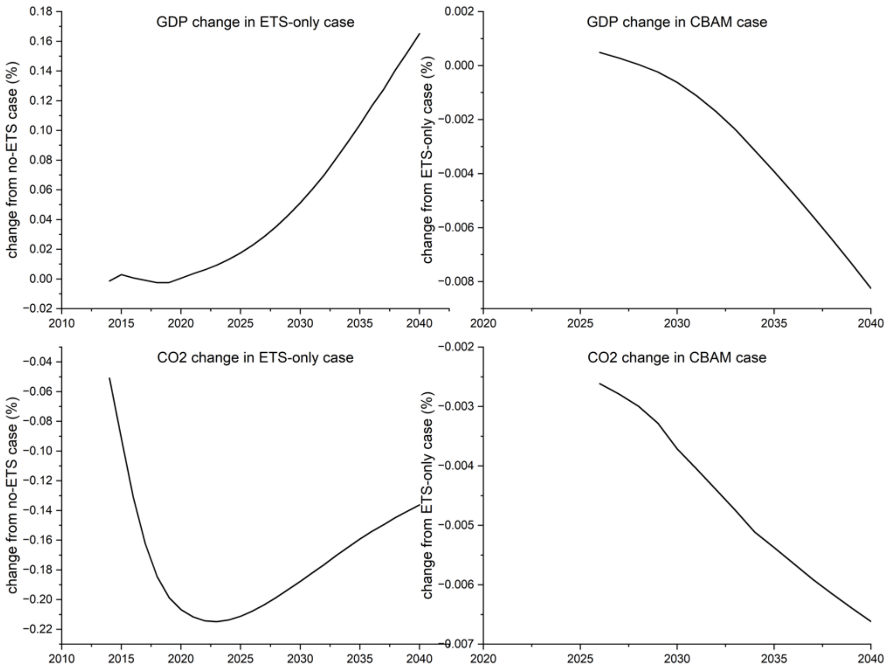
Supplementary Fig.1. Carbon price and free allowance settings in scenario simulations



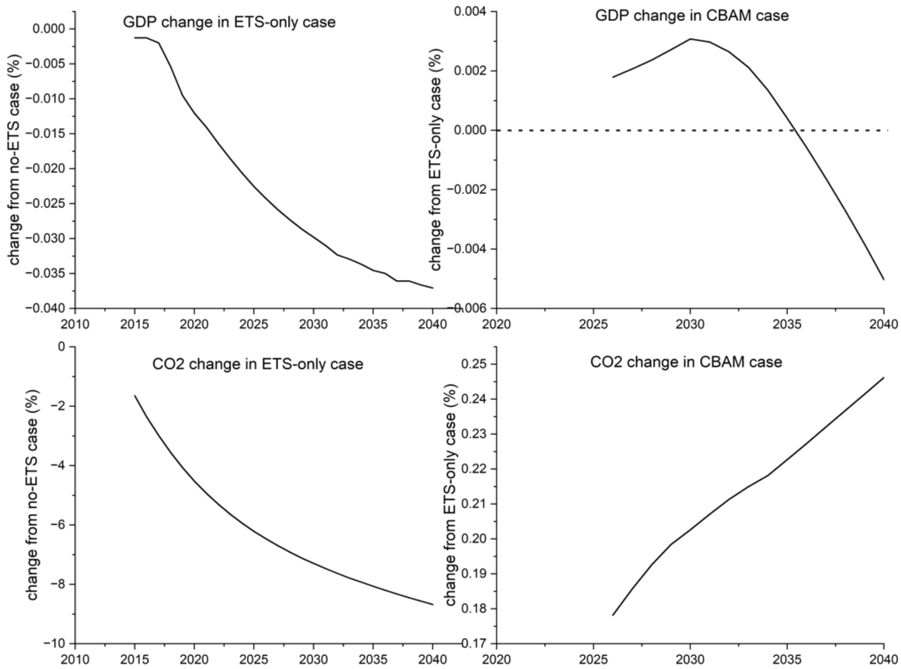
Supplementary Fig.2. EU imports from other countries in 2026 in no-ETS case (billion $)



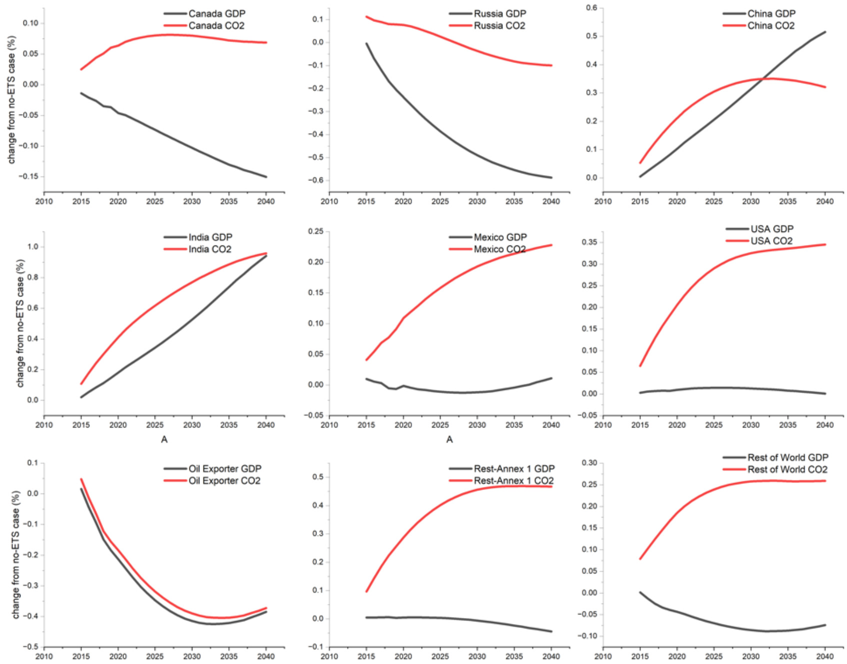
Supplementary Fig.3. Carbon tariff rates on CBAM products under the three scopes of emission coverage (assuming a carbon price of $100/ton)



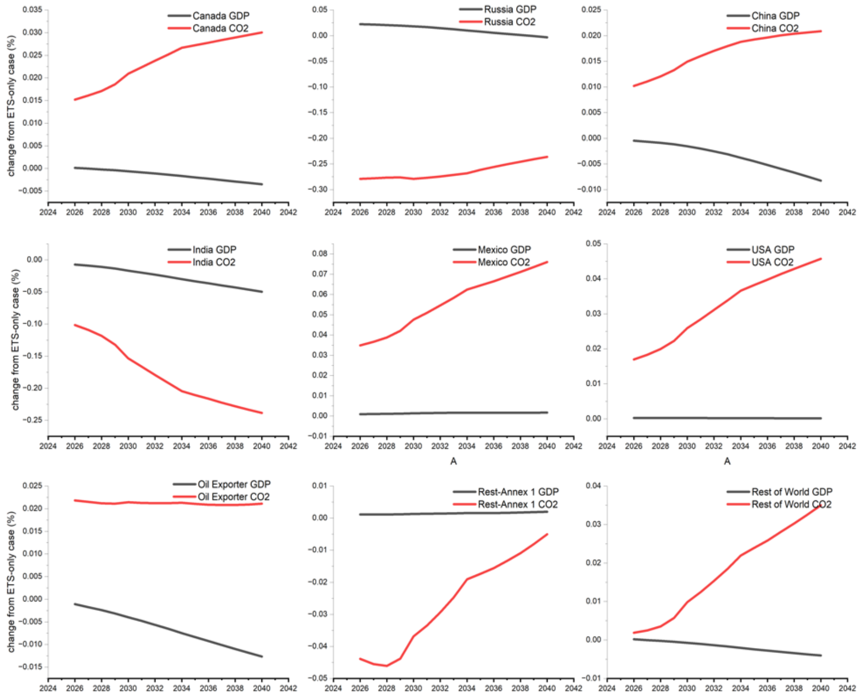
Supplementary Fig.4(a): Dynamic change of global GDP and CO2 emissions



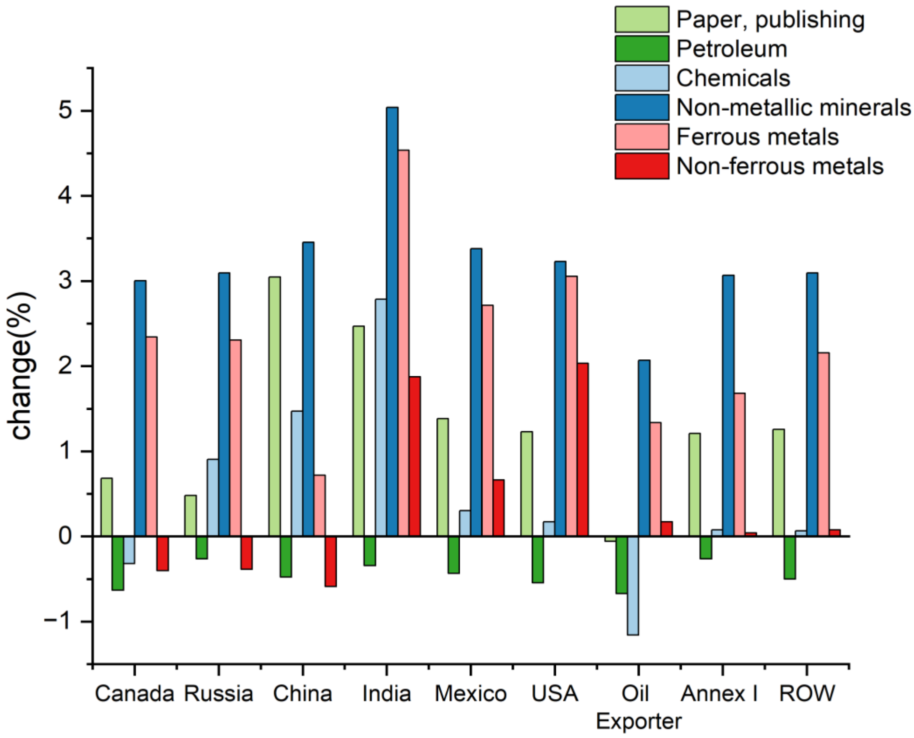
Supplementary Fig.4(b): Dynamic change of EU GDP and CO2 emissions



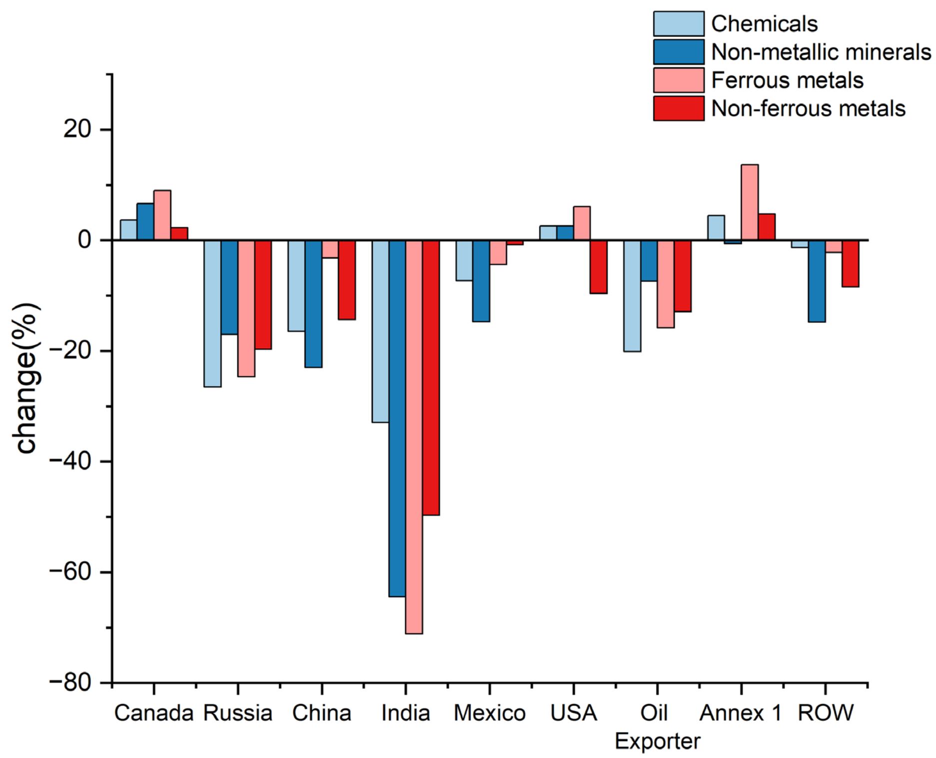
Supplementary Fig.4(c): Dynamic effects of EU ETS on GDP and CO2 in major regions (% change from no-ETS case)



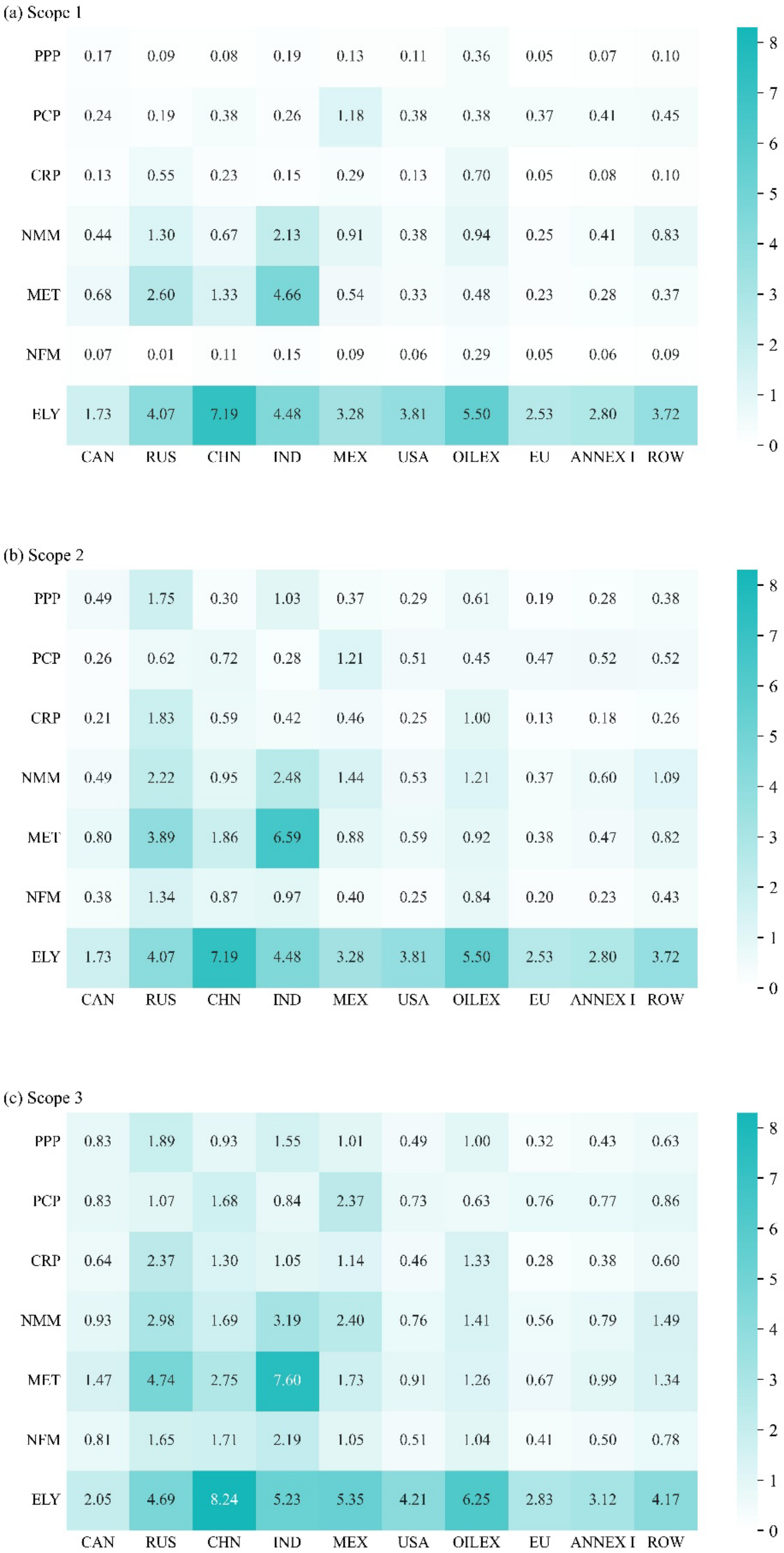
Supplementary Fig.4(d): Dynamic effects of EU CBAM on GDP and CO2 in major regions (% change from ETS-only case)



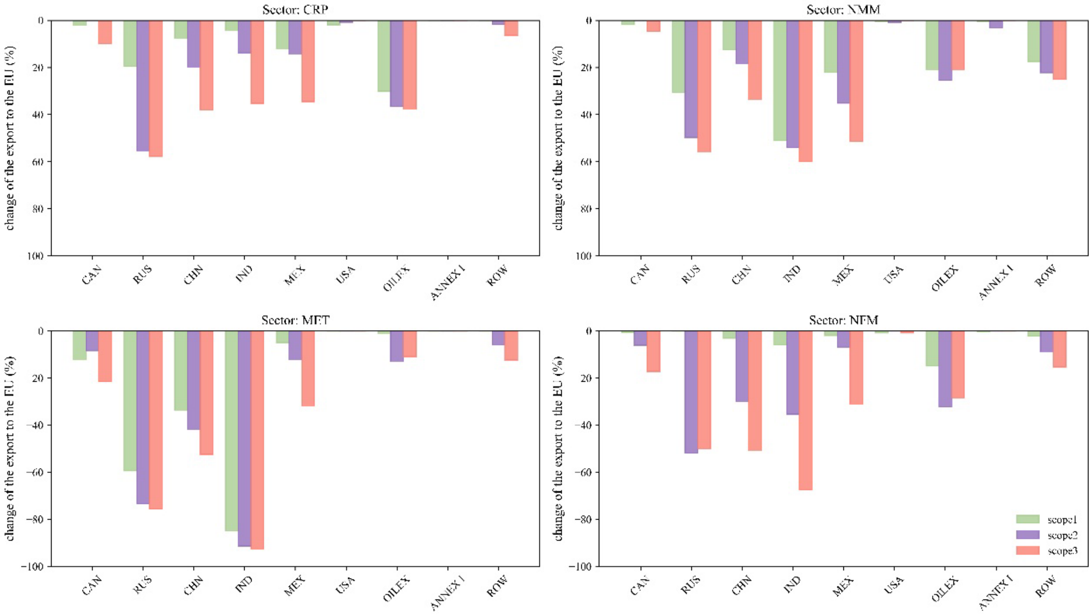
Supplementary Fig.5. (a) Effects of ETS on 2040 imports of ETS products by EU (% change from no-ETS case)



Supplementary Fig.5. (b) Effects of CBAM on imports by EU in 2040 (% change from ETS-only case)



Supplementary Fig.6. Sectoral carbon intensity across countries under different carbon-accounting scopes



Supplementary Fig.7. Effects of CBAM on imports by EU in 2040 under 3 scopes of coverage, (% change from ETS-only case)

Supplementary Discussion

3. 1 Further Details on Impacts of EU ETS and CBAM

3.1.1 ETS-only (without CBAM)

In Section 2.1 we summarized the effects of the unilateral EU ETS policy, the ETS-only policy without the CBAM. Here we provide further details about the impacts on output and trade. These effects are derived from comparing the S.ETS scenario with the S.no-ETS one. The effects on the main macro variables and CO2 emissions are given in Fig. 1. in the main text and now we discuss the effects on sector output, imports and exports reported in Appendix Tables below.

Supplementary Table 5 gives the effects of EU ETS on output, exports, and imports for all 10 regions for the 7 ETS sectors in 2040. In the EU, electricity output fall by a large-11.3% since it does not receive free permits, while output of the other ETS sectors also shrink due to the loss of competitiveness (Petroleum -5.55%, Chemicals -1.82%, Non-metallic minerals -1.78%, Ferrous metals -3.18%, Non-ferrous metals -4.18%). Imports of ETS goods into the EU rise in response to the less competitive EU prices (Paper +1.61%, Chemicals +0.31%, Non-metallic minerals +3.27%, Ferrous Metal +4.60%). The exception is Petroleum Products, which sees a small fall in imports in line with a fall in overall petroleum demand. The exports of ETS goods from India, USA, and China to the EU rise significantly while Canada, Russia and Oil exporters see a small fall in exports in some goods despite an overall increase in their exports due to a depreciated exchange rate. These changes in exports and imports leads to corresponding changes in sector output, e.g., Chemicals in India (+2.82%), in China (-0.98%), in Canada (-0.20%).

Supplementary Table 6 gives the changes in output and trade for all 29 sectors in 2040 for the EU, China, Russia, and India with the ETS sectors marked in bolder texts. The higher costs of production in S.ETS raise prices of the ETS sectors even after including output subsidies representing the limited free permits. This cuts demand and ETS sector output falls the most. They reduce their oil and gas inputs and thus the output of coal falls by 15.26% and Gas Utilities by 7.06%. Supplementary Table 6 also shows that China increased its exports of the ETS goods, Chemicals +1.41%, NMM +0.51%), and reduced their imports when EU prices of these goods rise, resulting in a small increase in output.

Supplementary Fig.5 shows the effect on exports of ETS goods from other regions to EU after implementation of the EU ETS in 2040. We can see that China, India, USA, and Annex I countries increase these exports to the EU (except for Petroleum products that have a big fall in overall EU demand). The exports of Ferrous metals from China, India and USA rise by 0.72%, 4.54%, 3.05% respectively. Exports of Chemicals and non-metal minerals also increase. There is a small twist in the structure of non-ferrous metals trade with exports from most regions to the EU rising except for Canada, Russia, and China exports.

3.1.2 CBAM effects

The effects of the CBAM are discussed in section 2.2, where the changes in the macro variables from the ETS-only case are given in Fig. 2. The effects on sector output and trade are presented in Supplementary Tables 7 and 8. The main text noted that the CBAM led to a big change in exports of CBAM covered products from the non-EU regions to the EU, but the change in total exports of CBAM goods to the world from non-EU regions is small.

Supplementary Fig.5 shows the large reductions in exports from India to the EU (Chemicals -32%, NMM -63%, Ferrous metals -70%). The reductions in Russia exports are about 20% for these CBAM goods, and about 10% for China exports. There is a shift to exports from the low-intensity countries; the exports of CBAM goods from Canada, US and Annex 1 to the EU rise by up to 15%. Supplementary Table 7 shows substantial reductions of total CBAM goods exports to the world of India, Russia, and China in 2040. When the carbon tariffs are imposed, the exports of Chemicals, Non-metallic min., Ferrous metals, and Non-ferrous metals from India fall by 0.51%, 4.30%, 12.94%, 0.32% respectively, after rising by 4.97%, 9.20%, 25.19%, 5.03% in ETS-only case. China exports of Chemicals to the world fall by 1.87% after falling by 2.96% in the ETS-only case; Non-metallic min. exports fall by 2.14% after falling 1.31%.

3.1.3 CBAM effects under different CO2 coverage (scopes) rules

The main effects of using different rules to define the coverage of CO2 emissions under the ETS are compared in section 2.3 in the main text. Scope 1 covers only direct emissions from fossil fuel use by each producer, scope 2 includes CO2 embodied in electricity and scope 3 includes CO2 embodied in all intermediate inputs. The carbon tariffs under these 3 scopes are very different and shown in Supplementary Figure 3, and the main impacts are compared in Table 3. Here we describe the comparisons at the sector level.

Under scope 2, Chemical imports from India into the EU decrease by **32.9%**, but under scope 1, this reduction is only **9.7%** (Supplementary Fig.6). Similarly, Chemical imports from China fall by **16.4%** versus only **6.1%**, while imports from the Rest-of-Annex I are **4.4%** versus **1.3%**. A similar range of differences is observed for imports of ferrous metals, non-ferrous metals, and non-metallic mineral products. There is an interesting twist for Chemicals output in the EU, under scope 2 the carbon tariff raises output by 0.40% but lowers it by 0.21% under scope 1 given the very low protection and small change in imports (Supplementary Table 9). The effect is even more pronounced in countries like China, India, and Russia, where the power sector is still heavily reliant on fossil fuels.

If CBAM rules shift to scope 1 to scope 2, they experience larger impacts on output. In India, for example, the reduction in chemical exports to the EU leads to an increase in output by only 0.02% under scope 1, compared to a more significant decline 0.26% under scope 2, and an even larger 0.73% under scope 3. Similar trends are seen in China chemical output. Among the gainers, the rise in chemical exports from the USA to the EU leads to an output expansion of 0.09% under scope 2, but this increase is only 0.01% under scope 1.

For the EU, under scope 2 CBAM protection, ferrous metals output is higher by 0.85% compared to the ETS-only case, but rises by only 0.24% under scope 1, and falls by 0.25% in the scope 3 case given the overall negative GDP effect.

3.2 Sensitivity Analysis

3.2.1 Parameter uncertainty

It is well-known that the simulated policy responses using CGE models such as the one used here depends on the model structure and elasticities of the production and consumption functions. Although all the parameters in the model matter, the change in fuel demand depends to a large degree on the energy input elasticities in the production functions and the changes in imports are mainly driven by the Armington elasticities. The leakage rate would be affected by both sets of elasticities. The elasticities for the CES functions used are taken from the GTAP database. We show how they affect the size of the CBAM impacts under scope 2 coverage by running pairs of simulations – ETS-only case and CBAM case - with alternative values of 3 key elasticities. The parameters tested are: (i) the elasticity between imports from different countries (SGT, $\sigma^{t}_{t,r}$ in Model App. eq. 68); (ii) the Armington elasticity between domestic and imported commodities (SGM, $\sigma^{m}_{t,r}$ eq. 64); (iii) the energy composite elasticity (SEN, $\sigma^{en}_{t,r}$ eq 27c). We use two alternative values of these 3 parameters – 0.5 times and 1.5 times their base values. They are changed one at a time.

The results are presented in Supplementary Table 12 where Panel A shows how the effects of CBAM on 2040 GDP are changed when the elasticities are changed, Panel B for CO2 emissions, and Panel C for global leakage rates. Recall that the CBAM reduces the imports of covered products into the EU, raises the output of ETS goods and worsens EU GDP a little. With a more elastic SGM, the tariffs reduce imports more, and domestic output of ETS goods rises, thus a bigger increase in CO2 (.703 vs. .331) and a more positive impact on GDP (-.009 vs. -.017). With a more elastic SGT, the exports of the different regions to the EU have bigger changes than with the base elasticity (i.e. India exports are hurt more, US exports are hurt less), on net, the reduction in total imports of ETS goods into the EU is smaller, the rise in EU output is smaller and thus the increase in EU emissions is smaller (.264 vs. .331). The bigger reduction in India exports makes the reduction in CO2 emissions of India slightly bigger (-.155 vs. -.228). The CBAM reduces the leakage rate, and the more elastic SGM generates a slightly poorer leakage reduction (6.610 vs. 4.855) while a more elastic SGT generates a much worse leakage reduction (4.580 vs. 4.855).

The CBAM does not change carbon prices, and thus changes in the energy composite elasticity have only tiny effects. In the EU, the CBAM raises ETS output (relative to the ETS-only case), and the more elastic SEN means that the higher ETS output raise energy prices in the EU by less, which encourages the non-ETS sectors to consume more fuels, and thus EU CO2 rises modestly (.353 vs. .331). The impact on EU GDP is essentially zero. Globally, however, the more elastic energy substitution generates a bigger reduction in exports from Russia and India to the EU and the reduction in global CO2 is a bit bigger (-.031 vs. -.028).

To summarize the sensitivity analysis, we may conclude that these key parameters affect the estimated size of policy impacts to a noticeable degree. However, the direction of the change in emissions in the EU and globally is not reversed. The sign of the change in emissions in only 1 region is reversed by the different elasticities (Rest of Annex I). The change in GDP due to the CBAM is very small for all regions, and the sign of the change is sensitive to the parameter values, however, the effect on global GDP is not reversed. The change in leakage rates is also not reversed by the different elasticities tested.

3.2.2 CBAM adjustment for existing carbon prices in non-EU regions

The EU CBAM rules would allow importers to report effective carbon prices faced by the foreign producers and reduce the carbon tariff rates accordingly. However, carbon prices outside the EU are implemented in complex ways covering only certain industries or certain states/regions. World Bank (2024) provides an accounting of this complex system of world carbon prices. They are small on average, for example, the ETS in China was only in 7 pilot areas until the recent extension to the whole country for just the electricity sector. The prices observed were in the \$4-\$13/ton range. We thus ignored these non-EU prices in the S.CBAM scenario. To show how these non-EU prices might affect the operation of the CBAM we ran another pair of scenarios, S.ROWets and S.ROWcbam, where we assume that the US, Canada, and other Annex I countries have carbon prices at 50% of the EU's price, while China and Mexico have prices at 20% of the EU's price. These are merely illustrative prices, somewhat higher than the actual prices to show the possible extent of the effects. The covered sectors and allowance allocation mirror the EU ETS settings. These countries will now pay a tariff that is lower by the amount of their assumed carbon price.

The results of these S.ROW cases are given in Supplementary Fig.8 and Supplementary Table 10. In the ETS-only case, the introduction of carbon prices in these 5 non-EU countries mitigates the negative impact of ETS on EU's GDP. For all 5 countries with carbon prices, except China, the GDP impact shifted from a previously positive effect under the EU ETS-only scenario to a negative effect. For China, the previously positive impact of EU ETS was reduced by its carbon price. The big change from S.ETS to S.ROWets is that the leakage rate is reduced from 70% in Table 1 to 27%. However, the introduction of CBAM in S.ROWcbam, only marginally reduced the leakage rate further to 25.90%. Despite a reduction in CBAM fees, there is a slight negative impact of the EU-CBAM on the GDP of the 5 countries, for example, in Table 2 the change in China GDP was -.008, but in Supplementary Table 10, it is -.023.

3.2.3 Making sector coverage of CBAM match ETS

While the current CBAM covers only 5 of the 7 ETS sectors, there are indications that it would be extended to cover all 7 sectors after a transitional phase. We consider a scenario where there are carbon tariffs on all 7 ETS sectors (scenario S.CBAM7sec), that is, including paper and petroleum products. The aggregate results are given in Supplementary Table 11a which should be compared with the S.CBAM results in Table 2, and the sector results are in A11b (compare with Supplementary Table 7).

The 2 sectors affected, paper and petroleum, are in bold in Supplementary Table 11b and obviously have the biggest difference. In the original CBAM case in Supplementary Table 7, the output of paper in EU in 2040 changes by -.09% due to the smaller CBAM coverage, but with the carbon tariff protection in S.CBAM7sec, it changes by 0.32% accompanied by a big fall in imports into the EU. For petroleum, the change was .07% but is -.26% in Supplementary Table 11b. When the price of imported petroleum products rises in S.CBAM7sec, it discourages consumption and imports into the EU falls. This changes global demand so much that exports from the EU falls, leading to a small fall in EU output of petroleum products. Output in the other CBAM sectors is slightly lower than in the original S.CBAM case but output in the non-CBAM sectors is higher.

At the aggregate level, EU GDP effects are minor, it changes by -.005% in Table 2, and by .003% when the CBAM covers all 7 ETS sectors. This is likely due to the effects of slightly lower global crude oil prices.

1. Supplementary Model

4.1 Model Summary

This appendix describes the global economic growth model used in Hu, Cao and Ho (2022) to simulate the impact of greenhouse-gas (GHG) emissions control policies and the parallel border carbon adjustment policies. Section 3 of the main text summarizes the main features of the model, here we provide the full list of equations of the model.

This is a multi-sector, multi-regional general equilibrium model of world economic growth with a dynamic recursive structure, that is, with exogenous savings rates driving capital accumulation. The within-period structure of the economy is a standard formulation used in many CGE models; goods and factor markets are competitive, production technology has constant returns to scale and is represented by a nested series of constant-elasticity of substitution (CES) functions, imported goods are imperfect substitutes with local varieties, and labor is mobile across sectors.

The within-period structure of the model is adapted from one used by Adkins et al. (2012) to study the leakage rates associated with US carbon prices combined with output-based subsidies (see also Adkins and Garbaccio 2007). That model is based on data from the Global Trade Analysis Project (GTAP) version 7, while our model is based on the latest GTAP10.

Our focus is on the European Union carbon policies and leakage-reduction policies, and how they might affect trade flows. We also consider the possibility that the US and other regions implement carbon-leakage policies. This leads to the choice of 10 world regions, as listed in Table 1, which are the major exporters to the EU or major exporters of fossil fuels that will be most affected by GHG policies. The countries that have imposed explicit or implicit carbon prices are the more developed countries and we thus have a Rest of Annex I group that are countries listed in Annex I of the Kyoto Protocol, excluding those explicitly modeled – US, Canada, Russia, EU. Annex I countries have explicit targets under Kyoto.

29 industries are identified in the model, as listed in Table 2. Six are energy related (coal, oil mining, gas, refining, electricity, gas utilities) and 15 are manufacturing ranging from low to very high energy intensity; these allow us to track the trade in commodities in some detail especially those that would suffer the biggest burden from a carbon price.

The model employs standard neoclassical assumptions of competitive markets and constant returns to scale. The supply from each industry in each region is described by the behavior of a representative firm, and a representative household in each region government consumption demand. We describe the sub-models for production, consumption, government and trade sectors in turn below. Then we turn to the model closures and market equilibrium in section A.5. The data sources and construction are described in A.6 where we present a summary Social Accounting Matrix. The model is implemented using the General Algebraic Modeling System (GAMS) (Brooke et al., 2006), and is specified and solved in levels.

For convenient reference, all the variables in the model are listed in Supplementary Table 1, with a brief description of each variable. Parameters used are listed in Supplementary Table 2. The indexes used with variables are:

t, k	Sectors (industries/commodities)
r, s	Countries/regions
f	Factors {capital, labor, land, resources}
ff0	All factors except natural resources
t1	Fuel commodities with CO2 emissions {COA,OIL,GAS,PCP,GDT}
e	Energy sectors { COA,OIL,GAS,PCP,ELY,GDT }
S^{ETS}	set of industries subject to emission trading system
S^{BCA}	set of industries subject to border carbon adjustments

t6 Non-energy sectors
y time (yearly intervals)

A complete list of equations is given at the end of this appendix. To avoid being bogged down in details we ignore the minor equations in the discussion here. Equation numbers in the body of this Appendix refer to those in the complete list at the end.

4.1.1 Household consumption and labor supply

Each regional economy has a representative household which owns the factors of production, F_{fr}, where f={labor, capital, land and resources} and *r* indexes the 10 regions. It receives factor income in the form of wages and returns on assets, net of factor taxes. It may also receive government transfer payments (*GTRANS*). Household disposable income (*HDI*) is thus:

$$HDI_r = \sum_{t,f} apf_{ftr} PF_{fr} DF_{ftr} - deprt_r FS_{"cap",r} + GTRANS_r - FTAX\_L_r - HTAX_r \quad (4b)$$

PF denote factor prices paid by employers, and the *apf* coefficients are explained in section A.2 below. See Supplementary Table 1 for a glossary of the other terms.

Household divides its disposable income between consumption and savings. Savings (SAV) is used for financing investment, the government deficit, and the current account (CA) surplus (explained in eq. 94 below).

$$SAV_r = HDI_r - \sum_t PC_{t,r} \cdot C_{t,r} \quad (5)$$

The allocation of consumption expenditures to goods and services is through an extended linear expenditure demand system (ELES) derived from a Stone-Geary utility function that includes leisure as an argument (see eq. 0). These demands for consumption of good t and leisure are, respectively:

$$PC_{t,r}C_{t,r} = PC_{t,r}\gamma_{t,r} + \left(\frac{\beta_{t,r}}{1-\beta_r^0}\right)\left[SUPY_r - SAV_r\right] \quad (1)$$

$$Leis_r = MT_r - FS_{"lab",r} = \frac{\beta_r^0}{1-\beta_r^0}\left[\frac{SUPY_r - SAV_r}{PFN_{"lab",r} / CPI}\right] \quad (3)$$

where $\gamma_{t,r}$ is the commitment (subsistence) consumption, MT is the time endowment and $FS_{"lab"}$ is the supply of labor. SUPY is the supernumerary income defined in (5b). Note that the LES has an income elasticity determined by $\beta_{t,r}$, unlike some commonly used CES functions that imposes unit elasticities. The function also gives rise to a flexible household labor supply function, in which reductions in the net wage, resulting from reductions in the before-tax wage, or increases in the tax on labor, will reduce the amount of labor supplied. Flexible labor supply is allowed for Canada, EU, USA, and Rest of Annex 1, while the other regions are assumed to have fixed supplies.

4.1.2 Production

In each region *r*, producers in each of the 29 sectors supply commodities for the domestic and export markets. A representative firm in each sector maximizes profits by combining primary factors and intermediate goods according to a nested production structure with constant returns to scale technology. The factors include labor, capital, land, and resources. The nest structure is illustrated below.

At the top nest, firms combine a value-added-energy (VE_{tr}) composite with a non-energy intermediate bundle (*NX*) according to a constant elasticity of substitution (CES) function to produce output Q_{tr}. The intermediate bundle is a fixed-proportions combination of non-energy intermediate inputs (i.e. a Leontief function). The value-added-energy composite is a CES combination of a value-added composite and an energy composite.

We represent the production technologies using cost duals, at the top nest the price of output, net of sales tax, in sector t, $(1-ty_{tr})P_{tr}$, is equal to the unit total cost, PTC_{tr}, and is given as a CES function of the price of the value-added-energy composite (PVE_{tr}) and the price of the intermediate bundle (PN_{tr}):

$$PTC_{t,r} = \left(\frac{1}{aa_{try}}\right) \cdot \left[\zeta_{t,r}^{\sigma_{t,r}^{n}} \cdot PN_{t,r}^{\left(1-\sigma_{t,r}^{n}\right)} + \left(1 - \zeta_{t,r}\right)^{\sigma_{t,r}^{n}} \cdot PVE_{t,r}^{\left(1-\sigma_{t,r}^{n}\right)} \right]^{\frac{1}{1-\sigma_{t,r}^{n}}} \qquad (21)$$

$\sigma_{t,r}^{n}$ is the elasticity of substitution and aa_{try} is the index of technology for year *y*. The value of output to the seller exactly equals total cost in this constant returns, perfectly competitive model:

$$(1-ty_{tr})P_{tr}Q_{tr} = PTC_{tr}Q_{tr} = PVE_{tr}VE_{tr} + PN_{tr}NX_{tr} \qquad (20)$$

Eq. (21) is a standard CES cost function with the well-known input demand functions for VE and NX given in eqs. (30) and (33).

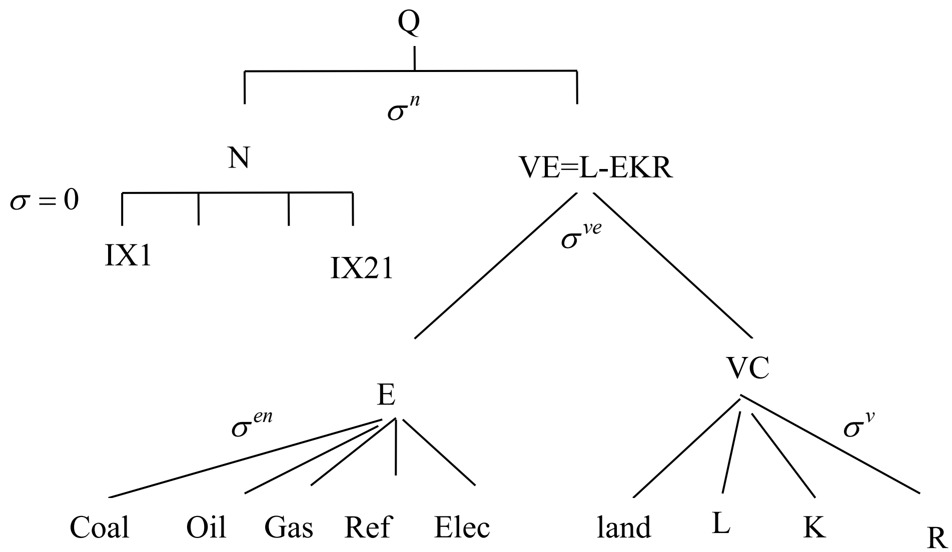
In the second nest, VE_{tr} is an aggregate of value-added (VA) and total energy (EN), and the cost dual for the price of *VE*, PVE_{tr}, is written as:

$$PVE_{t,r} = \left(\frac{1}{ee_{t,r}}\right) \left[\eta_{t,r}^{\sigma_{t,r}^{ve}} \cdot PEN_{t,r}^{\left(1-\sigma_{t,r}^{ve}\right)} + \left(1 - \eta_{t,r}\right)^{\sigma_{t,r}^{ve}} \cdot PVC_{t,r}^{\left(1-\sigma_{t,r}^{ve}\right)} \right]^{\frac{1}{1-\sigma_{t,r}^{ve}}} \qquad (22)$$

$\sigma_{t,r}^{ve}$ is the elasticity of substitution between value-added and energy. The demands for VA and EN are given in equations (31) and (32) [4], and the value identity is (29c).

Production function nests:
Gross output: Q=f(VE[VC(K,L), E], M)
Energy bundle: E=f(Coal, Oil mining, Gas mining, Refining, Electricity, Gas utilities}

[4] The specification of industry energy demand is a much-discussed issue in energy/environmental models. Burniaux and Truong (2002) and Lecca, Swales and Turner (2011) discuss the implications of alternative production structures for the overall elasticity of substitution between energy and capital.


Q
σ^n
N
σ = 0
IX1
IX21
VE=L-EKR
σ^ve
E
σ^en
Coal
Oil
Gas
Ref
Elec
VC
σ^v
land
L
K
R

In the other node of the second nest, aggregate non-energy intermediate is allocated to the 23 commodities using a Leontief function in (35); the value identity for this is eq. (29d).

In the third nest, the value-added composite is a CES combination of labor and capital in most industries; the agriculture function also includes crop land as a specific factor, and natural resources are used in agriculture, coal mining, oil mining, gas mining, other mining. The quantity of factor input is denoted as F_{ftr}, f={capital, labor, land, resources}. In the standard version of the model, we assume that both capital and labor are mobile across sectors but immobile internationally. For sensitivity tests, we have a version where capital is immobile within a given period. Land and resources are sector-specific factors. The price of the value-added composite, PVC_{tr}, is a CES function of the factor prices, $apf_{ftr}PF_{fr}$:

$$PVC_{t,r} \quad = \quad \left(\frac{1}{a_{t,r}}\right) \cdot \left[\sum_f \delta_{f,t,r}^{\sigma_{t,r}^v} \cdot (apf_{ftr} PF_{f,r})^{\left(1-\sigma_{t,r}^v\right)} \right]^{\frac{1}{1-\sigma_{t,r}^v}} \tag{23}$$

$\sigma_{t,r}^v$ is the elasticity of substitution between the primary factors, and PF_{fr} is the price of the mobile factor f in region r. We recognize that factor prices differ across sectors, e.g. different wages per worker, and adjust the regional price with exogenous coefficients, apf_{ftr}. The primal production function counterpart of the cost dual (23) is given in (25). The factor demands for DF_{fr} are given in (36) and the value equation is (29e).

The energy composite is a CES combination of the six energy goods, and the cost function for PEN_{tr} is written as:

$$PEN_{t,r} \quad = \quad \left(\frac{1}{kk_{t,r}}\right) \cdot \left[\sum_e \kappa_{e,t,r}^{\sigma_{t,r}^{en}} \cdot PB_{e,t,r}^{\left(1-\sigma_{t,r}^{en}\right)} \right]^{\frac{1}{1-\sigma_{t,r}^{en}}} \tag{27c}$$

$\sigma_{t,r}^{en}$ is the elasticity of substitution between the energy commodities, and PB_{etr} is the price of energy of type e={coal, oil, gas, refining, electricity, gas utilities}. The demands for each of the 6 types are given in (34), and the value equation is (29f).

4.1.3 Investment and Capital

The household owns all private assets in each region, and we find it convenient to consider an aggregate investor in each region collecting savings from enterprises (retained earnings), households, the government, and foreigners, and uses these savings to purchase investment goods. The total value of investment in year y, in each region r, is set as an exogenous share of GDP:

$$INV_{ry} \quad = \quad inv\_s_{ry} \cdot GNPR_{ry} \tag{11}$$

We simply set retained earnings as the value of depreciation, $deprt_r FS_{"cap",r}$ (as reflected in (4) and (94)).

The current account surplus is the net inflow of foreign investment, NETINFL, discussed later in section A.4. The total investment is thus financed by the retained earnings, household savings, government savings (GSAV, or negative of the deficit) and savings from the rest-of-the-world:

$$INV_r = deprt_r FS_{"cap",r} \; + \; SAV_r + GSAV_r \; - \; ERT_r NETINFL_r \tag{94}$$

NETINLF is denominated in base region (US) currency, and is converted to region r units using the exchange rate, ERT.

Total investment spending in each region is allocated to the 29 commodities using a simple Cobb-Douglas function, where the share parameters are set to benchmark year values:

$$PINV_{t,r} \cdot ID_{t,r} \quad = \quad \beta_{t,r}^{ID} \cdot INV_r \tag{12}$$

Aggregate quantity of investment, I^{agg}, is given by (98). The aggregate stock of capital in region r accumulates according to:

$$K_{rt+1}^{agg} = (1-\delta_r)K_{rt}^{agg} + \psi_{rt}^{K} I_{rt}^{agg} \tag{99b}$$

ψ_{rt}^{K} is a composition coefficient to reconcile the distinct composition of the investment flow from capital stock. This is called quality of capital stock in Jorgenson et al. (2013).

4.1.4 International trade and current account balance

World trade is represented as a set of bilateral commodities trade flows. In each region, imports arriving from different source countries are first bundled into a composite import according to an Armington specification, which treats imports from different source countries as imperfect substitutes.[5] Total demand for each commodity (SX) is allocated to the import composite (MX) and the domestic variety (DX) using a CES function:

$$SX_{t,r} = b_{t,r}\left[\alpha_{t,r} DX_{t,r}^{\frac{\sigma_{t,r}^{m}-1}{\sigma_{t,r}^{m}}} + \left(1-\alpha_{t,r}\right) MX_{t,r}^{\frac{\sigma_{t,r}^{m}-1}{\sigma_{t,r}^{m}}}\right]^{\frac{\sigma_{t,r}^{m}}{\sigma_{t,r}^{m}-1}} \tag{64}$$

$\sigma_{t,r}^{m}$ is the elasticity of substitution between imports and domestic goods. The demand for imports and domestic varieties derived from this CES function are given in (65) and (67). The import composite in region r is a CES function over the exports from each region s, X_{tsr}:

$$MX_{t,r} = \mu_{t,r}\left[\sum_{s} ts_{t,s,r} X_{t,s,r}^{\frac{\sigma_{t,r}^{t}-1}{\sigma_{t,r}^{t}}}\right]^{\frac{\sigma_{t,r}^{t}}{\sigma_{t,r}^{t}-1}} \tag{68b}$$

The world price of commodity t exported by r in base region (US) units is PWE_{trs}, and is equal to the price received by the producer in r (PE_{tr}) plus export taxes less any border carbon adjustments, and all scaled by the exchange rate:

$$PWE_{t,r,s} = ((1 + te_{t,r,s})PE_{t,r} - se_{tr}^{co2})\left(\frac{1}{ERT_r}\right) \tag{61b}$$

The unit export rebate, se_{tr}^{co2}, is given by the government of the region r that has imposed a carbon price on producer of t in r. The landed price of imports from s to r is PWM_{tsr} and is given as the world price plus shipping margins:

$$PWM_{t,s,r} = (1 + trs_{t,s,r}) \cdot PWE_{t,s,r} \tag{62}$$

The exports from s to r derived from (68c) is given in (68b). The total value of imports of good t is the sum over all exporters s, inclusive of tariffs (tm), border carbon taxes (tm^{co2}) and non-tariff barrier equivalents (tn):

$$PM_{tr}MX_{tr} = \sum_{s}\left(1 + adjtm_{tsr}tn_{tsr} + tm_{tsr}\right)ERT_r PWM_{tsr}X_{tsr} + tm_{tsr}^{co2}ERT_r X_{tsr} \tag{63b}$$

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[5] The Armington assumption is commonly used in multi-region CGE models to account for two-way trade, or cross-hauling of seemingly identical goods.

The unit tm^{co2} tariff on imports into *r* is imposed by the region with a carbon price policy to preserve the competitiveness of producer *t* in *r*.

International shipping services is treated in a special fashion, this is part of the transportation services sector. On the export side, each region supplies exports of its transport services commodity to an international shipping sector, which maximizes its own profits and generates "input" demand for such exports according to a CES technology (eq. 79). In turn, each region demands international shipping services for each exported commodity and a fixed transport cost is applied that is route- and commodity-specific (eq. 80). In equilibrium, total world supply of shipping services must equal total world demand.

For each region, the current account surplus, *NETINFL*, is given as total export revenue less import expenditure, plus the non-trade net flow, *FDI*, in eq. (70). This balance is fixed exogenous for all periods and is met by the endogenous exchange rate, *ERT*.

4.1.5 Government

The government in each region imposes taxes, purchases goods, and pays interest and transfers. It borrows to finance any deficits which is set exogenously in our standard closure. Taxes are imposed on sales (ty, eq. 49), factors (tf, 51), household income, (th, 52), imports (tm, 47), exports (te, 48), and consumption (tc, 50). Carbon taxes or emission permit prices are represented in eq. (55) and (53), border carbon prices are given in (58) and (59). The total revenue of the government is given by eq. (45).

Government purchases of commodities is allocated according to a simple share function in eq. (44). Transfers (inclusive of interest payments) are set as an exogenous share of GDP (43). The government savings (*GSAV*, the negative of the government deficit) is total revenue minus total expenditures (41). This GSAV is set exogenously and this constraint is met by the endogenous total government purchases, *GPUR*. (In the list of options for the government account closure given in eq. (41-43), this is option 4.) Our model is focus on long-run effects of environmental policy and thus ignore short-run fiscal adjustments found, for example, in Jorgenson et al. (2013). We avoid the complication of accounting for rising debt and embed interest payments in the transfer variable.

4.1.6 Equilibrium and macro closures

This model uses a neoclassical system where prices clear all commodity and factor markets. That is, for commodity t, in each region r, the general equilibrium solution looks for a set of prices so that total supply equals total demand as given in eq. (92). Total supply is the sum of domestically produced goods (DX) plus imports (MX) as given by the CES function in (64) as noted in section A.4 above, and by the value identity in (91). Total demand is the sum of intermediate goods demand and final demand (eq. 92).

Similarly, a set of factor prices is chosen so that the supply of labor, capital, land, and resources equal the total demand for them (eq. 93). In the international markets, the exchange rates, ERT_r, adjust to meet the exogenous current account balance constraint in (70). This implies also that total world exports of good t is equal to total world imports, and the sum over all regions of $NETINFL_r$ is zero (eq. 95). The exchange rate for the US is set at 1 to be the model's numeraire.

The next macro closure is the savings-investment eq. 94 discussed in section A.3. Investment demand is set as an exogenous share of GDP (eq. 11), the current account surplus and government savings are set exogenously, retained earnings are set equal to depreciation allowances, and thus the last item, household savings, is endogenous to satisfy the savings-investment constraint. This setup is equivalent to an exogenous savings rate out of household income and investment demand being endogenous.

We have noted the closure regarding the government flows in section A.5; that is, we set tax rates equal to the base year values, set the deficit exogenously, and let government total purchases, GPUR, be endogenous in eq. (41) (option 4 among the closure options).

4.1.7 Energy and emissions accounting

The GTAP10 database provides estimates of CO2 emissions by fuel for each sector, in each region, separately for domestic fuels and imported fuels. Let $EGHG_{eztr}^{CO2}$ denote the emissions of CO2, the main greenhouse gas, from the use of fuel t1 in sector t, region r, and where z={domestic, imported}. The total emissions due to fuel t1 in sector r, region r is:

$$EMIS_{t1,tr} = \sum_z EGHG_{t1ztr}^{CO2} \qquad \text{t1=\{COA,OIL,GAS,PCP,GDT\}} \qquad (111)$$

From this emission estimate we derive the implied emission coefficients – per unit of fuel input in sector t and per unit of fuel e in the whole economy (in model units of billions of base year dollars):

$$\theta_{etr} = \frac{EMIS_{etr}}{IX_{etr}^{baseyear0}}\ ;\ \theta_{er}^{F} = \frac{\sum_t EMIS_{etr}}{\sum_t IX_{etr}^{baseyear0}} \qquad (112, 113)$$

A parallel set of emission coefficients are defined for the household sector, in terms of emissions per unit fuel consumption (in base year dollars, eq 112b).

The emissions per unit output used to calculate free allocations of emission permits may be derived from the base year data:

$$\theta_{tr}^{Q0} = \frac{\sum_{t1} EMIS_{t1,tr}}{Q_{tr}^{baseyear0}} \qquad (114)$$

Total emissions from region r is the sum of producers' and household emissions:

$$EMR_r^{CO2} = EM_r^{IND,CO2} + EM_r^{HH,CO2} = \sum_{e,t} \theta_{etr} IX_{etr} + \sum_e \theta_{e,HH,r} C_{er} \qquad (118)$$

When a region or regions (set RL) imposes a GHG policy, it will likely affect production and emissions in the rest-of-the-world (ROW). Leakage is defined as the rise in ROW emissions that offset part of the reductions in the policy region. To calculate this, we compute eq. 118 once for the base case without policies, and once for the policy case. The leakage rate for a particular sector t in policy group RL is defined in eq. (119). The global leakage rates for industry, household and total emissions, are defined, respectively, as:

$$LEAK_{IND}^{World} = \frac{\sum_{r\in NRL} EMR_r^{policy,IND,CO2} - EMR_r^{base,IND,CO2}}{\sum_{r\in RL} EMR_r^{base,IND,CO2} - EMR_r^{policy,IND,CO2}} \qquad (119c)$$

$$LEAK_{HH}^{World} = \frac{\sum_{r\in NRL} EMR_r^{policy,HH,CO2} - EMR_r^{base,HH,CO2}}{\sum_{r\in RL} EMR_r^{base,HH,CO2} - EMR_r^{policy,HH,CO2}} \qquad (119d)$$

$$LEAK^{World} = \frac{\sum_{r\in NRL} EMR_r^{policy,CO2} - EMR_r^{base,CO2}}{\sum_{r\in RL} EMR_r^{base,CO2} - EMR_r^{policy,CO2}} \qquad (119b)$$

4.2 Model Equation Listing

Notation

r,s index for region
i,t index for industries/commodities
e index for energy sectors
t1 index for fuels with CO2 emissions
f index for factors
y (or t) time (yearly intervals)
S^{ETS} set of industries subject to an ETS
S^{ETS2} set of industries subject to an ETS with free allocations
S^{CBA} set of industries subject to the carbon border tariff (CBA)

Households, consumption and investment

$$u_r = \beta_r^0 \ln Leis_r + (1-\beta_r^0)\sum_t \beta_{tr} \ln(c_{tr} - \gamma_{tr}); \quad \sum_t \beta_{tr} = 1 \tag{0}$$

$$PC_{t,r} \cdot C_{t,r} = PC_{t,r} \cdot \gamma_{t,r} + \left(\frac{\beta_{t,r}}{1 - \beta_r^0}\right) \cdot \left[SUPY_r - CPI_r \cdot SAV_r\right] \tag{1}$$

$$FS_{"lab",r} = MT_r - \left(\frac{\beta_r^0}{1 - \beta_r^0}\right) \cdot \left[\frac{SUPY_r - SAV_r}{PFN_{"lab",r} / CPI}\right] \tag{2}$$

$$Leis_r = MT_r - FS_{"lab",r} = \frac{\beta_r^0}{1-\beta_r^0}\left[\frac{SUPY_r - SAV_r}{PFN_{"lab",r} / CPI}\right]; \tag{3}$$

$$PFN_{lab,r} Leis_r = \beta_r^0 \left[PFN_{lab,r} Leis_r + Cons\right]$$

$$FS_{cap,r} = FS0("cap") \qquad FS_{lnd,r} = FS0("land") \qquad FS_{res,r} = FS0("resources") \tag{3b}$$

$$HDI_r = \sum\nolimits_{t,f} PFN_{f,r} \cdot DF_{f,t,r} - deprt_r \cdot FS_{"cap",r} + GTRANS_r - HTAX_r$$

(4)

$$HDI_r = \sum\nolimits_{t,f} apf_{ftr} PF_{f,r} \cdot DF_{f,t,r} - deprt_r \cdot FS_{"cap",r} + GTRANS_r$$
$$- FTAX\_L_r - HTAX_r + GT\_CBAM_r$$

(4b)

$$SUPY_r = HDI_r - \sum_t PC_{t,r}\gamma_{t,r} \tag{5b}$$

$$SAV_r = HDI_r - \sum\nolimits_t PC_{t,r} \cdot C_{t,r} \tag{5}$$

$$TCON_r = \sum\nolimits_t PC_{t,r} \cdot C_{t,r} \tag{6}$$

$$PFN_{f,r} = (1 - \lambda_r \cdot tf_{f,r}) \cdot PF_{f,r} \tag{7}$$

$$PC_{t,r} = (1 + tc_{t,r}) \cdot PX_{t,r} \tag{8}$$

$$PGC_{t,r} = (1 + tgc_{t,r}) PX_{t,r}; \quad PINV_{t,r} = (1 + tinv_{t,r}) PX_{t,r} \tag{8b}$$

$$CPI_r = \frac{\sum_t PC_{t,r} \cdot C_{t,r}}{\sum_t PC0_{t,r} \cdot C_{t,r}} \quad (9)$$

Param calib. (FA=Frisch param):

$$\beta_r^0 = \frac{\eta_r^{LS} PFN0_{lab,r} FS0_{lab,r}}{\eta_r^{LS} PFN0_{lab,r} FS0_{lab,r} - (HDI0_r - SAV0_r)} \quad (10a)$$

$$\beta_{t,r} = \frac{(1-\beta_r^0)\eta_{t,r} PC0_{t,r} C0_{t,r} / (HDI0_r - SAV0_r)}{\sum_k \eta_{t,r} PC0_{k,r} C0_{k,r} / (HDI0_r - SAV0_r)}$$

$$\gamma_{t,r} = C0_{t,r} + \frac{1}{1-\beta_r^0} \frac{\beta_{t,r}}{PC0_{t,r}} \frac{HDI0_r - SAV0_r}{FA_r}$$

$$SUPY0_r = HDI0_r - \sum_t PC0_{t,r} \gamma_{t,r};$$

$$PF_{lab,r}(MT_r - FS_{lab,r}) = \beta_r^0 (PF * leis + PC.(C-\gamma)) \quad (10e)$$

$$MT_r = FS0_{lab,r} + \frac{\beta_r^0}{1-\beta_r^0} \frac{SUPY0_r - SAV0_r}{PFN0_{lab,r}} = FS0_{lab,r} + \frac{\beta_r^0}{1-\beta_r^0} \frac{PC.(C-\gamma)_r}{PFN0_{lab,r}}$$

Investment

$$INV_r = inv\_s_r \cdot GNPR_r \quad (11)$$

$$PINV_{t,r} \cdot ID_{t,r} = \beta_{t,r}^{ID} \cdot INV_r \quad (12)$$

$$PK_r = \sum_t \beta_{tr}^{ID} PINV_{tr} \quad (13)$$

Producers

$$(1-ty_{t,r}) P_{t,r} \cdot Q_{t,r} = PVE_{t,r} VE_{t,r} + PN_{t,r} NX_{t,r} \quad (20)$$

$$PTC_{t,r} = \left(\frac{1}{aa_{t,r}}\right) \cdot \left[\zeta_{t,r}^{\sigma_{t,r}^n} \cdot PN_{t,r}^{\left(1-\sigma_{t,r}^n\right)} + \left(1 - \zeta_{t,r}\right)^{\sigma_{t,r}^n} \cdot PVE_{t,r}^{\left(1-\sigma_{t,r}^n\right)} \right]^{\frac{1}{1-\sigma_{t,r}^n}} \quad (21)$$

$$PVE_{t,r} = \left(\frac{1}{ee_{t,r}}\right) \cdot \left[\eta_{t,r}^{\sigma_{t,r}^{ve}} \cdot PEN_{t,r}^{\left(1-\sigma_{t,r}^{ve}\right)} + \left(1 - \eta_{t,r}\right)^{\sigma_{t,r}^{ve}} \cdot PVC_{t,r}^{\left(1-\sigma_{t,r}^{ve}\right)} \right]^{\frac{1}{1-\sigma_{t,r}^{ve}}} \quad (22)$$

$$PVC_{t,r} = \left(\frac{1}{a_{t,r}}\right) \cdot \left[\sum_f \delta_{f,t,r}^{\sigma_{t,r}^v} \cdot (apf_{ftr} PF_{f,r})^{\left(1-\sigma_{t,r}^v\right)} \right]^{\frac{1}{1-\sigma_{t,r}^v}} \quad (23)$$

$$\zeta_{tr} = \frac{PN0_{tr} NX0_{tr}^{1/\sigma_{t,r}^n}}{PVE0_{tr} VE0_{tr}^{1/\sigma_{t,r}^n} + PN0_{tr} NX0_{tr}^{1/\sigma_{t,r}^n}} \quad (24a)$$

$$aa_{t,r} = Q0_{t,r} / \left[\zeta_{t,r} NX0_{t,r}^{\frac{\sigma_{t,r}^n - 1}{\sigma_{t,r}^n}} + \left(1-\zeta_{t,r}\right) VE0_{t,r}^{\frac{\sigma_{t,r}^n - 1}{\sigma_{t,r}^n}} \right]^{\frac{\sigma_{t,r}^n}{\sigma_{t,r}^n - 1}}$$

$$\eta_{t,r} = \frac{PEN0_{tr} EN0_{tr}^{1/\sigma^{ve}_{t,r}}}{PEN0_{tr} EN0_{tr}^{1/\sigma^{ve}_{t,r}} + PVC0_{tr} VA0_{tr}^{1/\sigma^{ve}_{t,r}}}$$

$$ee_{t,r} = VE0_{t,r} / \left[\eta_{t,r} EN0_{t,r}^{\frac{\sigma^{ve}_{t,r}-1}{\sigma^{ve}_{t,r}}} + \left(1-\eta_{t,r}\right) VE0_{t,r}^{\frac{\sigma^{ve}_{t,r}-1}{\sigma^{ve}_{t,r}}} \right]^{\frac{\sigma^{ve}_{t,r}}{\sigma^{ve}_{t,r}-1}}$$

Primal fn. is $VA_{t,r} = a_{t,r} \left[\sum_f \delta_{f,t,r} DF_{f,r}^{\frac{\sigma^{v}_{t,r}-1}{\sigma^{v}_{t,r}}} \right]^{\frac{\sigma^{v}_{t,r}}{\sigma^{v}_{t,r}-1}} \; ; \; \sum_f \delta_{f,t,r} = 1$ (25)

$$\delta_{f,t,r} = [1 + \sum_{\phi \neq f} \frac{PF0_{\phi r}}{PF0_{fr}} \left(\frac{DF0_{\phi r}}{DF0_{fr}} \right)^{1/\sigma^{v}_{t,r}}]^{-1} = \frac{PF0_{ftr} DF0_{ftr}^{1/\sigma^{v}_{t,r}}}{\sum_\phi PF0_{\phi tr} DF0_{\phi tr}^{1/\sigma^{v}_{t,r}}} \tag{26a}$$

$$a_{t,r} = VA0_{tr} / [\sum_f \delta_{ftr} DF0_{ftr}^{\frac{\sigma^{v}_{t,r}-1}{\sigma^{v}_{t,r}}}]^{\frac{\sigma^{v}_{t,r}}{\sigma^{v}_{t,r}-1}}$$

$$a_{t,r} \quad = \quad atfp\; tfp_r\; itfp_{tr} a_{t,r}$$

Version with energy prices common to all buyers:

$$PEN_{t,r} \quad = \quad \left(\frac{1}{kk_{t,r}} \right) \cdot \left[\sum_e \kappa_{e,t,r}^{\sigma^{en}_{t,r}} \cdot PX_{e,r}^{\left(1-\sigma^{en}_{t,r}\right)} \right]^{\frac{1}{1-\sigma^{en}_{t,r}}} \tag{27}$$

$$kk_{t,r} = EN0_{tr} / [\sum_e \kappa_{e,t,r}^{\sigma^{en}_{t,r}} IX0_{e,r}^{\frac{\sigma^{en}_{t,r}-1}{\sigma^{en}_{t,r}}}]^{\frac{\sigma^{en}_{t,r}}{\sigma^{en}_{t,r}-1}}$$

In the general version, each sector faces sector-specific taxes for input e, e.g. ETS price:

$$PEN_{t,r} \quad = \quad \left(\frac{1}{kk_{t,r}} \right) \cdot \left[\sum_e \kappa_{e,t,r}^{\sigma^{en}_{t,r}} \cdot PB_{e,t,r}^{\left(1-\sigma^{en}_{t,r}\right)} \right]^{\frac{1}{1-\sigma^{en}_{t,r}}} \tag{27b}$$

$$PB_{e,t,r} = (1 + t^{en}_{e,t,r}) PX_{e,r} + tx^{ETS}_{e,t,r} \tag{27c}$$

$$PN_{t,r} \quad = \quad \sum_{t6} PX_{t6,r} \cdot io_{t6,t,r} \tag{28}$$

$$P_{t,r} \cdot Q_{t,r} \quad = \quad PN_{t,r} \cdot NX_{t,r} \quad + \quad PEN_{t,r} \cdot EN_{t,r} \quad + PVC_{t,r} \cdot VA_{t,r} \quad + \quad ty_{t,r} \cdot P_{t,r} \cdot Q_{t,r} \tag{29}$$

$$(1 - ty_{t,r} + s^{co2}_{tr}) P_{t,r} \cdot Q_{t,r} \quad = \quad PN_{t,r} \cdot NX_{t,r} \; + \; PEN_{t,r} \cdot EN_{t,r} \; + PVC_{t,r} \cdot VA_{t,r} \tag{29b}$$

$$PVE_{t,r} VE_{t,r} = PVC_{t,r} VA_{t,r} + PEN_{t,r} EN_{t,r} \tag{29c}$$

$$PN_{t,r} NX_{t,r} = \sum_{ne} PX_{ne,r} IX_{ne,r} \tag{29d}$$

$$PVC_{t,r} VA_{t,r} = \sum_f PF_{ftr} DF_{ftr} \tag{29e}$$

$$PEN_{t,r} EN_{t,r} = \sum_e PX_{er} IX_{er} \tag{29f}$$

$$VE_{t,r} = \left(\frac{1}{aa_{t,r}}\right)^{1-\sigma^{n}_{t,r}} \cdot \left[\left(1 - \zeta_{t,r}\right)\cdot \frac{PTC_{t,r}}{PVE_{t,r}}\right]^{\sigma^{n}_{t,r}} \cdot Q_{t,r}$$ value-added-energy bundle (30)

$$VA_{t,r} = \left(\frac{1}{ee_{t,r}}\right)^{1-\sigma^{ve}_{t,r}} \cdot \left[\left(1 - \eta_{t,r}\right)\cdot \frac{PVE_{t,r}}{PVC_{t,r}}\right]^{\sigma^{ve}_{t,r}} \cdot VE_{t,r} \tag{31}$$

$$EN_{t,r} = \left(\frac{1}{ee_{t,r}}\right)^{1-\sigma^{ve}_{t,r}} \cdot \left[\eta_{t,r} \cdot \frac{PVE_{t,r}}{PEN_{t,r}}\right]^{\sigma^{ve}_{t,r}} \cdot VE_{t,r} \tag{32}$$

$$NX_{t,r} = \left(\frac{1}{aa_{t,r}}\right)^{1-\sigma^{n}_{t,r}} \cdot \left[\zeta_{t,r} \cdot \frac{PTC_{t,r}}{PN_{t,r}}\right]^{\sigma^{n}_{t,r}} \cdot Q_{t,r}$$ total interm input (33)

$$IX_{e,t,r} = \left(\frac{1}{kk_{t,r}}\right)^{1-\sigma^{en}_{t,r}} \left[\kappa_{e,t,r} \frac{PEN_{t,r}}{PX_{e,r}}\right]^{\sigma^{en}_{t,r}} \cdot EN_{t,r}$$ energy commod; common p

(34)

$$IX_{e,t,r} = \left(\frac{1}{kk_{t,r}}\right)^{1-\sigma^{en}_{t,r}} \cdot \left[\kappa_{t5,t,r} \cdot \frac{PEN_{t,r}}{PB_{e,t,r}}\right]^{\sigma^{en}_{t,r}} \cdot EN_{t,r}$$ sector-specific energy price (34b)

$$IX_{t6,t,r} = io_{t6,t,r} \cdot NX_{t,r}$$ Leontief demand for nonenergy (35)

$$DF_{f,t,r} = \left(\frac{1}{a_{t,r}}\right)^{1-\sigma^{v}_{t,r}} \cdot \left[\delta_{f,t,r} \cdot \frac{PVC_{t,r}}{apf_{ftr} PF_{f,r}}\right]^{\sigma^{v}_{t,r}} \cdot VA_{t,r}$$ factor demands (36)

Capital mobility assumptions:

Mobile capital: $apf_{"CAP",tr} = 1$ (37)

Fixed capital: $apf_{"CAP",tr} = endog$; $apf_{"LAB",tr} = 1$; (38)

$DF_{"CAP",tr} = DF0_{"CAP",tr}$; $PF_{"CAP",r} = PF0_{"CAP",r}$

Government

$$GSAV_r = GREV_r - GPUR_r - GTRANS_r = 0 \tag{41}$$

Closure option 1 {fix GSAV, GPUR=sGDP, GTRANS=sGDP, endog tax (lambda)}:

$$GPUR_r = gpur\_s_r \cdot GNPR_r \tag{42a}$$

$$GTRANS_r = gtrans\_s_r \cdot GNPR_r \tag{42b}$$

$GSAV_r.FX = GSAV0$; endogenous $\lambda_t tf_{"lab",r}$ (43)

Option 2 {fix GTRANS also}: $GTRANS_r.FX = GTRANS0$; (42c)

Option 3 free deficit; fixed lambda, fixed GPUR

Option 4: fix tax rates, $\lambda_t tf_{"lab",r}$; λ_t.FX=1.0;

endogenous GPUR (i.e. no 42a); $GSAV_r.FX = GSAV0$

$$PGC_{t,r} \cdot GC_{t,r} \quad = \quad \beta^{GC}_{t,r} \cdot GPUR_r \qquad (44)$$

$$GG_r = \prod_t GC_{t,r}^{\beta^{GC}_{tr}} \qquad \text{index of real govt. purchases} \qquad (44b)$$

$$GREV_r \; = \; TARIFF_r + ETAX_r + PTAX_r + CTAX_r + FTAX\_L_r + HTAX_r$$
$$+ CO2TAXR_r - CO2SUB_r + CO2BOR_r + CO2BORTX_r$$

(45)

$$GR_r = GREV_r - GSAV_r \qquad (46)$$

$$TARIFF_r \quad = \quad \sum\nolimits_{t,s} ERT_r \cdot (adjtm_{tr} TN_{tsr} + tm_{t,s,r}) \cdot PWM_{t,s,r} \cdot X_{t,s,r} \qquad (47)$$

$$ETAX_r \quad = \quad \sum\nolimits_{t,s} te_{t,r,s} \cdot PE_{t,r} \cdot X_{t,r,s} \qquad (48)$$

$$PTAX_r \quad = \quad \sum\nolimits_t ty_{t,r} \cdot P_{t,r} \cdot Q_{t,r} \qquad (49)$$

$$CTAX_r \quad = \quad \sum\nolimits_t tc_{t,r} \cdot PX_{t,r} \cdot \left(C_{t,r} \; + \; GC_{t,r} \; + \; ID_{t,r}\right) \qquad (50)$$

$$FTAX_r \quad = \quad \sum\nolimits_t \lambda_r \cdot tf_{"lab",r} \cdot PF_{"lab",r} \cdot DF_{"lab",t,r} \quad + \quad \sum\nolimits_t tf_{"cap",r} \cdot PF_{"cap",r} \cdot DF_{"cap",t,r} \qquad (51)$$

$$FTAX\_L_r \quad = \quad \sum\nolimits_t \lambda_r \cdot tf_{"lab",r} \cdot PF_{"lab",r} \cdot DF_{"lab",t,r} \qquad (51b)$$

$$HTAX_r \quad = \quad th_r \cdot \sum\nolimits_f PFN_{f,r} \cdot FS_{f,r} \qquad (52)$$

$$HTAX_r \quad = \quad th_r \cdot \sum\nolimits_{t,f} apf_{f,t,r} PF_{f,r} \cdot DF_{f,t,r} \qquad (52b)$$

$$ETS\_TAX_r = \sum\nolimits_{t \in ETS} \sum\nolimits_e tx^{ETS}_{e,r} IX_{e,t,r} \qquad \text{shadow rev from ETS permits} \qquad (53)$$

$$ETS\_AUC_r = (1 - \phi^{ETS}_{free}) \sum\nolimits_{t \in ETS \setminus ELY} \sum\nolimits_e tx^{ETS}_{e,r} IX_{e,t,r} + \sum\nolimits_e tx^{ETS}_{e,r} IX_{e,"ELY",r} \qquad \text{auction rev} \qquad (53b)$$

$$ETS\_SUB_{tr} = \phi^{ETS}_{free;tr} \sum\nolimits_e tx^{ETS}_{e,r} IX_{e,t,r} \qquad t \in S^{ETS} \setminus ELY \qquad \text{free alloc as output subsidy}$$

(53c)

$$ETS\_SUB_r = \sum\nolimits_t ETS\_SUB_{tr} = ETS\_TAX_r - ETA\_AUC_r \qquad (53d)$$

Policy switches

In policy cases we may want to change tax rates endogenously to hit exogenous government purchases (to equal base case value). To do so, we add an endogenous scale variable to the desired tax rates, e.g. :

Replace $th_r, \ldots$ by $\lambda_r th_r, \lambda_r ty_r$ for r=policy region

Constrain (see 109c): $GG^{basep}_{r,y} = GG^{y0}_{r,y}$

Carbon Tax Equations *(upstream tax, no noncombustion exemption)*

$$CO2TAXF_{t1,r} = tf^{co2}_{t1,r} \quad = \quad CO2TAXON_r . t^{co2}_r \cdot \theta^F_{t1,r} \qquad \text{tax per unit input t1} \qquad (54)$$

If desire carbon tax set CO2TAXON=1, else =0

$$CO2TAXR_r \quad = \quad \sum\nolimits_{t1 \in fossil} tf^{co2}_{t1,r} \cdot SX_{t1,r} \qquad \text{revenue} \qquad (55)$$

$$CO2TOT_r \quad = \quad \sum\nolimits_{t1} \sum\nolimits_t \theta_{t1,t,r} \cdot io_{t1,t,r} \cdot NX_{t,r} \quad + \quad \theta_{t1,hh,r} \cdot C_{t1,r} \qquad (56)$$

$$CO2TOT_r \quad = \quad CO20_r \qquad \text{set CO2TAXON=1 to impose limit} \qquad (57)$$

$$\theta^F_{t1,r} = [\sum_{t1}\sum_t \theta_{t1,t,r} io_{t1,t,r} NX_{t,r} + \theta_{t1,hh,r} C_{t1,r}] / [\sum_{t1}\sum_t io_{t1,t,r} NX_{t,r} + C_{t1,r}] \quad \text{baseyr}$$

If choose policy "pure carbon tax, no subsidy"

$$s^{co2}_{t,r} = 0; \quad tm^{co2}_{t,r} = 0; \qquad (58)$$

If choose "carbon price in some sectors and output subsidy offsets" (s>0 for $t \in S^{ETS}$)

$$CO2SUB_r = \sum_t s^{co2}_{t,r} P_{t,r} Q_{t,r} \qquad \text{r=ctax regions} \qquad (58b)$$

If choose "carbon tax and border adjustment"

$$CO2TMF_{t,r} = tm^{co2}_{t,r} = t^{BTAco2}_r \cdot \theta^Q_{t,r} \qquad \text{option based on importer emis} \qquad (58c)$$

$$CO2TMF_{t,s,r} = tm^{co2}_{t,s,r} = t^{BTAco2}_r \cdot \theta^Q_{t,s} \qquad \text{option based on exporter emis} \qquad (58d)$$

ETS permit price/tax per unit fuel t1

$$TX\_CO2_{t1,r} = tx^{ETS}_{t1,r} = t^{ETSco2}_r \cdot \theta^F_{t1,r} \qquad (58e)$$

ETS permit price/tax per unit fuel t1 that is sector specific (see 27b):

$$TX\_CO2_{t1,t,r} = tx^{ETS}_{t1,t,r} = t^{ETSco2}_r \cdot \theta_{t1,t,r} \qquad (58f)$$

Unit Export Tax

$$CO2TU_{t,r,s} = tu^{co2}_{t,r,s} = t^{BTAco2}_r \cdot \theta^Q_{t,r} \qquad \text{based on exporter emis}$$

(58g)

Total border carbon revenue:

ad valorem option $$CO2BOR_r = \sum_t tm^{co2}_{t,r} PM_{t,r} MX_{t,r} - \sum_t se^{co2}_{t,r} PE_{t,r} EX_{t,r} \qquad (59a)$$

per unit option $$CO2BOR_r = \sum_t tm^{co2}_{t,r} MX_{t,r} - \sum_t se^{co2}_{t,r} EX_{t,r} \qquad (59b)$$

$$CO2BOR_r = \sum_t \sum_s tm^{co2}_{t,s,r} X_{t,s,r} - \sum_t se^{co2}_{t,r} EX_{t,r} \qquad r \in RL$$

(59c)

$$CO2BOR_r = \sum_t \sum_s ERT_r \cdot PWM_{t,s,r} \cdot tm^{co2}_{t,s,r} \cdot X_{t,s,r} - \sum_t se^{co2}_{t,r} EX_{t,r}$$

(59chx)

$$CO2BORTX_r = \sum_t \sum_s tu^{co2}_{t,r,s} \cdot X_{t,r,s} \qquad r \in LDC \qquad (59d)$$

$$CO2BORTX_r = \sum_t \sum_s ERT_s \cdot PWM_{t,r,s} \cdot tu^{co2}_{t,r,s} \cdot X_{t,r,s}$$

(59dhx)

Option: treat ETS free allocation as output subsidy; CO2SUB not added to total revenue; subsidy rate is endogenous:

$$ETS\_SUB_{tr} = s^{co2}_{t,r} P_{t,r} Q_{t,r} \qquad t \in ETS \setminus ELY \qquad (60)$$

$$s^{co2}_{t,r,y=0} = \frac{\phi^{ETS}_{free;tr} \sum_e tx^{ETS}_{e,r,y=0} IX_{e,t,r,y=0}}{P_{t,r,y=0} Q_{t,r,y=0}}$$

In ETS, may impose emission cap which is met by an endogenous $tx^{ETS}_{e,r}$:

$$CO2^{ETSCAP}_r = \sum_{t \in ETS} \sum_{t1} \theta_{t1,t,r} io_{t1,t,r} NX_{t,r} \qquad (60b)$$

International Trade and Income

PE=exporter price in r currency; PWE is fob for importer in US$

Ad valorem: $PWE_{t,r,s} \quad = \quad (1 \ + \ te_{t,r,s} - se_{tr}^{co2}) \cdot \left(\dfrac{1}{ERT_r} \right) \cdot PE_{t,r}$ (61a)

Unit subsidy: $PWE_{t,r,s} \quad = \quad ((1 \ + \ te_{t,r,s})PE_{t,r} - se_{tr}^{co2})\left(\dfrac{1}{ERT_r} \right)$ (61b)

Unit export tax: $PWE_{t,r,s} \quad = \quad ((1 \ + \ te_{t,r,s})PE_{t,r} - se_{tr}^{co2})\left(\dfrac{1}{ERT_r} \right) + tu_{t,r,s}^{co2}\left(\dfrac{1}{ERT_r} \right)$ (61c)

$PWM_{t,s,r} \quad = \quad (1 \ + \ trs_{t,s,r}) \cdot PWE_{t,s,r}$ incl shipping margin (62)

Landed price includes shipping and tariffs and BCA:

Ad valorem: $PM_{t,r}MX_{t,r} = \sum_s \left(1 \ + adjtm_{t,s,r}tn_{t,s,r} + tm_{t,s,r} + tm_{tsr}^{co2}\right)ERT_r PWM_{t,s,r} X_{t,s,r}$
(63a)

Unit bca: $PM_{tr}MX_{tr} = \sum_s \left(1 \ + adjtm_{tsr}tn_{tsr} + tm_{tsr}\right)ERT_r PWM_{tsr} X_{tsr} + tm_{tsr}^{co2} ERT_r X_{tsr}$
(63b)

$PWMSQ_{t,s} = \left(1 \ + adjtm_{tsr}tn_{tsr} + tm_{tsr}\right) ERT_r PWM_{tsr} + tm_{tsr}^{co2} ERT_r$

$PX_{t,r} \cdot SX_{t,r} \quad = \quad PD_{t,r} \cdot DX_{t,r} \ + \ PM_{t,r} \cdot MX_{t,r}$ is (91) below.

$$SX_{t,r} \quad = \quad b_{t,r} \cdot \left[\alpha_{t,r} \cdot DX_{t,r}^{\frac{\sigma_{t,r}^m - 1}{\sigma_{t,r}^m}} \ + \ \left(1 \ - \ \alpha_{t,r}\right) \cdot MX_{t,r}^{\frac{\sigma_{t,r}^m - 1}{\sigma_{t,r}^m}} \right]^{\frac{\sigma_{t,r}^m}{\sigma_{t,r}^m - 1}} \qquad (64)$$

$$DX_{t,r} \quad = \quad MX_{t,r} \cdot \left[\frac{\alpha_{t,r}}{1 \ - \ \alpha_{t,r}} \cdot \frac{PM_{t,r}}{PD_{t,r}} \right]^{\sigma_{t,r}^m} \qquad \text{if both>0} \qquad (65)$$

$DX_{t,r} = SX_{t,r}$ if MX=0; $MX_{t,r} = SX_{t,r}$ if DX=0; (66)

Or equivalently: $DX_{t,r} = SX_{t,r} \left(\dfrac{1}{b_{tr}} \right)^{1-\sigma_{t,r}^m} \left[\dfrac{\alpha_{t,r} PM_{t,r}}{PD_{t,r}} \right]^{\sigma_{t,r}^m}$ (67)

If use ad-valorem bca:

$$X_{t.s,r} = \left(\frac{1}{mu_{t,r}} \right)^{1-\sigma_{t,r}^t} \left[ts_{t,s,r} \frac{PM_{t,r}}{\left(1 + adjtm_{tr}TN_{tsr} + tm_{t,s,r} + tm_{tsr}^{co2}\right) ERT_r PWM_{t,s,r}} \right]^{\sigma_{t,r}^t} MX_{t,r} \qquad (68a)$$

If unit bca:

$$X_{t.s,r} = \left(\frac{1}{mu_{t,r}} \right)^{1-\sigma_{t,r}^t} \left[ts_{t,s,r} \frac{PM_{t,r}}{\left(1 + adjtm_{tr}TN_{tsr} + tm_{t,s,r}\right) ERT_r PWM_{t,s,r} + tm_{tsr}^{co2} ERT_r} \right]^{\sigma_{t,r}^t} MX_{t,r}$$

(68b)

$$\text{Derived from:}\quad MX_{t,r} = \mu_{t,r}\left[\sum_s ts_{t,s,r} X_{t,s,r}^{\frac{\sigma^t_{t,r}-1}{\sigma^t_{t,r}}}\right]^{\frac{\sigma^t_{t,r}}{\sigma^t_{t,r}-1}} \tag{68c}$$

If use ad-valorem export subsidy:

$$PE_{t,r}\cdot EX_{t,r} \quad = \quad \sum\nolimits_s\left(\frac{1}{1\ +\ te_{t,r,s} - se^{co2}_{tr}}\right)\cdot ERT_r\cdot PWE_{t,r,s}\cdot X_{t,r,s}$$

(69a)

If unit subsidy:

$$PE_{t,r}\cdot EX_{t,r} \quad = \quad \sum\nolimits_s\left(\frac{ERT_r\cdot PWE_{t,r,s} + se^{co2}_{tr}}{1\ +\ te_{t,r,s}}\right)\cdot X_{t,r,s}$$

(69b)

If unit export tax:

$$PE_{t,r}\cdot EX_{t,r} \quad = \quad \sum\nolimits_s\left(\frac{ERT_r\cdot PWE_{t,r,s} + se^{co2}_{tr} - tu^{co2}_{t,r,s}}{1\ +\ te_{t,r,s}}\right)\cdot X_{t,r,s}$$

(69c)

$$\begin{aligned} NETINFL_r \quad &= \quad \sum\nolimits_{t,s} PWE_{t,r,s}\cdot X_{t,r,s} \ + \ \left[\frac{1}{ERT_r}\right]\cdot P_{"trn",r}\cdot TRQS_r \\ &- \sum\nolimits_{t,s} PWM_{t,s,r}\cdot X_{t,s,r} + FDI_r - GTROW_r \end{aligned} \tag{70}$$

$$IMPS_{tr} = \frac{MX_{tr}}{SX_{tr}} \qquad \text{unused variable} \tag{71}$$

$$GTROW_r = \sum\nolimits_s GTR_{r,s} = \sum\nolimits_s \ \mathrm{CO2TMN}_s = \sum\nolimits_s \sum\nolimits_{t,r} CO2TMF_{t,s,r}\times X_{t,s,r}$$
$$r = RL, s = LDC$$

Output allocation

If choose **CET option** (imperfect subst bet dom and export):

$P_{tr}Q_{t,r} = PD_{tr}DX_{t,r} + PE_{tr}EX_{t,r}$ is (97) below

$$Q_{t,r} \quad = \quad be_{t,r}\cdot\left[\alpha^e_{tr}\cdot DX_{t,r}^{\frac{\sigma^e_{t,r}-1}{\sigma^e_{t,r}}} \ + \ \left(1\ -\alpha^e_{tr}\right)\cdot EX_{t,r}^{\frac{\sigma^e_{t,r}-1}{\sigma^e_{t,r}}}\right]^{\frac{\sigma^e_{t,r}}{\sigma^e_{t,r}-1}} \qquad \text{t=/=TRN} \tag{72}$$

$$Q_{t,r} - TRSQ_r \quad = \quad \ldots \qquad \text{t=TRN} \tag{73}$$

$$DX_{t,r} \quad = \quad EX_{t,r}\cdot\left[\frac{\alpha^e_{tr}}{1\ -\alpha^e_{tr}}\cdot\frac{PE_{tr}}{PD_{tr}}\right]^{\sigma^e_{t,r}} \tag{74}$$

$$\text{Or equivalently:}\quad DX_{t,r} \quad = \quad Q_{t,r}\left(\frac{1}{be_{tr}}\right)^{1-\sigma^e_{t,r}}\left[\frac{\alpha^e_{tr}P_{tr}}{PD_{tr}}\right]^{\sigma^e_{t,r}} \tag{75}$$

$$P_{t,r} = \frac{1}{be_{t,r}}\left[\alpha_{tr}^{e\sigma_{t,r}^{e}} PD_{t,r}^{1-\sigma_{t,r}^{e}} \quad + \left(1-\alpha_{tr}^{e}\right)^{\sigma_{t,r}^{e}} PE_{t,r}^{1-\sigma_{t,r}^{e}}\right]^{\frac{1}{1-\sigma_{t,r}^{e}}}$$ is dual to 72 (72b)

If choose **not CET option**:

$PD_{tr} = P_{tr}$ (76)

$PE_{tr} = PD_{tr}$ if EX>0 (77)

$Q_{tr} = DX_{tr}$ if EX=0

$$\alpha_{t,r}^{e} = [1+\frac{PE0_{tr}}{PD0_{tr}}\left(\frac{DX0_{tr}}{EQ0_{tr}}\right)^{-1/\sigma_{t,r}^{e}}]^{-1} = \frac{PD0_{tr}EQ0_{tr}^{-1/\sigma_{t,r}^{e}}}{PD0_{tr}EQ0_{tr}^{-1/\sigma_{t,r}^{e}} + PE0_{tr}DX0_{tr}^{-1/\sigma_{t,r}^{e}}} \quad (78a)$$

$$be_{t,r} = Q0_{t,r} / \left[\alpha_{t,r}^{e} DX0_{t,r}^{\frac{\sigma_{t,r}^{e}-1}{\sigma_{t,r}^{e}}} + \left(1-\alpha_{t,r}^{e}\right) EQ0_{t,r}^{\frac{\sigma_{t,r}^{e}-1}{\sigma_{t,r}^{e}}}\right]^{\frac{\sigma_{t,r}^{e}}{\sigma_{t,r}^{e}-1}}$$

International Shipping Equations

$P_{"trn",rr} \cdot TRQS_{rr} = ERT_{rr} \cdot its_{rr} \cdot \sum_{s} \frac{P_{"trn",s}}{ERT_{s}} \cdot TRQS_{s}$ r's share of world shipping output (79)

$PTR \cdot TRQD_{t,r} = \sum_{s} trs_{t,s,r} \cdot PWE_{t,s,r} \cdot X_{t,s,r}$ shipping reqd for good t (80)

$TRQ = \sum_{t,r} TRQD_{t,r}$ total intl trn not used anywhere (81)

Is this a missing equation (or satisfied by 73)

$\sum_{r} TRQS_{r} = \sum_{t,r} TRQD_{t,r}$ (82)

These eqs are commented out:

$PTR * TRQ = \sum_{r} \frac{P_{"trn",r}}{ERT_{r}} TRQS_{r}$ (83)

Markets for commodities and factors

$PX_{t,r} \cdot SX_{t,r} = PD_{t,r} \cdot DX_{t,r} + PM_{t,r} \cdot MX_{t,r} + CO2TAXON_{r} tf_{t,r}^{co2} SX_{tr}$ (91)

This is the carbon tax effect on input prices $PX_{t,r} = agg[PD + tf_{t,r}^{co2}, PM + tf_{t,r}^{co2}]$

$SX_{t,r} = C_{t,r} + GC_{t,r} + ID_{t,r} + \sum_{k} IX_{t,k,r}$ (92)

$\sum_{t} DF_{f0,t,r} = FS_{f0,r} \cdot FP_{f0,r}$ (93)

$INV_{r} = deprt_{r} \cdot FS_{"cap",r} + SAV_{r} + GSAV_{r} - ERT_{r} \cdot NETINFL_{r}$ (94)

$\sum_{r} NETINFL_{r} = 0$ (95)

$$FDI_r = 0 \qquad (96)$$

$$P_{i,r}Q_{i,r} = PE_{i,r}EX_{i,r} + PD_{i,r}DX_{i,r} \qquad i \neq TRN$$
$$= PE_{i,r}EX_{i,r} + PD_{i,r}DX_{i,r} + P_{i,r}TRQS_r \quad i = TRN$$

output=export+domes (97)

Dynamics. Capital

$$I^{agg}_{rt} = \sum_i PC_{i,r,t-1}ID_{irt} \qquad PI^{agg}_{rt}I^{agg}_{rt} = INV_{rt} \qquad (98)$$

$$K^{agg}_{rt+1} = (1-\delta_r)K^{agg}_{rt} + I^{agg}_{rt} \qquad (99)$$

$$K^{agg}_{rt+1} = (1-\delta_r)K^{agg}_{rt} + \psi^K_{rt}I^{agg}_{rt}$$ ver with capital composition adjustment (99b)

Numeraire and closures

$PINDEX_r = PINDEX0_r$ i.e. PGDP(r)=1 for all r (instead of PL(r)=1) (101)

$ERT("US") = 1$ (102)

$PTR = 1$ (since TRQD not specified indep) (103)

$NETINFL_r = NET0_r = bots * GNP0 \quad r \in \{\text{all except USA}\}$ (104)

GDP Equations

(orig model var name GNPR is confusing, it is actually nominal GDP not real GDP. 105rg is the original equation which Mun thinks is wrong; GDP should be at purchaser's prices, so should be 105M)

$$GNPR_r = \sum_t PC_{t,r} \cdot \left(C_{t,r} + GC_{t,r} + ID_{t,r}\right) + ERT_r \cdot NETINFL_r - CO2TAXR_r \qquad (105rg)$$

$$GNPR_r = \sum_t PC_{t,r}C_{t,r} + PGC_{t,r}GC_{t,r} + PINV_{t,r}ID_{t,r} + ERT_r \cdot NETINFL_r - CO2TAXR_r \qquad (105)$$

$$GNPR_r = \sum_t PC_{t,r} \cdot \left(C_{t,r} + GC_{t,r} + ID_{t,r}\right) + ERT_r \cdot NETINFL_r$$

(105M)

$$GDPVA_r = \sum_f \sum_t apf_{ftr}PF_{f,r} \cdot DF_{f,t,r} + \sum_t tc^{CIG}_{t,r} \cdot PX_{t,r} \cdot \left(C_{t,r} + GC_{t,r} + ID_{t,r}\right)$$
$$+ \sum_s \sum_t te_{t,r,s} \cdot PE_{t,r} \cdot X_{t,r,s} + \sum_t ty_{t,r} \cdot P_{t,r} \cdot Q_{t,r}$$

(106M)

$$+\sum_s \sum_t ERT_r \left((adjtm_{t,r}tn_{t,s,r} + tm_{t,s,r})pwm_{t,s,r}X_{t,s,r}\right) + CO2TAXR_r + CO2BOR_r$$

$$GDPVA_r = \sum_f \sum_t apf_{ftr}PF_{f,r} \cdot DF_{f,t,r} + \sum_t tc_{t,r}PX_{t,r}C_{t,r} + \sum_t tgc_{t,r}PX_{t,r}GC_{t,r}$$
$$+ \sum_t tinv_{t,r}PX_{t,r}ID_{t,r} + \sum_s \sum_t te_{t,r,s} \cdot PE_{t,r} \cdot X_{t,r,s} + \sum_t ty_{t,r} \cdot P_{t,r} \cdot Q_{t,r}$$
$$+\sum_s \sum_t ERT_r \cdot \left((adjtm_{t,r}tn_{t,s,r} + tm_{t,s,r}) \cdot pwm_{t,s,r} \cdot X_{t,s,r}\right) \qquad (106)$$
$$+CO2TAXR_r + CO2BOR_r$$

$$PINDEX_r = \frac{GDPVA_r}{GDPR_r} \qquad (107)$$

$$GNPG = \sum_r GNPVA_r \tag{108}$$

GDP in base year prices:

$$GDPR_r \quad = \quad \sum\nolimits_t PC0_{t,r} \cdot \left(C_{t,r} + \ GC_{t,r} + ID_{t,r} \right)$$
$$+ ERT0_r (\sum\nolimits_{t,s} PWE0_{t,r,s} \cdot X_{t,r,s} \ + \left[\frac{1}{ERT0_r} \right] \cdot P0_{"trn",r} \cdot TRQS_r - \sum\nolimits_{t,s} PWM0_{t,s,r} \cdot X_{t,s,r} \ )$$

(109rg)

$$\begin{aligned} GDPR_r \quad &= \quad \sum\nolimits_t PC0_{t,r} C_{t,r} + \ PGC0_{t,r} GC_{t,r} + PINV0_{t,r} ID_{t,r} \\ &+ ERT0_r (\sum\nolimits_{t,s} PWE0_{t,r,s} \cdot X_{t,r,s} \ + \left[\frac{1}{ERT0_r} \right] \cdot P0_{"trn",r} \cdot TRQS_r - \sum\nolimits_{t,s} PWM0_{t,s,r} \cdot X_{t,s,r} \ ) \end{aligned} \tag{109}$$

$$INV\_ag_r = \sum_t PINV0_{t,r} ID_{t,r} \tag{109b}$$

$$GG_{ry}^{base} \quad = \quad \sum\nolimits_t PC_{t,r,0} GC_{try} \tag{110b}$$

Dynamic version. In base case for y>1:

$$\begin{aligned} GDPR_{ry} \quad &= \quad \sum\nolimits_t PC_{t,r,y-1} \cdot \left(C_{try} + \ GC_{try} + ID_{try} \right) + \\ &ERT_{r,y-1} (\sum\nolimits_{t,s} PWE0_{trsy} X_{trsy} \ + \left[\frac{1}{ERT_{r,y-1}} \right] P0_{"trn",r,y} TRQS_{ry} - \sum\nolimits_{t,s} PWM0_{t,s,r,t} X_{t,s,r,y} \ ) \end{aligned} \tag{110}$$

Carbon and energy coefficients

$EGHG_{fztr}^{CO2}$ input data of CO2 emissions in 2004 {z=dom,imp} (1000tons)

EVF_{ftr}^{toe} energy in (mil) tons of oil equivalent

$$EMIS_{ftr} = \sum\nolimits_z \ EGHG_{fztr}^{CO2} \tag{111}$$

$\theta_{t1,tr} = \dfrac{EMIS_{t1,tr}}{IX_{t1,tr}^{baseyear0}}$ sector-specific emission coeff. of fuel t1 (kg CO2/\$) (112)

$\theta_{t1,HH,r} = \dfrac{EMIS_{t1,HH,r}}{C_{t1,HH,r}^{baseyear0}}$ household emissions coeff of fuel t1 (112b)

$\theta_{t1,r}^{F} = \dfrac{\sum_t EMIS_{t1,tr}}{\sum_t IX_{t1,tr}^{baseyear0}}$ average fuel emission coeff of fuel t1 (113)

$\theta_{tr}^{Q0} = \dfrac{\sum_{t1} EMIS_{t1,tr}}{Q_{tr}^{baseyear0}}$ fossil emission per unit gross output of t in r (114)

$$\theta_{tr}^{Q} = \frac{\sum_{t1} EMIS_{t1,tr}}{Q_{tr}} = \sum_{t1} \frac{\theta_{t1,tr} IX_{t1,tr}}{Q_{tr}} = \sum_{t1} \theta_{t1,tr} \frac{IX_{t1,tr}}{EN_{tr}} \frac{EN_{t1,tr}}{VE_{tr}} \frac{VE_{t1,tr}}{Q_{tr}} \tag{114b}$$

$$= \sum_{t1} \theta_{t1,tr} (\frac{1}{kk_{t,r}})^{1-\sigma_{t,r}^{en}} \left[\kappa_{t1,t,r} \frac{PEN_{t,r}}{PX_{t1,r}} \right]^{\sigma_{t,r}^{en}} (\frac{1}{ee_{t,r}})^{1-\sigma_{t,r}^{ve}} \left[\eta_{t,r} \frac{PVE_{t,r}}{PEN_{t,r}} \right]^{\sigma_{t,r}^{ve}} (\frac{1}{aa_{t,r}})^{1-\sigma_{t,r}^{n}} \left[\left(1-\zeta_{t,r}\right) \frac{PTC_{t,r}}{PVE_{t,r}} \right]^{\sigma_{t,r}^{n}}$$

$$\phi_{tr} = \frac{Q_{tr}}{\sum_{s \in \theta_{ts}^{Q} > 0} Q_{ts}}; \qquad \overline{\theta}_{t}^{Q} = \sum_{s} \phi_{t,s} \theta_{t,s}^{Q} \tag{115}$$

$$\theta_{tr}^{Q;ALT} = \frac{\sum_{t1} \theta_{t1,tr} IX_{t1,tr}}{Q_{tr}}; \quad EMIS_{TOT,r}^{Q;ALT} = \sum_{t} \theta_{tr}^{Q;ALT} Q_{tr} \tag{116}$$

$$\alpha_{t,r}^{ELY} = IX_{ELY,tr} / \sum_{k7} IX_{ELY,k7,r} \qquad \text{for t=/=ELY} \tag{117}$$

$$EMIS_{ftry} = \theta_{ftry} IX_{ftr}^{y} \tag{118d}$$

$$EM_{r}^{IND,CO2} = \sum_{f,t} EMIS_{ftr} \tag{118}$$

$$EM_{r}^{HH,CO2} = \sum_{e} \theta_{e,HH,r} C_{er} \tag{118b}$$

$$EMR_{r}^{CO2} = EM_{r}^{IND,CO2} + EM_{r}^{HH,CO2} \tag{118c}$$

$$LEAK^{World} = \frac{\sum_{r \in NRL} EMR_{r}^{policy,CO2} - EMR_{r}^{base,CO2}}{\sum_{r \in RL} EMR_{r}^{base,CO2} - EMR_{r}^{policy,CO2}} \qquad \text{RL=\{policy regions\} NRL=nonpolicy} \tag{119}$$

$$LEAK_{rl}^{Q\_lev\_A} = \theta_{t,rl}^{Q} (Q_{t,rl} - Q0_{t,rl}); \quad LEAK_{rl}^{I\_sub\_A} = (\theta_{t,rl}^{Q} - \theta_{t,rl}^{Q0}) Q0_{t,rl} \tag{120}$$

$$LEAK_{rl}^{Q\_lev\_B} = \theta_{t,rl}^{Q0} (Q_{t,rl} - Q0_{t,rl}); \quad LEAK_{rl}^{I\_sub\_B} = (\theta_{t,rl}^{Q} - \theta_{t,rl}^{Q0}) Q_{t,rl} \tag{120b}$$

$$LEAK_{rl}^{Use\_A} = \theta_{t,rl}^{Q} (SX_{t,rl} - SX0_{t,rl}) \tag{126a,b,c}$$

$$LEAK_{rl}^{EX\_A} = \theta_{t,rl}^{Q} (EX_{t,rl} - EX0_{t,rl}); \qquad LEAK_{rl}^{MX\_A} = \theta_{t,rl}^{Q} (MX_{t,rl} - MX0_{t,rl})$$

$$LEAK_{rl}^{Total\_1} = LEAK_{rl}^{Q\_lev\_A} + LEAK_{rl}^{I\_sub\_A} \tag{121}$$

$$LEAK_{rl}^{Total\_2} = LEAK_{rl}^{Use\_A} + LEAK_{rl}^{EX\_A} - LEAK_{rl}^{MX\_A} + LEAK_{rl}^{I\_sub\_A} \tag{122}$$

$$LEAK_{rl}^{Total\_3} = LEAK_{rl}^{Use\_B} + LEAK_{rl}^{EX\_B} - BEAK_{rl}^{MX\_B} + LEAK_{rl}^{I\_sub\_B} \tag{123}$$

$$\Lambda_{t,nrl}^{\theta X} = (\theta_{t,nrl}^{Q} - \theta_{t,USA}^{Q}) [\sum_{rl} (X_{t,nrl,rl} - X0_{t,nrl,rl}) - \sum_{rl} (X_{t,rl,nrl} - X0_{t,rl,nrl})] \tag{124}$$

$$\Lambda_{t}^{\theta X,USA} = \sum_{nrl} (\theta_{t,nrl}^{Q} - \theta_{t,USA}^{Q}) [\sum_{rl} (X_{t,nrl,rl} - X0_{t,nrl,rl}) - \sum_{rl} (X_{t,rl,nrl} - X0_{t,rl,nrl})] \tag{125}$$

$$LEAK_{nrl}^{Use\_R} = \theta_{t,rl}^{Q} (SX_{t,nrl} - SX0_{t,nrl}); \qquad LEAK_{t,nrl}^{I\_sub\_R} = (\theta_{t,nrl}^{Q} - \theta_{t,nrl}^{Q0}) Q0_{t,nrl} \tag{127}$$

ϕ_{ftr} = combustion ratio (portion of fuel f in t that is actually combusted)

η_{f} = emission of CO2 per physical unit of fuel f

e_f = energy in oil-equivalents per physical unit of fuel f

FQ_{ft} = physical units of fuel f (tons of coal, bbl of oil, etc); total incl. feedstocks

PF_f = price per physical unit of fuel f

$$FQ_{ftr} = IX_{ftr} / PF_{ftr} \tag{201}$$

$$EVF_{ftr} = e_{fr} FQ_{ftr} \tag{202}$$

$$EMIS_{ftr} = \eta_{fr} \phi_{ftr} FQ_{ftr} \tag{203}$$

$$EMIS_{ftr} = \theta_{ftr} IX_{ftr} \tag{204}$$

Therefore: $\theta_{ftr} IX_{ftr} = \eta_{fr} \phi_{ftr} FQ_{ftr}$

$$\theta_{ftr} = \eta_{fr} \phi_{ftr} / PF_{ftr} \tag{205}$$

The theta is made up of 3 parts, the emission coeff per ton of coal, the combustion ratio and the price per ton of coal used in sector t. We do not need to decompose it yet, but this is the way to do it if we want to introduce a combustion ratio explicitly.

4.3 Model Variable Listing

Symbol	Description
$PWE_{t,s,r}$	World price (seller price FOB)
$PE_{t,r}$	Exported goods price
$PWM_{t,s,r}$	Buyer price (CIF)
$PM_{t,r}$	Aggregate imported goods price
$PX_{t,r}$	Composite goods price
$PD_{t,r}$	Domestic goods price
$P_{t,r}$	Average output price
$PTC_{t,r}$	Sectoral unit cost of production
$PVE_{t,r}$	Value added-energy composite price
$PVC_{t,r}$	Value added composite price
$PEN_{t,r}$	Energy composite price
$PN_{t,r}$	Intermediate good composite price
$PFN_{f,r}$	Factor price (net of tax)
$PF_{f,r}$	Factor price (gross of tax)
$PC_{t,r}$	Consumer purchase price
CPI_{r}	Consumer price index
ERT_{r}	Exchange rate
$VE_{t,r}$	Value added-energy composite good
$VA_{t,r}$	Value added composite
$EN_{t,r}$	Energy composite
$VC_{t,r}$	Sectoral variable production cost
$NX_{t,r}$	Composite intermediate good
$IX_{t,k,r}$	Intermediate demand
$DF_{f,t,r}$	Sectoral factor demand
$C_{t,r}$	Household consumption
$GC_{t,r}$	Government consumption
$ID_{t,r}$	Investment demand
$SUPY_{r}$	Household consumption above subsistence level
$SX_{t,r}$	Composite good supply
$DX_{t,r}$	Domestic sales of domestically made good
$X_{t,s,r}$	Trade flows
$EX_{t,r}$	Exports
$MX_{t,r}$	Sectoral imports by region
$TRQS_{r}$	International shipping supply by region
PTR	International shipping service price
$TRQD_{t,r}$	International shipping demand by region
TRQ	Total international transport supply

HDI_r	Household disposable income
SAV_r	Household savings
$GREV_r$	Government revenue
$TARIFF_r$	Tariff revenue
$ETAX_r$	Export tax revenue
$PTAX_r$	Output tax revenue
$CTAX_r$	Consumption tax revenue
$FTAX_r$	Factor tax revenue
$HTAX_r$	Household tax revenue
$NETINFL_r$	Net capital inflow by country
$CO2TAXR_r$	Country carbon tax revenue
$CO2BOR_r$	Revenue from border adj tariff for carbon tax
$CO2TOT_r$	Total CO_2 emissions by country
$GDPR_r$	GDP (final demand)
$GDPVA_r$	GDP (value added)
$PINDEX_r$	GDP deflator (*numeraire*)
$Q_{t,r}$	Sectoral output
$FS_{f,r}$	Factor endowment by region
INV_r	Gross investment by region
$GSAV_r$	Government savings
$GPUR_r$	Government purchases
$GTRANS_r$	Net government transfers

4.4 Model Parameter Listing

Symbol	**Description**
$te_{t,r,s}$	Export tax rate
$tm_{t,s,r}$	Tariff rate
$tn_{t,s,r}$	Nontariff barrier
$tf_{f,r}$	Factor tax rate
$tc_{t,r}$	Consumption tax rate
$tgc_{t,r}$	Government consumption tax rate (future version)
$ty_{t,r}$	Output tax rate
th_r	Household tax rate
t_r^{co2}	Tax rate on carbon dioxide in country r
$tf_{t,r}^{co2}$	Tax rate on carbon content of fuel ($ of tax per unit fuel($baseyear))
$s_{t,r}^{co2}$	Subsidy on output for offsetting carbon tax burden
t_r^{BTAco2}	Border tax for offsetting carbon tax ($ per ton CO2 embodied)
$tm_{t,s}^{co2}$	Border tax adj rate for offsetting carbon tax on imports from s
$se_{t,r}^{co2}$	Subsidy on exports to offset carbon tax in region r
λ_r	Tax rate shift parameter
$\zeta_{t,r}$	Unit cost share parameter
σ^n	Unit cost elasticity (SGN)
$\eta_{t,r}$	Value added-energy composite share parameter
σ^{ve}	Value added-energy composite elasticity (SVE)
aa_{tr}	aa
$\delta_{f,t,r}$	Value added composite share parameter
σ^v	Value added composite elasticity (SGV)
a_{tr}	a

$\kappa_{t5,t,r}$	Energy composite share parameter
σ^{en}	Energy composite elasticity (SEN)
$io_{t6,t,r}$	Input-output coefficient
σ^{e}	Elasticity bet domestic sales and exports (SGE)
α^{e}	Domestic share parameter in CET
MT_r	Maximum working time
β_r^0	Leisure share parameter
$\beta_{t,r}$	Sectoral household consumption budget share
$\gamma_{t,r}$	Minimum consumption in LES
$\beta_{t,r}^{GC}$	Sectoral government consumption budget share
$\beta_{t,r}^{ID}$	Sectoral investment budget share
$\alpha_{t,r}$	Absorption share parameter
σ^{m}	Armington elasticity bet dom and imports (SGM)
σ^{t}	Lower level Armington elasticity bet imports from different countries (SGT)
$trs_{t,s,r}$	Transportation cost
$ts_{t,s,r}$	Transportation share parameter
its_{rr}	International transportation share parameter
$deprt_r$	Depreciation rate
$\theta_{t1,r}^{f}$	Carbon intensity (1000 tons CO2 per $100mil of t1) (THATA_F)
$\theta_{t1,t,r}$	Carbon emissions factor by fuel and sector (THETA)
$EGHG_{fztr}$	Emissions of CO2 (1000 tons)
$EMIS_{ftr}$	Emissions of CO2 (1000 tons)
$pwm_{t,s,r}$	World price of imports
inv_s_r	Investment expenditure as a percentage of GDP
$gpur\_s_r$	Government purchases as a percentage of GDP
$gtrans\_s_r$	Government transfers as a percentage of GDP

Table of elasticities

σ^{n}	SGN	0.15 all industries
σ^{ve}	SVE	0.5 all industries
σ^{v}	SGV	0.2(COA,OIL,GAS), 1.1, 1.3(PCP,ELY), 1.4
σ^{en}	SEN	0.5 all industries
σ^{e}	SGE	-2.1, -3.5, -5.6, -7.2
σ^{m}	SGM	1.9, 2.1, 2.3(PCP), 2.8(COA,OIL,GAS), 4.0(WAP), 5.2(MVH)