Carbon policies in developed countries: effect on world trade and welfare

Jing CAO[1,2], Mun HO[2], Xian HU[1,2]

June 7, 2022

Abstract

The EU has proposed using border carbon adjustments (BCA) to accompany their carbon price policies to protect domestic producers from imports that are not subject to similar carbon prices, and to reduce leakage. To address how BCA rules impact trade and growth in different regions of the world, we construct a dynamic CGE model with 10 world regions and 29 sectors using the GTAP10. We find first, that EU carbon pricing policies have significant carbon leakage due to higher fuel use and energy-intensive manufacturing in the rest of the world. Second, carbon tariffs reduce carbon leakage by more than half, they have a sizable effect on improving the competitiveness of firms in carbon pricing countries. Carbon tariffs have a very small additional negative impact on the world economy, for this reduction in leakage. Third, the EU carbon price have a negative economic impact on the GDP of Russia, oil exporting countries, Canada, and other countries but positive on the others; the addition of carbon tariffs hurt China, India and Oil Exporters.

Keywords: dynamic global CGE model, border carbon adjustment, EU

---

1. Tsinghua University, School of Economics and Management. 2. Harvard University, School of Engineering and Applied Sciences, China Project on Energy, Economy and Environment. Mun Ho is supported by a grant from the Harvard Global Institute.

1 Introduction

At the Paris Climate Change Conference in 2015, nearly 200 countries agreed to the long-term goal to keep the global temperature rise to below 2ºC compared to pre-industrial times. This is essentially the first universally applicable global governance system in history and recognizes a "common but differentiated responsibility" towards a common goal This acknowledges that rich and poor countries have different capacities to act and need flexibility for such a long-range task, and thus each party decides on its own national contribution to achieve that global goal. Most of the developed countries, and some major developing ones, have set emission reduction targets and some have even announced carbon neutrality (net-zero emission) goals. Most countries are pursuing national policies, with the important exception of the European Union where a group of countries banded together to implement regional climate policies, EU Carbon Emission Trading Scheme (EU ETS) to reduce CO2 emissions.

The climate is a global commons, one ton of greenhouse gas (GHG) emitted anywhere in the world produce the same impact on global temperatures. Unilateral climate policies will suffer from under-provision and free riding. In the absence of effective global cooperation to curb global warming, unilateral policies may even cause some other countries to increase their fossil fuel use since a reduction in demand in the policy countries will likely lower global fuel prices. This shift of carbon emissions to countries with no, or looser, climate regulations – carbon leakage – has been widely discussed, at least as far back as Felder and Rutherford (1993). Empirical studies such as Aichele and Felbermayr (2012) find that the Kyoto protocol led to carbon leakage. Another difficult political economy issue facing governments considering unilateral policies is the complaints of unfair competition by domestic producers subject to GHG limits or carbon prices; they would be facing imports from countries not subject to a similar level of GHS control. Nordhaus (2015) discuss how a Climate Club with carbon pricing and trade sanctions acts as a mechanism to overcome free riding problems and induce abatement

Border adjustments to accompany national carbon price policies have long been suggested to protect domestic producers from imports that are not subject to similar carbon prices and to reduce leakage, see, for example, the survey by Cosbey et al. (2019). Recent years have seen active consideration by policymakers and this attention has drawn renewed interest from economists and other policy advisers. There is particular interest among the European Union policy community in the run-up to the COP26 meeting in November 2021. The European Commission issued a "Proposal for a Directive (Carbon Border Adjustment Mechanism) Roadmap" in 2020, later the Council reached an agreement (general approach) on the CBAM regulation in March 2022, which is one of the key elements of the European Union's 'Fit for 55' package. Droege and Fischer (2020) discuss the “key questions for the EU” to answer in considering border carbon adjustments (BCAs) to level the playing field.

While national carbon price policies may be less likely in the U.S. in the near future, there are also active discussions of how border adjustments may be included. Flanery et al. (2020), for example, advance a proposal for border adjustments for a US greenhouse-gas tax that they claim is compliant with World Trade Organization rules. Pizer and Campbell (2021) discuss how BCAs may be constructed even in the cases where carbon restrictions are not solely due to carbon price policies – partial carbon prices or direct regulations.

In theory, a carbon border tax would have a positive impact on reducing carbon leakage and transboundary pollution transfer. But imposing a carbon border tax unilaterally or unevenly could create an unfair situation for exporters of carbon-intensive goods. On one hand, it may drive up the transaction costs of traded goods (including the costs of monitoring and verifying carbon emissions), creating inequities for countries that have chosen a different time path for carbon policies under the common but differentiated responsibility principle. The countries imposing the carbon border tax benefit from higher tax revenues and lower carbon leakage; the producers in the exporting countries could end up paying all or part of the carbon border taxes (depending on demand elasticities) and bearing the new transaction costs. Böhringer et al. (2012) concludes from their model-comparison study that there is little room for global cost savings and that the main effect of a BCA “is to shift the economic burden of emission reductions to non-abating countries through implicit changes in international prices.”

The proposed "border carbon adjustments" are usually tariffs on imports based on the carbon content of the goods, where the tariff rates are designed to match the cost of carbon emissions for domestic producers. However, there is widespread concern that they may violate the trade provisions of the World Trade Organization (WTO), and lead to trade disputes, leading to a reversal of the long trend of post-WW2 trade liberalization that have raised global incomes. Policy makers have to address a long list of difficult issues to reach a global consensus on such national climate policy provisions and their detailed implementation rules. Policy analysts may help by carefully thinking about projecting the effects of the various policy proposals.

Given the active consideration of BCAs by the EU and other developed countries, the governments of countries whose exports will be subject to such border policies are concerned and keen to understand the nature and impacts of the BCAs. These adjustments are complex, as noted by Droege and Fischer (2020) among many others. First, the carbon prices are themselves not a simple economy-wide price that applies to all CO2 emissions, but combinations of carbon taxes and emission permit requirements, permits that may cover only direct emissions, or include primary indirect emissions. Second, these prices may not be fixed tax rates but fluctuating in the carbon permit markets. Third, the sectors subject to these carbon regulations are not universal but with exemptions. Border adjustments are additional layers of complexity to the overall carbon policy framework; they have to first distinguish imports from countries that also have some carbon regulation from countries that do not, and then, among the exporters that have carbon regulations, determine how these regulations affect each commodity exported (e.g. how a carbon price in the electricity sector affect their steel export prices).

Many middle-income and low-income countries are not going to have comparable carbon policies in the medium term but are large exporters to these countries considering BCAs. These include China, Southeast Asia, and Latin America, and to some extent, India. In the case of China, exports were 20% of GDP in 2016 and 19% of those exports went to Europe and 18% to the U.S. (The export/GDP share was 25% in 2012.) China has emission trading pilot programs in a few provinces and just started a national program for the electricity sector which complicates the analysis of BCAs rules that might be implemented by the EU or the US. Understanding the various carbon rules and analyzing the likely impacts are thus important priorities for these countries. A primary objective of this paper is to examine how the EU BCA proposals affect the exports and economic structure of these partner countries.

To address these issues of BCA rules and impact on various regions of the world, we construct a dynamic model of the global economy and simulate the impact on trade patterns, output, and welfare. Our paper will focus on the impacts on China, India and Mexico as major exporters to the US and EU, and on Russia and Other Oil Exporters as major fossil fuel exporters affected directly by the EU carbon price. We construct a model with 10 world regions and 29 sectors using the GTAP database (version 10). In addition to the 7 regions just mentioned, we have Canada, the Rest of Annex 1, and Rest-of-the-World. This allows us to have a tractable discussion to focus on the impact of EU and US carbon-and-BCA policies on these countries.

The remainder of the paper is structured as follows: Section 2 reviews the border adjustment literature and policy background. Section 3 describes the dynamic global CGE model, the GTAP database and policy scenarios. Our numerical simulation results are presented in Section 4. Section 5 concludes.

2 Literature Review

The theoretical papers such as Markusen (1975) and Hoel (1996) demonstrate that border measures can be used as a suboptimal tool to improve the economic efficiency of unilateral emissions pricing policies, measures including import tariffs and export subsidies based on the carbon contained in the traded commodities. The literature suggests that the most efficient import tariff regimes are those that mimic the pricing of carbon from domestic emissions. The feasibility of border measures, however, depends on various legal and political considerations, and practical implementation issues; these are discussed by Droege and Fischer (2020).

A wide variety of GHG emission control policies has been proposed, some cover only the electricity sector since it is the largest emitter and the industry usually regarded as one which can reduce emissions most easily. Some cover a few of the highest emitting sectors or companies, while a carbon price on all fossil fuels would directly affect everyone in the economy. Policies may directly limit emissions, or set standards for emissions per unit output, or set a price for emissions to encourage less GHG-intensive methods of production. The covered industry may be obliged to pay a carbon price for some or all embodied carbon among its inputs, for example, all fossil fuels only, or also including carbon-embodied in the electricity used, or even including carbon-embodied in other intermediate inputs. These features of the actual GHG coverage would directly impact the form of an efficient border adjustment policy.

A comprehensive border tax adjustment consists of two components - a rebate paid to exporters to compensate them for their higher costs due to the domestic GHG emission reduction policy, and a tariff on imported goods based on the corresponding covered carbon content of imported goods. The import border adjustment levels the playing field between domestic goods and imported goods by ensuring that the price of imported goods includes the carbon price for the covered emissions associated with their production in the exporting country. In contrast, export rebates are intended to allow domestic producers to be competitive in world markets where there are sellers not subject to any GHG policy; the rebate of the payments for the covered carbon emitted during the production of these goods will allow the exporters to compete on terms that prevailed before the climate policy was introduced. These border adjustments would allow emissions pricing to encourage domestic producers to reduce emissions (reduce the use of inputs that generated emissions) without putting them at an international disadvantage.

The carbon border adjustment tax is thus set by considering the following five aspects (see also Böhringer, Balistreri et al. 2012):

(1) Embodied carbon coverage: covering embodied emissions from the production of imported goods (direct emissions only, direct emissions plus indirect emissions embodied in electricity production, or total embodied emissions in all intermediate inputs)

(2) Industry coverage: selection of industries or commodities subject to tariffs (only energy-intensive and trade-exposed sectors (EITE) or all manufactured goods, or including services such as electricity)

(3) Tariff rate differentials on imports: whether the carbon content basis is country and sector specific (i.e. based on the production characteristics in each exporting country), or sector specific only (using the average carbon content rates in the policy country (region) or the rates in the non-policy regions)

(4) Export rebates: Some proposals only provide for a BCA on imports, but a full system may include rebates on carbon taxes paid to produce goods exported from the policy country

(5) Use of import levy: The revenues from the carbon border taxes, like regular carbon tax revenues, may be turned over to the Treasury as general revenues, or explicitly designated for some purpose such as R&D subsidies or clean investment credits.

Discussions of BCAs go back at least to Meade (1974) and Grossman (1980) who show that border tax adjustments on imports can be effective in restoring competitiveness when there is a difference in taxation under origin and destination rules. When carbon reduction policies are proposed, the literature then turned to assessing the use of carbon border taxes to restore competitiveness domestic producers of carbon-intensive goods against imports (Babiker and Rutherford 2005, Demailly and Quirion 2006, Ismer and Neuhoff 2007, Mattoo, Subramanian et al. 2009, Fischer and Fox 2012). These papers find that a carbon border adjustment tax can alleviate, to varying degrees, the competitiveness problem faced by energy-intensive industries.

Böhringer, Carbone and Rutherford (2012) compare 3 leakage reduction policies – BCAs, output-based allocations and industry exemptions – and find that BCA exacerbate regional inequality, output subsidies provide only small efficiency gains, and exemptions provide little leakage reduction. Fischer and Fox (2012) compare the effectiveness of four policy options (import border tax, export border rebate, full border adjustment, and domestic production rebate) in reducing carbon leakage and find that while these policies can restore competitiveness, they were not effective in reducing leakage. Several papers have discussed how border adjustment measures can be added specifically to the EU carbon emission trading system (ETS) – de Cendra (2006), Kuik and Hofkes (2010), Monjon and Quirion (2010), Lanzi, Chateau et al. (2012), Springmann (2012). Peterson and Schleich (2007) consider how a BCA affects import competition in the main 15 countries in the EU differently from the rest of the EU zone, and that it has little effect on abatement costs and leakage. Dong and Walley (2012) assess the impacts on world trade, welfare, and emissions, and note that the difference in emission intensity between domestic and foreign producers is key in determining global net effects.

Some papers focus on the effects of BCAs on specific sectors. Mathiesen and Mæstad (2004) assess the impact of the Kyoto Protocol on the global steel industry using a partial equilibrium model and finds that border taxes reduce leakage, while Demailly and Quirion (2008) studies the cement industry under the EU-ETS. Ghosh et al. (2012) compares the efficiency impact of a BCA based on carbon only with one based on all GHG emissions and find that the latter would cause smaller efficiency losses and less redistribution. A system based on all GHG emissions would hurt countries where a large portion of GHG emissions is non-CO2 such as major agricultural producers like Brazil. Weitzel et al. (2012) argue that border adjustment taxes could be a strategic tool for trade policy; on the one hand, a BCA tax could induce other countries to take action to reduce emissions and lower the cost of global climate policy, but on the other hand, it could lead to countervailing tariffs in the affected countries, thus triggering a trade war. From a strategic perspective, a carbon border adjustment tax without compensatory transfer policies may not be able to get large carbon emitters such as China and India to join an emissions reduction coalition. Adding a carbon border adjustment tax to a carbon price system reduces the rate of carbon leakage from 20 to 18%, resulting in an average 8.5% reduction in global abatement costs.

Li and Zhang (2012) find that if China's exports are subject to a BCA by the OECD then there would be a shift in production across regions and a reduction in world emissions, but such a policy would be costly and inefficient. A system where China would also impose a carbon price would lead to less costly outcomes. Lin and Li (2011) find that a carbon border adjustment tax would trigger structural changes in China with a shift from industrial to non-industrial sectors, leading to a shift in production across regions, thus raising implications for regional development policies. Only a few other studies have analyzed the impact of BCA tariffs on China, and the focus on those studies are usually on exports from China. For example, Li, Wang et al. (2012) investigate the economic rationale for taxing direct emissions from the production of Chinese exports under different policy scenarios and find that the impact on export structure is significant: the export of major energy-intensive products falls and the export of labor-intensive sectors rises. Sectors with higher value-added grow relative to those with lower ones. They also suggest that redistributing the tax revenue to stimulate consumption is a welfare improving policy.

Many of the studies of policies to reduce leakage cited above use numerical general equilibrium models to simulate the impacts, including those in the Energy Modeling Forum comparison by Böhringer, Balistreri and Rutherford (2012). Some of them focused on different leakage reducing mechanisms, such as comparing a carbon tariff with a domestic output subsidy for those affected by the carbon price, or comparing a tariff-only border adjustment system with one that has export rebates. Given their global nature, most are focused on global metrics of net reduction in carbon emissions and the calculation of leakage rates, and not provide details on specific economies.

We also use a numerical GE model in our study of carbon price policies with border adjustment mechanisms, but we pay attention to the heterogeneity of impacts across different countries/regions in addition to the impacts on different industries. We not only consider long-run impacts but also the adjustment dynamics over time.

3. Modeling carbon prices and border adjustments

3.1. Dynamic model of the world economy

To model how the EU carbon policies, combined with alternative border adjustment rules, affect world output, trade, emissions, and consumption we constructed a dynamic multi-region, multi-sector computable general equilibrium (CGE) model. By using the general equilibrium approach, we can describe the comprehensive impact of the carbon tax and BCAs on the major economies and the industries most affected by the carbon price. The inter-industry aspect of the model tracks the impact of higher electricity prices on all sectors, including those that do not have high direct use of fossil fuels. The inclusion of capital accumulation and productivity growth allows us to track the impact of these policies on economic growth over the 2020-40 horizon. The model is based on GTAP version 10 (Aguiar et al 2019) and has a dynamic recursive structure (that is, with an exogenous investment rate assumption) which is described in detail in the Model Appendix. We summarize the main features here.

There are 10 countries/regions (listed in Table 1) and 29 industries (Table 2) identified in the model. The behavior of the economic agents in each regional economy follows neoclassical competitive assumptions. Production is represented by constant elasticity of substitution (CES) functions where an energy-value-added bundle substitute against a non-energy intermediate bundle. The former is an aggregate of a capital-labor-resources bundle and total energy. Energy is an aggregate of the commodities from coal mining, oil mining, gas mining, petroleum products, electricity, and gas utilities.

Economic growth in this model is driven by population growth, capital accumulation, resource depletion, and total factor productivity growth. Our model has a standard representation of trade flows, where total imports of a commodity in each region is an aggregate over the supply from all other regions, and imports are imperfect substitutes for domestically produced commodities determined by CES functions.

A representative household in each region receives income from wages and returns to capital, net of taxes on production factors, and government transfers. The disposable income is allocated to consumption and savings according to an Extended Linear Expenditure System (ELES). The utility function includes leisure, and generates an endogenous labor supply in the advanced regions of the world. In the other regions we specify exogenous labor supply to reflect the less developed nature of the labor market. In the flexible form, a reduction in taxes on labor income will lead to a higher labor supply. In either case, a tax cut from recycling carbon revenues will lead to higher consumption and savings. Investment demand is driven by household savings and retained earnings. Total investment is allocated to the 29 commodities using a fixed expenditure share function.

Government revenues in each region are derived from tariffs, indirect taxes on consumption and production, and direct taxes on labor, capital, and household income. Government expenditures include purchases of goods and services, subsidies, and transfer payments (inclusive of interest payments that are regarded as exogenous). Government demand for final commodities is expressed by a fixed expenditure share function.

For each period, given an inherited stock of capital and resources, we find a set of prices that clear all goods and factor markets. At that equilibrium point three macro equalities hold: i) a balance between savings and investment plus government borrowing plus current account surplus, ii) a balance between government spending and revenues plus deficit, and iii) a current account balance equal to net exports plus net factor inflows. The closure rules are the following. (1) In each region, aggregate investment is set as a fixed proportion of GDP, thus household savings adjust endogenously to satisfy the first macro equality. (2) Government deficits, transfers and tax rates are exogenous, and the second macro equality is satisfied with endogenous government purchases. (3) The current account balance for each region is set exogenously, and the require net exports of commodities is achieved through an endogenous exchange rate (a rate relative to the US price normalized to 1). The system is homogenous in prices, and the GDP deflator for each region is set to 1. With such a system, sector quantities reported are in constant 2014 U.S. dollars. Conversion coefficients from the base year translate these to TWh, EJ, or tons of carbon.

Real GDP over time is computed as a Laspeyres index over base year commodity prices. Comparisons of real GDP across policy cases are done using commodity prices from the base case path using the Laspeyres index.

3.2. Data

Our model is based on the GTAP10 dataset which provides national economic and input-output accounts for 65 sectors in 141 countries/regions for 2014 as described in Aguiar et al. (2019). The dataset includes bilateral trade flows between countries where inconsistent trade data from different countries are reconciled. These data are in US$ values. There is also a parallel set of accounts of energy use in physical units (tons of coal or MWh of electricity) together with CO2 emissions (Chapter 11 of Aguiar et al. 2019). We aggregated these accounts to our 10 regions and 29 sectors.

Elasticities of substitution between factors of production, between domestic and imported goods, and between goods from different regions are provided by the GTAP10 dataset (Chapter 14 of Aguiar et al. 2019). In the production functions presented in the Appendix, the elasticities of substitution are from Adkins et al. (2012) and Adkins and Garbaccio (2007) who describe how the elasticity between the value-added-energy and non-energy intermediate inputs are adapted from Noland et al. (1998); the elasticities of substitution between the value-added of factors of production and the amount of input energy at node 2, and the elasticities of substitution between different types of energy at node 3 are from Burniaux and Truong (2002).

In the utility function, the Frisch parameter (marginal utility of income/income) is set uniformly across regions and is taken from Deaton and Muellbauer (1980, p. 141). We allow a flexible labor supply in the developed regions and the income elasticity of labor supply has to be calibrated to the labor supply function for each region. We use the data for the US from Ballard et al. (2004) and de Melo and Tarr (1992) and also apply it to the other developed regions. The share parameters in the production and consumption functions are calibrated to satisfy the equilibrium equations of the 2014 base year.

The developers of the GTAP trade protection data incorporate non-tariff trade barriers (NTBs) in some sectors by converting them into equivalent import tariffs, export subsidies, and producer subsidies as described in Adkins and Garbaccio (2007) and Aguiar et al. (2019). These equivalents are incorporated in our model.

The monthly average EU-ETS permit prices are taken from the Trading Economics website[1]. We use monthly exchange rate data from the IMF to convert Euros to US dollar. We average the monthly carbon price to get annual values.

3.3. Modeling the EU Emission Trading System and BCA scenarios

[1] The daily permit prices are given at tradingeconomics.com/commodity/carbon.

We first simulate a base case path over 2014-2040 using the base year tax parameters, that is, without any additional carbon price policies beyond what were in place in 2014 in each region (scenario S.BASE). We then simulate a growth path with the EU-ETS policy in the EU region that are in the EU(2020) proposals, but without any border adjustments (scenario S.ETS1). This policy covers a few high CO2-emissions sectors - iron and steel, petroleum refining, cement, and certain chemicals; we denote this set by S^{ETS}. The producers in S^{ETS} are required to have permits for each ton of CO2 from the fossil fuels used. They are allocated some quota of permits for free, and we represent this allocation as a subsidy on output. Producers in region *r* are required to buy the remaining permits from the market at price t_r^{ETSco2} ($ per ton of CO2). The EU-ETS covers the electricity sector which are not allocated any free permits, and this means that the electricity prices incorporate the carbon price[2]. Producers are thus not required to acquire emission permits for the CO2 embodied in the electricity used, unlike, for example, the ETS pilots in China.

We then simulate the impact of adding a border carbon adjustment. According to EU(2020), tariffs will be imposed on certain imports to maintain the competitiveness of domestic producers. The tariff rates will be based on the carbon content of these imports, that is, the direct emissions and indirect CO2 embodied in electricity used in producing those goods in the exporting country.

We first note that the products subject to the EU carbon price is classified at a finer level than the classification of industries in our GTAP model. In this analysis we simply assume the entire GTAP sector is subject to the ETS or the CBAM, leaving refinements to future work. For our 29 sectors the set of ETS industries is S^{ETS} ={PPP, PCP, CRP, NMM, MET, NFM, ELY}. The shadow price per unit of fuel input *t1* is the carbon permit price times the emission coefficient:

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

The set of inputs that generate CO2 emissions from their use is $S_{CO2emit}^{ETS}$ = {COA, OIL, GAS, PCP, GDT}. Note that electricity is not in this set. Eq. (1) correspond to (58e) in the Model Appendix, and $\theta_{t1,r}^{F}$ is given in eq. (113).

The producers subject to the permit requirement (set S^{ETS}) thus pay a different shadow price for the inputs of coal, oil and gas. Let PB denote the buyer's price of

2 In the early years of the EU-ETS electricity producers were given free quotas but the inefficiency of these transfers was quickly evident, and this was stopped.

intermediate inputs, the price of energy input e into industry t, inclusive of the permit price, is:

$$PB_{e,t,r} = (1+t_{e,t,r}^{en})PX_{e,r} + tx_{e,t,r}^{ETS} \tag{2}$$

where $tx_{e,t,r}^{ETS}$ is positive for $t \in S^{ETS}$ and zero otherwise. The price of the energy input bundle in industry t is a function of these *PB*'s (Appendix eq. 27b). Intermediate inputs of quantity IX_{etr} are required to produce output Q_{tr} according to the production functions laid out in eqs. (21-36). The total value of the permits required by sector t is thus $\sum_e tx_{e,r}^{ETS} IX_{e,t,r}$ (eq. 53).

Producers in S^{ETS} are given some free allocations of the emission permits, but a rising share of the permits will be auctioned. We represent the value of these allocations as a subsidy, s_{tr}^{co2}, on their output. The revenue equal total costs equation for competitive markets, inclusive of these subsidies, is (29b). The subsidy rate is chosen endogenously so that total value of subsidy exactly equals the free allocation for sector t (eq 60):

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

$\phi_{free;try}^{ETS}$ 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 Appendix eq. 53b. The recycling of this revenue is an important policy choice as discussed by many, e.g. Jorgenson et al. (2013). In this scenario we cut the factor tax on labor ($tf_{labor,r}$ in eq. 51b, 4b) so that real government purchases are maintained at base case levels for each year. Keeping an index of government purchases (eq. 44b) the same across scenarios allow a simple comparison of household utility across policies without having to worry about different levels of public goods.

EU (2020) does not discuss the future path of the overall carbon cap nor the expected permit prices. Currently, given a cap on the number of permits there is a permit price that clears the emissions market continuously. We computed annual averages of the observed permit prices for 2014-2021. The path of prices (in € per ton) is plotted in Figure 1 (bold line) showing the sharp rise in 2020-21. Given this volatility, we assume a smooth projection of permit prices that avoids these sharp changes for our long-run analyses. We first compute the growth rate of prices between 2014 and 2019. Then for the ETS1 case, we implement a path where the permit price start from the 2014 price of 3.35$ per ton of CO2, rising linearly at this 2014-19 growth rate and reaching 100.8$ in 2040. That is, under our simple assumptions, the price in 2040 is about a quarter higher than the unusual high price observed in 2022, as shown in Figure 1.

After simulating scenario S.ETS1 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 carbon border adjustment mechanism (CBAM). These tariffs are placed on products in the Non-metallic Mineral Products, Chemicals-Rubber-Plastics, Non-ferrous metals, Electricity and Ferrous Metals groups. We denote this set as S^{CBA} ={CRP, NMM, MET,NFM, ELY}. According to the proposed rules in EU (2021), tariffs are linked to the permit prices and based on the emissions from fossil fuels used and the CO2 embodied in electricity used in producing the good exported from any region *s* to the EU. The proposal has various options to determine the carbon content of the exports into the EU, one 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 emission data in the GTAP10 database.

The rules specify that any carbon price that is in effect in *s* may be deducted from these border adjustments. Given the narrow nature of the ETS pilots in China we assume that the EU will not allow any exemption for China carbon prices. The adjustment for carbon prices in the US is likely to be part of a complex negotiation between the two regions and for this exercise we assume there is no carbon prices in the US eligible for adjustment (i.e. no further changes in carbon prices beyond those observed in the base year 2014).

While noting that the EU(2021) proposals contain different options for calculating carbon content, we use the most convenient and transparent method to calculate BCA tariff rates using the carbon emissions data and input-output tables in the GTAP10 database. For example, for the Ferrous Metals sector, the IO table for China gives the value of coal, petroleum products, gas products and electricity used and the corresponding CO2 emissions. We do not need to calculate the carbon intensity due to the use of particular inputs, but merely to calculate the total emissions per unit output in region *s*, $\theta^{Q}_{t,s}$, as given in appendix eq. (114). This covers the emissions from direct combustion of fossil fuels and the embodied CO2 in electricity used. Let t_r^{BTAco2} be the tariff rate per ton of CO2 on imports into r. The tariff on good t exported from s to r (X_{tsr}) is this rate times the carbon intensity (appendix 58d):

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

The estimated carbon tariff rates ($ of tax per dollar of imports) for 2026 are given in Figure 2a. The lowest rates are for Chemicals (CRP) and Nonferrous Metals (NFM) while the highest are for Electricity (ELY), Nonmetallic Mineral Products (NMM; cement, glass, etc.) and Ferrous Metals (MET). For imports from China, the rate on Chemicals is .005 and .023 for NMM, and for India they are .006 and .067 respectively.

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

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

where *PWM* is the world price, *PM* is the landed price of imports, *tm* is the regular tariff and *tn* is the non-tariff barrier equivalent (appendix 63b).

EC (2021) discuss the phasing in of these tariffs in parallel with the rising share of auctioned permits. We thus set the border carbon price equal to the permit price multiplied by the auction share:

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

The impact is a big increase in carbon tariffs over time as shown in Figure 2b. For example, the rate on Chemicals from China rises from .005 in 2026 to 0.018 in 2040, and from .023 to .084 for Nonmetallic Mineral Products.

EC (2021) also proposes 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, for example, Droege and Fischer suggest using them to help exporting countries to maintain the principle of Common but Differentiated Responsibilities. To maintain symmetry with the S.ETS1 case we also recycle the border tax revenue in scenario S.CBAM1 by reducing tax rates on factors (*tf* in eq. 51).

While the EU(2021) proposal does not mention rebates for exports, this option has been discussed by many analysts, including discussions around a possible US BCA system. Scenario S.CBAM2 consist of the full border adjustment with both tariffs and export rebates. The rebates are set equal to the effective carbon tax paid on producing the goods exported.

In our simulation results we focus on the impacts of output and exports of each of our 29 sectors in the countries of interest. The impact on aggregate GDP and consumption and capital accumulation are obviously important, as is 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:

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

4. Effects of EU-ETS and border adjustments

In the base case we do not impose any carbon prices in any of the 10 regions during 2014-2040 beyond those that are in the base year 2014. Our focus is on the change in economic outcomes due to a policy and not on the base path. In Table 3 we give a short summary of the growth rates of key variables in the base path for the 2020-40. In this analysis we have chosen to calibrate growth to a low rate of zero TFP growth to generate the least costly base growth of CO2. World GDP growth is 1.03% per year while the EU growth is 0.41%. CO2 emissions is rising at 0.21% in the EU and at 0.63% for the world.

4.1 ETS effects

In the ETS-only scenario (S.ETS1) we impose emission permit prices as shown in Figure 1. The price of CO2 rises from $25.8 per ton in 2020 to 48.3 in 2026, and to 100.8 in 2040, all in 2014 base year dollars. We focus on 2026 since that is the first year when the border tariffs will be imposed in the next scenario. The ETS revenue flows are plotted in Figure 3. As the free allocation share falls, the auction revenue rises from 60 billion dollars in 2026 to 162 in 2040. This is relative to total EU revenues of 8600 billion in 2040. The amount that is allocated free and represented as an output subsidy falls from 18 billion in 2026 to 0 in 2035. Recall that the ETS revenues are recycled by cutting factor taxes.

The impact of the ETS on key variables in 2026 and 2040 is given in Table 4. Keep in mind that there are substantial output subsidies for S^{ETS} in 2026 but zero in 2040. For the EU, the 2026 GDP is lower by 0.45% while CO2 emissions fall 1.1%. There are some interesting shifts in the composition of fuel use in the EU, coal -0.26%, oil -1.6% and gas -0.6%, due in part to the structure of electricity production in the EU.

Table 5a gives the changes in sector output and trade for the EU and China; the ETS sectors are marked in red. The higher costs of production in S^{ETS} raise their prices even after the output subsidies since the auction share is not zero. This cuts demand and their output falls the most, Petroleum in the EU falls by 3.4%, electricity by 4.4%, Chemicals by 1.5% and NMM by 1.0%. They reduce their oil and gas inputs and thus the output of Coal falls by 0.56% and Gas Utilities

(GDT) by 3.3%. Some resources are moved to the less energy intensive sectors and there is a small expansion of output in Electronic Equipment, Machinery and Apparel.

There in an increase in imports of the S^{ETS} goods into the EU (Chemicals +.48, Ferrous Metal +1.6) and a fall in their exports due to the loss of competitiveness. These changes lead to the fall in aggregate EU GDP of 0.45%, but there is a change in the composition of GDP. Government purchases is kept constant by construction, there is a fall in aggregate exports, consumption, and investment. Aggregate imports is unchanged and there is essentially no change in the exchange rate variable.

In the other regions of the world there are differing effects depending on whether they are energy exporters. We first consider China which is an energy importer and a major exporter to the EU. China GDP in 2026 has only a small change with a 0.21 increase in aggregate exports and a 0.75 increase in imports. From Table 5a we see that China increased its exports of the ETS goods (Chemicals +1.0%, Ferrous metals +0.78%), and reduced their imports when EU prices of these goods rises, resulting in a small increase in output. This is offset by lower exports of the low-energy intensity manufactures (Apparel, Electronics, Machinery).

Table 6 gives the effect of the ETS on exports and output of all 10 regions for the key sectors. Russia sees a .64% reduction in oil mining exports, but a 1.5% increase in refined petroleum exports. All regions see an increase in the exports of the S^{ETS} goods except for Russia, Other oil exporters (XOI) and the EU itself. This leads to a corresponding change in sector output; ETS goods output increased in all regions except for Russia, XOI and the EU. All regions see an increase in coal output except for the EU and XOI.

Over time, as the auction share rises and the output subsidy falls, the pressure on the ETS sectors increase. The output of the ETS sectors in EU shrink by a lot - Petroleum -9.8%, Chemicals -4.7%, NMM -2.7% (Table 5b). EU GDP falls by 0.85%, with a 1.11% fall in consumption and a 1.4% fall in aggregate exports. China exports of goods in S^{ETS} rise over time and by 2040, aggregate exports rise by 0.35% and imports rise by 0.89%. This improvement in their terms of trade contribute to higher consumption and the utility index rise a little compared to the fall in EU utility. The 2040 GDP in India, Mexico and Rest-Annex1 is slightly higher, while the GDP in oil exporters fall (Russia -0.23, XOI -0.19, Canada -0.02).

The CO2 emissions in the EU in 2040 is 2.9% lower than the base case but the emissions rise in all other regions of the world except Other Oil Exporters. Global CO2 only fall by 0.16%, giving a leakage rate of 34%, rising substantially from the leakage of 16% in 2026.

4.2 Border carbon adjustment effects

In the S.CBAM1 scenario we impose the border tariffs given in eq. 4, tariff rates that differ by export region depending on their carbon content. We consider the difference between this case and the ETS-only case, and Table 7 gives the effects on the main variables for 2026 and 2040.

There is only a trivial difference in GDP in 2026, and even by 2040 the additional fall in GDP in the EU and XOI are minor. CO2 emissions in the EU are now higher than in the ETS case, by 0.33%, compared to the 2.9% reduction with the ETS alone. However, global emissions is even lower by a small amount when the tariffs are added due to the great reduction in leakage rates, to 14.0% from 34.4%. This is due to the sizable reductions in emissions in Russia, India and Rest-of-World.

The sector impacts in 2040 with the CBAM are given in Table 8, again relative to the ETS-only case. The imports of most of the ETS goods in the EU are lower with the tariff protection – Chemicals -2.5%, NMM -13%, Ferrous metals -8.6%. This leads to a higher level of output for these sectors, e.g., Chemicals output is .24% higher than in the ETS case, after falling by 4.7% due to the ETS; Ferrous metals output is .88% higher after falling 2.5%; Non-metallic minerals is .99% higher after falling 2.7%. The protective effects of the border carbon adjustments are not uniform across sectors due to the different (assumed) elasticities of substitution.

The changes in sector activity in China mirror these differences. When the carbon tariffs are imposed China exports of S^{ETS} goods fall; exports of Ferrous metals fall by .38% after rising by 1.7% in the ETS-only case; NMM exports fall by 2.2% after rising 2.5%. Again there are big differences across sectors.

5 Conclusion

This paper draws the following conclusions from the simulation analysis using a global dynamic general equilibrium computable model. We find that first, unilateral carbon pricing policies can lead to severe carbon leakage, which is mainly due to the transfer of production sectors. Second, carbon tariffs have a very small effect on reducing carbon leakage and have no effect on improving the competitiveness of firms in carbon pricing countries. Carbon tariffs will negatively influence the world economy, nevertheless will have a very limited effect on reducing world CO2 emissions. Third, the carbon taxes and tariffs levied by the EU and the US will mainly cause a negative economic impact on Russia, oil exporting countries, Canada, Mexico, and other countries, as well as a negative impact on China's energy production industry.

Generally speaking, there are several ways to solve the problem of carbon leakage: first, to include all countries in the world in the emission reduction system and assume the obligation to reduce emissions. Second, a uniform global carbon tax (carbon pricing) could be imposed. Third, countries that reduce emissions could impose tariffs on imports from non-reducing countries, or subsidize their own exports. A cost-effective approach would be for the abatement country to induce non-abatement countries to take voluntary action to reduce emissions through certain transfer payments, thereby reducing leakage. According to Energy and Climate Information UK, 137 countries around the world have now committed to becoming carbon neutral by mid-century, with 124 of them setting a goal of becoming carbon neutral by 2050. According to Climate Action

Tracker, these countries cover 73% of global greenhouse gas emissions, demonstrating the global ambition to improve climate change. China also clearly stated in September 2020 that it will aim to peak its CO_2 emissions by 2030 and work towards carbon neutrality by 2060. China's initiative to make a solemn commitment to the world demonstrates its willingness to work together with the rest of the world to address global climate change.

Based on the current reality of international cooperation, the European Union and the United States have recently proposed a third way to reduce carbon leakage and weaken the competitiveness of domestic producers through a carbon border tax, but studies have found that the effect of a carbon tariff is very limited. Carbon pricing is essentially a response to regional abatement costs and the supply and demand of carbon allowances. If the EU or the US acts unilaterally to implement uniform carbon pricing for countries with different levels of development and different carbon costs, it will be unfair to developing countries with lower carbon costs. On the other hand, while the EU imposes carbon tariffs on enterprises outside the EU, it also provides free carbon quotas to competing enterprises in the same industry within the EU, providing double protection to EU enterprises. Such differential treatment is incompatible with the relevant WTO provisions. Without a compensatory transfer policy coordinated with the carbon border tax, it may cause the affected countries to adopt some trade policies such as countervailing tariffs, thus triggering trade wars.

If the EU or the US were to impose a carbon tariff, the scope of the included industries would need to be strictly defined, as well as whether to include the implicit carbon emissions from the production process of the goods. Another difficulty in policy implementation is whether it is possible to quantify the carbon taxes and emission allowances of other countries and other policy measures to make enterprises bear the invisible emission costs, and when imposing carbon tariffs, all should be deducted from the corresponding amounts already paid by enterprises. It is also unfair to levy carbon tariffs on all emissions from imported products, and the free emission credits received by enterprises of similar products in the EU should be deducted.

References

Adkins, Liwayway, and Richard Garbaccio. 2007. Coordinating Global Trade and Environmental Policy: The Role of Pre-Existing Distortions. Paper prepared for the Tenth Annual Conference on Global Economic Analysis, Purdue University.

Adkins, Liwayway, Richard Garbaccio, Mun Ho, Eric Moore, Richard Morgenstern. 2012. "Carbon Pricing with Output Based Subsidies: Impact on U.S. Industries over Multiple Time Frames," *Resources for the Future Discussion Paper*, 12-27, June.

Aguiar, Angel, M. Chepeliev, E. Corong, R. McDougall, D. van der Mensbrugghe. 2019. "The GTAP Data Base: Version 10," *Journal of Global Economic Analysis*, 4(1), 1-27. Further details at: https//www.gtap.agecon.purdue.edu/databases/v10/v10_doco.aspx

Böhringer, C., E. J. Balistreri and T. F. Rutherford (2012), "The Role of Border Carbon Adjustment in Unilateral Climate Policy: Overview of an Energy Modeling Forum Study (EMF 29)," *Energy Economics* 34 (2), 97–110.

Burniaux, Jean-Marc and Truong P. Truong (2002). "GTAP-E: An Energy-Environmental Version of the GTAP Model." GTAP Technical Paper No. 16, Center for Global Trade Analysis, Purdue University.

de Cendra, J. 2006. Can emissions trading schemes be coupled with border tax adjustments? An analysis vis-_a-vis WTO law. Review of European Community & International Environmental Law 15:131–45.

Demailly, D. & Quirion, P. CO2 abatement, competitiveness and leakage in the European cement industry under the EU ETS: grandfathering versus output-based allocation. *Clim. Pol.* **6**, 93–113 (2006).

Dong, Yan and John Whalley. 2012. "How large are the impacts of carbon motivated border tax adjustments?" Climate Change Economics, 3.

Droege, Susanne and Carolyn Fischer. 2020. Pricing Carbon at the Border: Key Questions for the EU. *Ifo DICE Report*, Spring, 18. https://www.ifo.de/en/publikationen/2020/article-journal/pricing-carbon-border-key-questions-eu

European Commission. 2021. Proposal for a Regulation of the European Parliament and of the Council establishing a carbon border adjustment mechanism. 2021/0214 (COD), Brussels, July.

Fischer, Carolyn and Alan Fox. 2012. Comparing policies to combat emissions leakage: Border carbon adjustments versus rebates. *Journal of Environmental Economics and Management*, 64, 199-216.

Felder, S. & Rutherford, T. F. Unilateral CO2 reductions and carbon leakage: the consequences of international trade in oil and basic materials. *J. Environ. Econ. Manag.* **25**, 162–176 (1993).

Flannery, Brian, Jennifer Hillman, Jan Mares and Matthew Porterfield. 2019. Framework Proposal for a US Upstream GHG Tax with WTO-Compliant Border Adjustments: 2020 Update. *Resources for the Future*, Report 20-14, October.

M. Gosh, D. Luo, M.S. Siddiqui, Y. Zhu. 2012. Border tax adjustments in the climate policy context: CO_2 versus broad-based GHG emission targeting, Energy Economics., 34 (S2), S154-S167

Hoel, M. Global environmental problems: the effects of unilateral actions taken by one country. *J. Environ. Econ. Manag.* **20**, 55–70 (1991).

Ismer, R. & Neuhoff, K. Border tax adjustment: a feasible way to support stringent emission trading. *Eur. J. Law Econ.* **24**, 137–164 (2007).

Dale Jorgenson, Richard Goettle, Mun Ho and Peter Wilcoxen. 2013. *Double Dividend: Environmental Taxes and Fiscal Reform in the US*, MIT Press, Cambridge, MA.

Lecca, Patrizio & Swales, Kim & Turner, Karen, 2011. "An investigation of issues relating to where energy should enter the production function," Economic Modelling, Elsevier, vol. 28(6), pages 2832-2841.

Li, Aijun and Aizhen Zhang. 2012. Will carbon motivated border tax adjustments function as a threat? Energy Policy, 47,81-90.

Lin, Boqiang and Aijun Li. 2011. “Impacts of carbon motivated border tax adjustments on competitiveness across regions in China,” Energy, 47,81-90.

Markusen, J. International externalities and optimal tax structures. *J. Int. Econ.* **5**, 15–29 (1975).

Mathiesen, L. and Mæstad, O., 2004. Climate policy and the steel industry: achieving global emission reductions by an incomplete climate agreement. Energy Journal 25, 91-114.

Mattoo, Aaditya, Arvind Subramanian, Dominique Van Der Mensbrugghe, and Jianwu He, “Reconciling Climate Change and Trade Policy,” World Bank Policy Research Working Paper No. 5123, 2009.

Noland, Marcus, Li-Gang Liu, Sherman Robinson, and Zhi Wang (1998). Global Economic Effects of the Asian Currency Devaluations. Washington, DC: Institute for International Economics.

E.B. Peterson, J. Schleich, Economic and Environmental Effects of Border Tax Adjustments, Working paper Sustainability and Innovation No. S1/2007. Karlsruhe, Germany: Fraunhofer Institute Systems and Innovation Research, 2007.

Pizer, William and Erin Campbell. 2021. Border Carbon Adjustments without Full (or Any) Carbon Pricing. *Resources for the Future*, Working Paper 21-21, July.

Weitzel, M., M. Hübler, and S. Peterson. 2012. Fair, optimal or detrimental? Environmental vs. strategic use of border carbon adjustment. Energy Economics 34(Suppl 2):S198–207.

Table 1. Regions in Model

Abbreviation	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
RXAX	Rest of Annex I	Australia New Zealand Japan United Kingdom Switzerland Norway Rest of EFTA Belarus
XOI	Oil Exporters	Indonesia Ecuador Venezuela Iran Islamic Republic of Kuwait Qatar Saudi Arabia United Arab Emirates Nigeria
XRW	Rest of the World	

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

Table 3. Base path of world economy

	World		EU	
	2026	growth rate 2026-2040	2026	growth rate 2026-2040
GDP (bil. $)	92491	0.93%	17468	0.72%
Consumption	53588	0.90%	10006	0.78%
Investment	23542	1.04%	3571	0.72%
Government	15347	0.82%	3699	0.57%
Export	19867	1.18%	3620	0.93%
Import	19853	1.17%	3429	0.98%
CO2 Emissions (mil tons)	34186	0.63%	3027	0.21%
Coal use	14023	0.42%	769	0.17%
Oil use	12594	0.51%	1601	0.22%
Gas use	7569	0.73%	656	0.21%

Table 4. Effects of EU-ETS without a border adjustment (% change from base case)

	World	EU	Canada	Russia	China	India	Mexico	USA	X-Oil Exporter	Rest-Annex 1	R o W
						2026					
GDP	-0.09	-0.45	-0.02	-0.14	0.07	0.06	0.01	0.00	-0.16	0.00	-0
Consumption	-0.13	-0.56	-0.17	-0.28	0.19	0.20	-0.03	-0.05	-0.30	-0.06	-0
Investment	-0.03	-0.26	-0.06	-0.47	0.25	0.20	0.03	0.03	-0.54	-0.01	-0
Government	0.00	0.03	-0.05	-0.38	-0.05	0.23	0.20	0.07	-0.33	0.04	0
Export	0.17	-0.38	0.23	0.87	0.21	0.45	0.15	0.24	0.53	0.21	0
Import	0.20	0.00	-0.13	0.22	0.75	0.97	0.14	0.06	-0.20	0.09	0
Utility		-0.19	0.00	-0.04	0.01	0.00	-0.01	0.00	-0.04	-0.01	-0
Exchange rate		0.01	-0.07	-0.20	0.03	0.03	-0.03	0.00	-0.19	0.02	-0
CO2 Emissions	-0.08	-1.06	0.11	-0.06	0.03	0.01	0.00	0.02	-0.18	0.14	0
Coal use	0.02	-0.26	0.31	-0.06	0.02	0.00	0.05	0.00	-0.18	0.28	0
Oil use	-0.21	-1.63	0.09	-0.06	0.03	0.01	-0.05	0.03	-0.18	0.05	0
Gas use	-0.04	-0.60	0.07	-0.06	0.03	0.11	0.06	0.04	-0.19	0.16	0
Leakage	15.9										
						2040					
GDP	-0.15	-0.85	-0.02	-0.23	0.15	0.12	0.04	0.00	-0.19	0.01	-0
Consumption	-0.23	-1.07	-0.15	-0.32	0.26	0.22	-0.02	-0.04	-0.28	-0.09	-0
Investment	-0.02	-0.48	-0.07	-0.48	0.34	0.28	0.06	0.00	-0.43	-0.03	-0
Government	-0.01	0.03	-0.09	-0.57	0.04	0.38	0.18	0.03	-0.35	0.06	-0
Export	0.02	-1.38	0.23	0.58	0.35	0.73	0.14	0.32	0.45	0.22	0
Import	0.02	-0.75	-0.09	-0.06	0.89	1.15	0.07	0.11	-0.06	-0.03	0
Utility		-0.33	0.01	-0.06	0.03	0.01	0.00	0.00	-0.04	-0.02	-0
Exchange rate		0.08	-0.11	-0.15	0.08	0.06	0.00	0.00	-0.24	0.06	0
CO2 Emissions	-0.16	-2.89	0.20	0.05	0.08	0.10	0.05	0.08	-0.16	0.31	0
Coal use	0.03	-0.90	0.61	0.01	0.05	0.05	0.13	0.04	-0.22	0.52	0
Oil use	-0.42	-4.33	0.20	0.17	0.19	0.20	0.01	0.11	-0.14	0.23	0
Gas use	-0.08	-1.69	0.11	0.00	0.07	0.25	0.12	0.08	-0.18	0.26	0
Leakage rate	34.4										

Table 5a. Sector impacts of EU-ETS in 2026, %change from base case

		EU/2026			China/2026		
		Output	Imports	Exports	Output	Imports	Exports
1	Agriculture	-0.34	-0.20	-0.25	0.03	0.14	-0.25
2	Coal	-0.56	-0.41	-0.08	0.07	-0.03	0.30
3	Oil	-0.28	-1.46	2.60	0.09	0.10	0.24
4	Natural Gas	0.00	-0.52	1.11	0.12	0.04	-0.03
5	Other Minerals	-0.61	-0.82	-0.03	0.08	0.12	-0.17
6	Food mfg	-0.33	-0.26	-0.16	0.05	-0.03	0.09
7	Textiles	-0.21	-0.27	-0.06	0.02	-0.12	0.06
8	Apparel, leather	0.28	-0.66	1.08	-0.03	0.10	-0.11
9	Wood	-0.46	0.10	-0.85	0.05	-0.17	0.33
10	Paper, publishing	-0.50	0.10	-0.85	0.10	-0.18	0.43
11	Petroleum	-3.38	2.16	-8.52	0.12	-0.12	1.05
12	Chemicals	-1.47	0.48	-2.35	0.26	-0.33	1.04
13	Non-metallic min.	-1.00	1.71	-3.83	0.10	-0.48	0.98
14	Ferrous metals	-0.97	1.58	-3.75	0.08	-0.40	0.78
15	Non-ferrous	-1.19	0.63	-2.57	0.08	-0.23	0.60
16	Fabricated metal	-0.04	-0.55	0.70	0.02	0.04	0.00
17	Transportation eq	0.08	-0.65	0.60	0.04	0.13	-0.08
18	Electronic, Com eq	0.54	-0.72	1.54	-0.06	-0.06	-0.17
19	Machinery	0.42	-1.11	1.58	-0.05	0.21	-0.35
20	Other mfg, recycl	0.28	-1.26	1.85	-0.09	0.13	-0.34
21	Electricity	-4.35	15.56	-21.74	0.10	-6.23	12.89
22	Gas utilities	-3.34	1.55	-8.79	0.03	-0.05	0.65
23	Construction	-0.25	-0.99	1.08	0.04	0.27	-0.40
24	Trade	-0.38	-1.06	1.04	0.03	0.27	-0.38
25	Transport	-2.17	2.57	-6.40	0.25	-1.00	2.29
26	Communication	-0.14	-1.27	1.67	0.05	0.32	-0.50
27	Finance, Insurance	0.00	-1.47	2.13	-0.02	0.37	-0.70
28	Other Services	-0.11	-1.25	1.74	0.06	0.33	-0.51
29	Own dwellings	-0.22	0.00	0.00	0.13	0.00	0.00

Table 5b. Sector impacts of EU-ETS in 2040, %change from base case

		EU/2040			China/2040		
		Output	Imports	Exports	Output	Imports	Exports
1	Agriculture	-0.58	-0.58	-0.09	0.05	0.42	-0.82
2	Coal	-1.11	-3.17	4.82	0.10	0.11	0.07
3	Oil	-0.68	-6.69	13.42	0.07	0.56	-0.21
4	Natural Gas	-0.01	-1.85	3.53	0.32	0.06	-0.33
5	Other Minerals	-1.09	-2.36	0.74	0.10	0.30	-0.63
6	Food mfg	-0.59	-0.70	0.03	0.09	0.09	-0.10
7	Textiles	-0.50	-0.68	0.00	0.04	-0.22	0.09
8	Apparel, leather	0.73	-1.37	2.51	-0.08	0.29	-0.28
9	Wood	-0.83	0.00	-1.26	0.06	-0.19	0.38
10	Paper, publishing	-1.15	0.38	-2.14	0.23	-0.35	0.96
11	Petroleum	-9.79	6.39	-23.27	0.41	-0.10	2.84
12	Chemicals	-4.68	2.06	-7.81	0.72	-0.86	3.09
13	Non-metallic min.	-2.68	5.36	-10.98	0.24	-1.19	2.47
14	Ferrous metals	-2.49	4.05	-9.08	0.14	-0.81	1.66
15	Non-ferrous	-2.55	1.29	-5.28	0.06	-0.28	0.71
16	Fabricated metal	-0.06	-1.22	1.61	0.03	0.16	-0.12
17	Transportation eq	0.26	-1.28	1.33	0.08	0.30	-0.17
18	Electronic, Com eq	1.27	-1.47	3.51	-0.14	-0.11	-0.37
19	Machinery	0.98	-2.38	3.53	-0.12	0.47	-0.79
20	Other mfg, recycl	0.70	-2.56	3.94	-0.21	0.32	-0.76
21	Electricity	-8.07	28.20	-34.88	0.20	-10.79	23.66
22	Gas utilities	-6.53	2.30	-15.48	0.06	-0.04	0.82
23	Construction	-0.48	-1.93	2.14	0.09	0.58	-0.87
24	Trade	-0.70	-2.22	2.45	0.07	0.63	-0.76
25	Transport	-4.38	5.16	-12.63	0.55	-1.90	4.48
26	Communication	-0.17	-2.64	3.73	0.12	0.72	-1.05
27	Finance, Insurance	0.16	-3.07	4.79	-0.05	0.82	-1.45
28	Other Services	-0.14	-2.68	3.96	0.12	0.76	-1.10
29	Own dwellings	-0.21	0.00	0.00	0.28	0.00	0.00

Table 6. Sector impacts of EU-ETS on world exports and output in 2026 (%change from base case)

	Canada	Russia	China	India	Mexico	USA	X-Oil Exporter	EU	Rest-Annex 1	Rest of World
	Exports									
Coal	-0.02	-0.06	0.30	0.26	0.24	0.23	0.01	-0.08	-0.04	-0.10
Oil	0.01	-0.64	0.24	0.00	0.06	-0.12	-0.05	2.60	-0.60	-0.22
Natural Gas	0.03	-0.08	-0.03	0.00	0.32	-0.08	-0.01	1.11	-0.25	-0.16
Paper, publ	-0.14	-0.60	0.43	0.34	0.03	0.24	-0.72	-0.85	0.20	0.04
Petroleum	0.82	1.52	1.05	1.06	0.96	0.80	0.78	-8.52	1.29	0.93
Chemicals	0.38	-0.50	1.04	0.83	0.71	0.71	-0.50	-2.35	0.47	0.37
Non-metallic min.	0.29	-0.01	0.98	0.66	0.44	0.79	-0.22	-3.83	0.81	0.66
Ferrous metals	0.29	-0.07	0.78	0.84	0.44	0.55	-0.39	-3.75	0.59	0.47
Non-ferrous	0.14	-0.39	0.60	0.27	0.29	0.40	-0.57	-2.57	0.21	0.12
Electricity	3.62	13.4	12.9	14.2	9.8	10.7	11.4	-21.7	14.6	12.3
Gas utilities	0.99	0.51	0.65	1.92	0.10	1.31	0.16	-8.79	1.52	1.27
	Output									
Coal	0.05	0.03	0.07	0.06	0.06	0.06	-0.01	-0.56	0.08	0.05
Oil	0.09	0.00	0.09	0.09	0.09	0.11	0.01	-0.28	0.07	0.06
Natural Gas	0.05	-0.02	0.12	0.06	0.06	0.07	-0.01	0.00	0.06	0.04
Paper, publ	-0.11	-0.30	0.10	0.09	-0.01	0.03	-0.41	-0.50	0.05	-0.04
Petroleum	0.29	0.45	0.12	0.23	0.15	0.23	0.20	-3.38	0.39	0.31
Chemicals	0.20	-0.13	0.26	0.39	0.26	0.32	-0.36	-1.47	0.39	0.13
Non-metallic min.	0.04	-0.09	0.10	0.07	0.07	0.13	-0.17	-1.00	0.21	0.02
Ferrous metals	0.05	-0.21	0.08	0.16	0.06	0.14	-0.38	-0.97	0.16	0.04
Non-ferrous	0.09	-0.42	0.08	0.21	0.10	0.17	-0.56	-1.19	0.19	0.03
Electricity	0.39	-0.05	0.10	0.07	0.07	0.05	-0.18	-4.35	0.35	0.18
Gas utilities	0.10	-0.03	0.03	0.20	-0.01	0.16	-0.17	-3.34	0.13	0.23

Table 7. Effects of adding a border carbon tariff to the EU-ETS

	World	EU	Canada	Russia	China	India	Mexico	USA	X-Oil Exporter	Rest-Annex 1	Rest of World
						2026					
GDP	0.000	-0.001	0.000	0.005	0.000	-0.003	0.000	0.000	-0.001	0.000	0.000
Consumption	0.001	0.013	-0.003	-0.013	0.001	0.000	0.002	0.000	-0.012	0.000	-0.002
Investment	-0.002	0.002	-0.005	-0.010	0.000	-0.008	-0.001	-0.001	-0.009	-0.003	-0.006
Government	-0.001	0.000	-0.001	0.015	-0.002	-0.027	-0.010	0.000	-0.008	0.000	-0.001
Export	-0.042	-0.184	0.009	-0.008	-0.005	-0.051	0.000	-0.001	-0.015	-0.012	-0.017
Import	-0.042	-0.150	-0.002	-0.064	-0.005	-0.054	-0.001	0.000	-0.060	-0.016	-0.026
Utility		0.003	-0.001	-0.004	0.000	0.000	0.001	0.000	-0.004	0.000	-0.001
Exchange rate		-0.031	0.007	0.031	0.004	0.028	0.002	0.000	0.033	0.002	0.013
CO2 Emissions	-0.009	0.163	0.004	-0.072	0.001	-0.064	0.006	-0.002	-0.006	-0.043	-0.070
Coal use	-0.013	0.404	0.002	-0.121	-0.002	-0.078	-0.012	-0.014	-0.003	-0.117	-0.144
Oil use	-0.001	0.033	0.003	-0.028	0.007	-0.032	0.008	0.009	-0.007	0.000	-0.019
Gas use	-0.016	0.192	0.005	-0.078	0.022	-0.026	0.009	-0.002	-0.005	-0.048	-0.085
Leakage	-10.69										
						2040					
GDP	-0.002	-0.001	-0.002	0.001	-0.001	-0.015	0.000	0.000	-0.009	0.000	-0.005
Consumption	0.003	0.042	-0.012	-0.039	0.002	-0.006	0.004	0.001	-0.034	-0.001	-0.009
Investment	-0.010	-0.003	-0.016	-0.036	-0.003	-0.032	-0.005	-0.002	-0.031	-0.008	-0.020
Government	-0.005	0.000	-0.004	0.032	-0.007	-0.083	-0.025	0.000	-0.029	0.000	-0.008
Export	-0.120	-0.535	0.021	-0.042	-0.021	-0.148	0.000	-0.001	-0.064	-0.025	-0.044
Import	-0.119	-0.438	-0.010	-0.172	-0.025	-0.164	-0.003	-0.001	-0.179	-0.034	-0.067
Utility		0.010	-0.005	-0.011	0.001	-0.002	0.002	0.000	-0.009	0.000	-0.002
Exchange rate		-0.081	0.023	0.076	0.013	0.081	0.006	0.000	0.092	0.001	0.032
CO2 Emissions	-0.015	0.327	0.006	-0.129	0.008	-0.188	0.024	0.005	-0.032	-0.057	-0.110
Coal use	-0.024	0.751	-0.014	-0.186	0.002	-0.227	-0.002	-0.015	-0.006	-0.179	-0.228
Oil use	-0.001	0.083	0.005	-0.070	0.016	-0.097	0.023	0.022	-0.030	0.011	-0.031
Gas use	-0.023	0.410	0.012	-0.140	0.049	-0.093	0.032	0.002	-0.038	-0.061	-0.130
Leakage	14.05										

Table 8. Sector impacts of border tariffs in 2040 (%change from ETS-only case)

		EU/2040			China/2040		
		Output	Imports	Exports	Output	Imports	Exports
1	Agriculture	-0.03	0.01	-0.06	0.00	0.00	-0.01
2	Coal	0.05	1.28	-2.60	-0.02	0.10	-0.26
3	Oil	-0.03	0.09	-0.20	-0.01	0.01	-0.05
4	Natural Gas	-0.05	0.54	-0.92	-0.14	0.09	-0.28
5	Other Minerals	0.04	0.34	-0.30	0.00	-0.02	0.05
6	Food mfg	-0.03	0.15	-0.24	0.00	-0.02	0.04
7	Textiles	-0.31	0.24	-0.79	0.01	0.01	0.03
8	Apparel, leather	-0.23	0.14	-0.47	0.01	-0.04	0.01
9	Wood	-0.15	0.21	-0.47	0.02	0.03	0.08
10	Paper, publishing	-0.08	0.23	-0.44	0.01	-0.02	0.09
11	Petroleum	0.06	0.17	-0.16	0.00	0.02	-0.03
12	Chemicals	0.24	-2.52	-0.85	-0.07	-0.07	-0.56
13	Non-metal min.	0.99	-13.42	-0.82	-0.12	-0.09	-2.20
14	Ferrous metals	0.88	-8.58	-1.57	0.01	-0.08	-0.38
15	Non-ferrous	-0.01	-1.69	-1.54	0.05	-0.01	-0.16
16	Fabricated metal	-0.34	0.51	-1.21	0.05	-0.25	0.25
17	Transportation eq	-0.33	0.16	-0.54	0.04	-0.15	0.16
18	Electronic, Com	-0.46	0.15	-0.84	0.06	0.00	0.10
19	Machinery	-0.41	0.36	-0.87	0.07	-0.15	0.24
20	Other mfg, recycl	-0.23	0.30	-0.67	0.05	-0.04	0.14
21	Electricity	0.85	-49.45	-0.45	-0.02	-0.03	-11.35
22	Gas utilities	0.08	0.38	-0.58	0.06	-0.07	0.33
23	Construction	-0.03	0.22	-0.38	0.00	-0.09	0.11
24	Trade	0.00	0.10	-0.17	0.01	-0.03	0.03
25	Transport	-0.03	0.11	-0.17	-0.01	0.01	0.00
26	Communication	0.01	0.13	-0.17	0.00	0.00	0.01
27	Finance, Insur	0.00	0.07	-0.12	0.00	-0.01	0.03
28	Other Services	0.00	0.12	-0.19	0.00	-0.02	0.02
29	Own dwellings	0.06	0.00	0.00	0.00	0.00	0.00

Figure 1. EU CO2 emission permit price, actual and projected

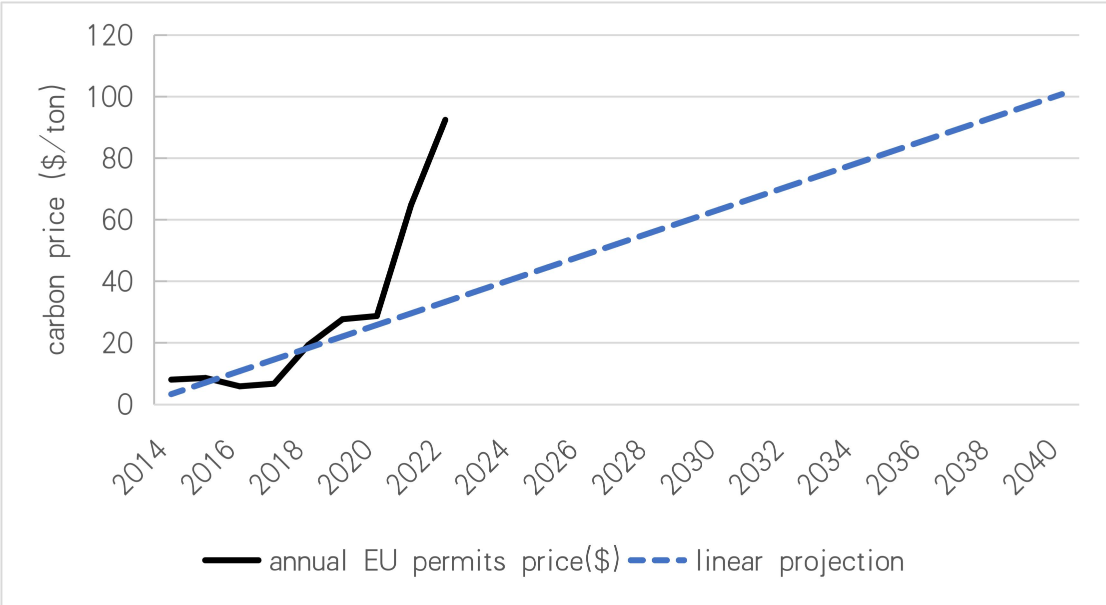

Figure 2. Carbon tariffs per dollar of imports into EU in 2026 and 2040.

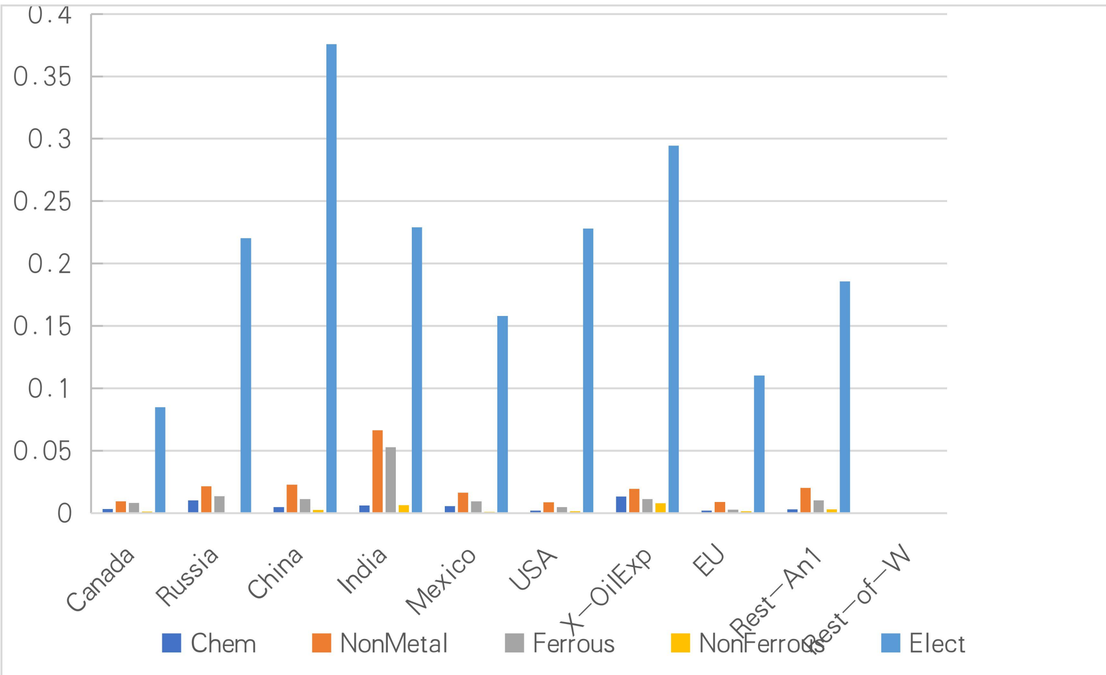

Figure 3. ETS auction revenue and free allocation (subsidy to producers)

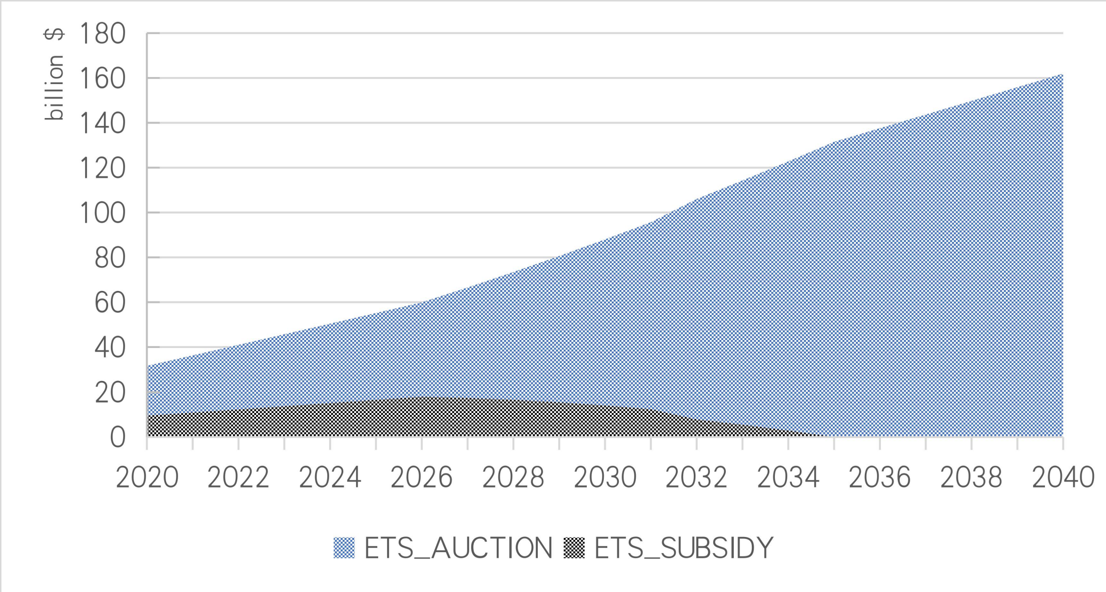

Figure 4. Leakage due to EU ETS and BCA policies