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ORIGINAL PAPER

The European carbon border adjustment mechanism: a small step in the right direction

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Abstract
We estimate the effects of a European Carbon Border Adjustment (CBA) mechanism on exports, real GDP, welfare and emissions using the multi-region, multi-sector structural gravity model of Larch and Wanner (2017). Incorporating the main industries covered in the proposal of the European Commission from mid-2021, as well as its other design features, and assuming prevailing CO_2 prices, we find only small effects of the European CBA mechanism. EU exports are estimated to decline by 0.04%, while CO_2 emissions in EU countries increase by 0.24%. These negligible results mask larger adjustments at the sectoral level. The structural changes will shift the EU economy towards more emission-intensive industries, which will make achieving its climate goals harder. On the positive side, the European CBA mechanism will reduce global emissions by 0.08%. Given the minute economic costs in terms of GDP and welfare losses, the CBA mechanism seems an appropriate policy tool, though its proposed design will not be able to make a significant contribution to mitigating global climate change.

Keywords Carbon border taxes · Carbon tariffs · Carbon leakage · Climate change

JEL Classification F13 · F14 · F17 · F18 · Q56

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1 Introduction

One of the most progressive elements in the EU's European Green Deal (EGD) is the introduction of a Carbon Border Adjustment (CBA) mechanism (European Commission 2019). According to schedule, the European Commission unveiled the first draft for a European CBA in July 2021 (European Commission 2021) which could be implemented as of 2023. The CBA mechanism constitutes a supplementary measure to the European Emissions Trading System (ETS), the EU's internal carbon pricing system, introduced in 2005, and one of its major instruments for achieving the emissions reduction target the EU committed to under the Paris Agreement and its stepped-up internal reduction target of 55% by 2030 (compared with levels in 1990).

The CBA mechanism has two main objectives, both of which are linked to the European ETS. The first objective is to counter 'carbon leakage', that is, additional imports due to the relocation of energy-intensive industries to countries without any domestic carbon pricing mechanism (Felder and Rutherford 1993).[1] By correcting negative externalities associated with CO_2 emissions, the European ETS also creates further asymmetries in CO_2 costs between the EU and third-country producers, with detrimental consequences for the competitiveness of EU exporters and the Single Market's locational attractiveness. Given these unintended distortions, the second objective of the CBA mechanism is to improve the export competitiveness of EU exporters by restoring a level playing field.

By imposing a particular tariff on EU imports, known as 'Carbon Border Tax' (CBT) or 'carbon tariff', the size of which depends on the carbon intensity of the imported product, the CBA mechanism will reduce (and in the ideal case eliminate) the existing asymmetries in CO_2 costs between the EU and third-country producers in the Single Market.

In this paper, we use the structural gravity model of Larch and Wanner (2017) to model the effects of the introduction of a CBA mechanism as envisaged in the current Commission proposal on exports, emissions, GDP and welfare for the EU and the global economy for more than 120 economies. While the focus is on the outcomes for the EU as the entity implementing the CBA mechanism, we also present results for the global economy because of the relevance global emission levels have for the climate. Moreover, the results for partner countries are interesting in light of possible retaliation measures (Felbermayr and Peterson 2020) or countries joining a 'carbon club' (Nordhaus 2015). Apart from modelling this 'base' scenario, we also provide results for different levels of carbon prices and other design features, including the addition of carbon rebates for exporters, the application of an alternative method for calculating the carbon intensity of imports and a wider industry coverage as the one foreseen in the current proposal. The comparisons of the results from the different scenarios will on the one hand shed light on the effectiveness of the European CBA mechanism as currently proposed and on the other hand reveal how sensitively the CBA mechanism reacts to individual design features.

[1] For a detailed discussion on policies to combat carbon leakage, see Zhang (2012).

We find that the introduction of the CBA mechanism in the proposed version leads to a decline in EU and world exports. EU GDP and welfare, however, increase due to increased domestic production. Moreover, as the emission-intensive sectors in the EU benefit from the carbon border tax, these will expand, causing EU CO_2 emissions to increase. However, at the global level, CO_2 emissions fall. Importantly, all global effects are very small in magnitude, amounting to −0.12% for exports and −0.08% for CO_2 emissions. By changing specific design features, we can show that the effects increase to various degrees, and in some cases also change direction from negative to positive, but in general remain small in absolute terms. Overall, these results suggest that the CBA mechanism is an appropriate, if not very effective, instrument for reducing global emissions and levelling the playing field for carbon-intensive industries.

We contribute to the literature by adding a very detailed study on the quantitative implications of the proposal for an EU CBA mechanism in the form it has been proposed. The results obtained for the base scenario are therefore a plausible prediction for the short-term economic and environmental effects of the CBA mechanism. Combined with the most suitable data available on CO_2 emissions, including official data on the verified emission in the ETS, we use all available information on the different elements of the CBA mechanism to develop a simple though plausible methodology to calculate expected carbon border tariffs applicable under the CBA mechanism. We feed these tariffs into a state-of-the-art multi-region, multi-sector structural gravity model that allows calculating effects for GDP and emissions.

The remainder of the paper is structured as follows. Section 2 reviews the literature on the effects of CBA mechanisms. Section 3 presents the different CBA scenarios investigated and the data used. Section 4 presents the model and the results of the quantitative analysis. Section 5 concludes with some reflections on the policy implications.

2 Related literature

The most commonly used tools for ex-ante assessments of the effects of a CBA mechanism are Computable General Equilibrium (CGE) models. Böhringer et al. (2012a) summarise findings of 29 different studies based on multi-region, multi-sector CGE models and conclude that CBA mechanisms are effective at reducing carbon leakage by a third of its benchmark value (the new mean leakage rate is 8%), and at maintaining domestic sectors' competitiveness by reducing output losses incurred due to domestic climate policy by almost two-thirds. Thus, the CBA mechanism has a slightly positive impact on the welfare of the implementing countries, and a negative effect on all other countries (Böhringer et al. 2019 2012b). These findings are generally confirmed in a meta-regression analysis of 25 empirical studies that rely mainly on CGE models and partial equilibrium (PE) models to a lesser extent (Branger and Quirion 2014). Similar conclusions are drawn, among others, by Elliot et al. (2015), Mattoo et al. (2013), Zhang (2012), Bednar-Friedl et al.(2012) and Fischer and Fox (2012).

Larch and Wanner (2017) construct a multi-region, multi-sector structural gravity model to decompose CO_2 emission changes arising from stricter emission regulations due to the Copenhagen Accord into scale, composition and technique effects. They show that carbon tariffs can help to reduce emissions worldwide, but at the expense of trade and welfare, especially for developing countries. The framework from Larch and Wanner (2017) is of particular relevance for this paper because it is used for all simulations of the European CBA mechanism.

Compared to the previously mentioned literature, which usually focuses on more ambitious configurations of a CBA mechanism, the economic and environmental effects of more recent simulations of a European CBA mechanism are very small, as shown in Table 1. In large part, this is because they correspond to scenarios with limited sector coverage and scope of the CBA mechanism, as well as the carbon price, and are thus closer to the proposal tabled by the European Commission in July 2021. One such example, though pre-dating the Commission proposal, is Kuusi et al. (2020). The authors simulate the effects of a CBA mechanism on the Finnish economy. The used GTAP CGE model shows decreased imports from non-EU countries, substituted by imports from EU countries, and increased Finnish exports to EU countries, with negligible, or slightly negative impacts on GDP, depending on the scope of the CBA. Pyrka et al. (2020) use the same CGE model to assess the effects of a carbon border tax (CBT) on imports in the European economy. The introduction of import tariffs ranging from 0.6% to 3% causes a slight increase in domestic consumption, offset by the drop in domestic production, producing a small decline in GDP.

Bellora and Fontagné (2021) use a dynamic general equilibrium model with endogenous CO_2 prices which delivers larger effects for European exports and GDP ranging from − 5% (intermediate goods) to 8.8% (final goods) and − 0.7% (GDP), respectively, in the scenario for a CBA mechanism that is limited to a carbon border tax and uses the actual emissions of the EU's partner countries for determining the size of those border taxes. In a revised version of the paper (Bellora and Fontagné 2022), these numbers change slightly but not dramatically. In comparison to these results, much larger effects on CO_2 emissions are reported by Mahlkow et al. (2021) who model a CBA mechanism, accompanied by an EU-wide carbon tax. In this case, EU emissions drop by 30% and world emissions drop by 2.7%, compared to a 2.5% drop in a scenario with a carbon tax only. Hence, the additional

Table 1 Comparison of simulated effects of a European CBA mechanism

Paper	Exports (EU)	CO_2 Emissions (world)	GDP (EU)
Bellora and Fontagné (2022)[1]	− 8.6%; − 6%	/	− 1.3%
Bellora and Fontagné (2021)[1]	− 5.0%; − 8.8%	− 13.6%	− 0.7%
Pyrka et al. (2020)	~ 0.7%	0.00%	0.00%
Kuusi et al. (2020)[2]	− 0.39%	/	~ − 0.018%
Mahlkow et al. (2021)	/	− 0.2%	/

'/' indicates that these results are not reported. The reported results are taken from the respective papers, cited in the first column, and represent a cross section of modelling scenarios, assessed to be closest to the current CBA mechanism proposal. The results may be approximated or rounded

[1]Numbers reported are those of the embodied emissions scenario in the paper (carbon tax imposed on exporter-specific emissions). The two values for EU exports refer to intermediate and final goods respectively

[2]Column for exports refers to gross extra-EU imports expressed in % of EU GDP

emission-reducing effect of the CBA mechanism is only 0.2 percentage points. These results are contrasting to the gains of a potential carbon club (see Nordhaus 2015), which is shown to be much more effective at reducing world emissions.

Studies on a sector level usually show that the more trade-exposed and energy-intensive EU-based sectors, such as cement, steel and aluminium, are more sensitive to the CBA mechanism and may experience output losses, although the cumulative effect of the CBA mechanism could still be positive (e.g. Bellora and Fontagné 2021; Pyrka et al. 2020; Monjon and Quirion 2011; Manders and Veenendaal 2008).

3 Definition of scenarios and data

3.1 Definition of European CBA scenarios

The economic and environmental effects of a European CBA mechanism will depend on its design. To this end, the proposal by the European Commission (2021) for how a European CBA mechanism could look like, tabled in July 2021, provides a natural starting point and serves as the base scenario for the analysis of the impact of the European CBA mechanism. Among the numerous design options and their consequences discussed in the literature,[2] five characteristics can be modelled within our model framework by Larch and Wanner (2017). These are (i) the general regime of the CBA mechanism; (ii) the applicable price of 1 t of CO_2 emissions; (iii) the carbon benchmark for the application of the carbon border tax; (iv) the treatment of free allowances granted within the ETS and (v) the sector coverage of the CBA mechanism. Each of these elements is briefly discussed below, and together they define our base scenario which reflects as closely as possible the European Commission's proposal.

(i) Regime There are two possible regimes for a CBA mechanism: either the mechanism is limited to a carbon border tax ('CBT only regime') or it comprises additional rebates for EU producers to cover their carbon costs incurred for the part of the production that is exported to extra-EU countries ('comprehensive regime'). The economic argument in favour of a 'CBT only regime' is that a partial rebate of the carbon costs for EU producers undermines the effectiveness of the ETS.[3] The economic argument in favour of a 'comprehensive regime' is that it allows for establishing a level playing field in terms of carbon costs not only in the Single Market but

[2] The economic and legal consequences of different design options for a CBA mechanism are discussed for example in Mehling et al. (2019); Cosbey et al. (2012); Cosbey et al. (2019); Mattoo et al. (2013); Böhringer et al. (2012b); Fischer and Fox (2012) and Kuik and Hofkes (2010). A more focused discussion on designing a potential European CBA mechanism is found, inter alia, in Ismer et al. (2020); Garicano (2021); and Marcu et al. (2020).

[3] A 'CBT only regime' also seems preferable from a legal perspective as rebates for exporters may constitute a form of export subsidies which are prohibited under the WTO Agreement on Subsidies and Countervailing Measures (ASCM) (e.g. Hillman 2013; Boratinsky et al. 2020; Krenek et al. 2020; WTO-UNEP 2009).

also in third markets. With regard to the effects on CO_2 emissions, one may assume that export rebates — in essence a form of export subsidies — will favour more production in CO_2-intensive sectors making the 'CBT only regime' the more attractive option. However, in the presence of differences in technologies across countries, this is not necessarily the case. If the export rebates shift production towards countries with less CO_2-intensive production methods global emissions could be lower in the 'comprehensive regime', making the choice of the preferred regime an empirical question. The European Commission's proposal for a CBA mechanism foresees a 'CBT only regime'.

(ii) CO_2 price There are several estimates and proposals for the adequate price of 1 t of CO_2, also referred to as carbon price, such as the Stiglitz-Stern proposal (High-Level Commission on Carbon Prices 2017), a recent proposal by the IMF (2019) or the estimate of the shadow price by the European Investment Bank (2020). Since the CBA mechanism is a supplement to the European ETS, we use the current price of one European Union Allowance (EUA), which is a certificate that grants the right to emit 1 t of CO_2, and amounts to EUR 62 (the 'current price').[4] The direct correspondence between the ETS price and the CO_2 price underlying the calculation of carbon tariffs is warranted to avoid discrimination against trading partners (which is required by the WTO GATT). This seems in line with the European Commission's proposal (respectively the accompanying staff working document) which states that the EU seeks 'to align, to the extent possible, the price paid under the CBAM with the price paid under the EU ETS' (European Commission 2021; p. 85).

(iii) Within-industry coverage ratio There are two issues to be considered when establishing the costs of carbon in any of the EU industries covered by the ETS. First, not all plants operating in all ETS sectors need to be registered. In particular, in some sectors firms below a certain size do not need to participate and hence are not required to buy emission certificates for their CO_2 emissions. This means that for some industries, the *within-industry* coverage ratio is lower than 100%. This within-industry coverage ratio needs to be taken into account in the calculation of the carbon border tax. A second complication for establishing the proper price of carbon within the ETS arises from the common practice of granting free emission allowances to producers in energy-intensive industries. This means that the carbon price for EU producers will be lower than the price of a EUA. In the extreme case, if a sector receives 100% of its required EUAs for free, its carbon costs will be zero. The proposal by the European Commission, while emphasising that free allowances will be reduced over time, is not very explicit, about how — if at all — the free allowances will be reflected in the CBA mechanism. As will be seen in the discussion of the carbon benchmarks, the free allowances cannot be properly accounted for in the base scenario. In the base scenario, it is therefore assumed that free allowances remain in place, though they do affect the size of the carbon border tariff ('no free allowances'). In any case, both issues, the exemption of plants from the ETS

[4] Price as of end of September 2021.

and the granting of free allowances, imply that the amount of CO_2 emissions 'used' by a sector is not necessarily equal to the amount of CO_2 emissions paid for. We define the within-industry coverage ratio as the ratio between the used CO_2 emissions and the paid CO_2 emissions in any sector.

(iv) Carbon benchmark Another element that strongly affects the carbon price charged within the CBA mechanism, and therefore also the carbon tariffs, is the method for calculating the carbon intensity of imports. Leaving aside plant-specific calculations, the literature has identified two main methods which are known as avoided emissions approach and embodied emissions approach, respectively (Rocchi et al. 2018). The avoided emissions approach applies the CO_2 intensity of EU producers for the calculation of the carbon border tariff on imported products. In contrast, the embodied emissions approach uses the CO_2 intensity of individual trading partners for the calculation of the carbon border tariff. The embodied emissions approach is the one opted for in the European Commission's proposal. The argument supporting this design choice is that 'the CBAM should ensure that imported products are subject to a regulatory system that applies carbon costs equivalent to the ones that otherwise would have been borne under the EU ETS' (European Commission 2021, p. 16). The equivalence here refers to the fact that in applying the embodied emissions approach, the size of the carbon tariffs imposed on imported products reflects — to the extent possible — their actual carbon content. In all likelihood, the EU CBA mechanism allows producers to report their firm-specific emissions. Such a procedure, however, requires detailed monitoring, reporting and verifying procedures for emissions and will not be a viable option for producers from numerous countries (see Eicke et al. 2021). In the absence of reported verified emissions, the carbon tariffs in the CBA mechanism will be set according to country-specific emission benchmarks. These benchmarks will have to be based on the average emission intensity of the respective country.[5] As we have no knowledge of future firm-specific verified emissions by importers and because it is not known to what extent this possibility will be used anyways, the best way to model the embodied emissions approach is to use sector-specific average emission intensities of partner countries for the calculation of the carbon tariffs. The embodied emissions approach is therefore the relevant carbon benchmark in the base scenario. Apart from being relevant for the size of the carbon border tax — most extra-EU trading partners have higher CO_2 intensities than the EU average — the embodied emissions approach also implies that the free allowances granted in the ETS are irrelevant, because free allowances only affect EU producers' carbon costs while for the emobdied emissions approach emissions of trading partners serve as benchmarks.

(v) Sector coverage The final element is the sector coverage. In this respect, our modelling must make some approximations. While the European Commission's proposal contains a very detailed list of products suggested to be covered by the CBA

[5] To the best of our knowledge, the exact modalities of the benchmarks for emissions of imported products are not known yet.

mechanism, our data on CO_2 emissions is available at a sector level.[6] Therefore, we assume that carbon tariffs are imposed in sectors whose products are predominantly included in the list of products in the European Commission's proposal for a CBA mechanism. These sectors are the basic chemicals, the basic metals and the non-metallic minerals sector.[7] As a consequence, in the base scenario, only these three sectors will carry a carbon border tariff as foreseen in the proposal for a CBA mechanism ('CBAM proposal').

Against the backdrop of the discussions on the optimal design of the CBA mechanism, we define a comprehensive set of scenarios to be investigated, taking the European Commission's CBA mechanism proposal (2021) as the starting point and therefore serving as the base scenario. The characteristics of the base scenario are summarised in the second column of Table 2 labelled 'base scenario'. To see how strongly the results react to changes in all of the discussed design options, we change each of them individually to arrive at a sort of sensitivity analysis. For example, to test the sensitivity of the results with regard to the choice in favour of a carbon tariff-only regime, an alternative 'comprehensive CBA regime' scenario is defined which deviates from the base scenario only in this one characteristic. The same principle is applied to each of the five characteristics discussed. In the case of the price of CO_2 emissions, we take two well-known carbon prices from the literature which are the Stiglitz-Stern-Proposal, suggesting a carbon price of USD 100 (EUR 85) (High-Level Commission on Carbon Prices 2017), and the more recent estimation of the shadow price of carbon for 2030 of EUR 250 by the European Investment Bank (2020). These two price suggestions form scenarios 1a and 1b.

Scenario 2, the 'avoided emissions scenario' assumes that all imports use EU-based carbon intensities to calculate carbon tariffs imposed by the EU. This means that the carbon intensities of countries of production are considered. This is contrary to the way the implicit carbon tariffs are calculated in the base scenario, which uses the 'embodied emissions approach'. The details of these calculations are explained further in the following.

Importantly, as the free allowances, which are still frequent in the European ETS, cannot be considered in the embodied emissions approach, no specific scenario for the within-industry coverage ratio is considered in the sensitivity analysis. The sensitivity scenario for the avoided emissions approach (scenario 2), however, assumes that free allowances are granted to EU producers as of 2014 (which is the last date for which we have all the necessary data). Therefore, technically, the free allowances are in place, but, as mentioned above, they do not make a difference in the embodied emissions approach.

6 Data on CO_2 emissions is available for 56 industries. The model by Larch and Wanner (2017) features 14 sectors.

7 In fact, the proposal for a CBA mechanism by the European Commission contains a fourth sector, which is electricity generation. Electricity generation is a very important sector in terms of CO_2 emissions. However, given the limited extra-EU trade in electricity, the sector is largely irrelevant in the context of a CBA mechanism. For this reason, electricity sector is treated as a non-tradable sector in the scenario analysis.

Table 2 Overview of scenarios for sensitivity analyses

Scenario	(0)	(1a)	(1b)	(2)	(3)	(4)
	Base	Price sensitivity		Avoided emission scenario	ETS sector coverage scenario	Comprehensive CBAM regime
characteristics		Moderate price	High price			
Regime	Carbon tax only	Carbon tax only		Carbon tax only	Carbon tax only	Comprehensive CBAM (incl. export rebates)
CO_2 price	Current ETS price (€62)	Stiglitz-Stern proposal (€85)	EIB shadow price (€250)	Current ETS price (€62)	Current ETS price (€62)	Current ETS price (€62)
Carbon benchmark	Embodied emissions	Embodied emissions		Avoided emissions	Embodied emissions	Embodied emissions
Within-industry coverage	As in the ETS	As in the ETS		As in the ETS	As in the ETS	As in the ETS
Sector coverage	CBAM proposal	CBAM proposal		CBAM proposal	Current ETS coverage	CBAM proposal

Source: authors' representation

The sector coverage in the base scenario is limited to three sectors: basic chemicals, basic metals and non-metallic minerals. This selection closely reflects the sectors outlined in the CBA mechanism proposal, subject to the limitations of the sectoral structure of GTAP data. Scenario 3 extends the sector coverage by assuming that carbon border taxes are imposed in all industries currently covered by the ETS ('current ETS coverage'). Scenario 4 assumes a comprehensive CBA regime where the carbon border tariffs are supplemented with export rebates.

We also present three additional scenarios of the CBA mechanism (Table 3). The first, labelled the 'WTO safe bet' scenario, maximises the chance of passing WTO scrutiny given ongoing legal discussions (e.g. Ismer et al. 2020; Mehling et al. 2019; Marcu et al. 2020). It employs the avoided emissions approach and expands the sector coverage to all ETS sectors. The avoided emissions approach is less problematic with a view to WTO/GATT compatibility because potential discrimination against foreign producers (in the form of higher carbon costs imposed on imports for a given product) is ruled out by construction.[8] Similarly, the ETS sector coverage should not be contentious either because foreign producers are charged the carbon tax in exactly those industries in which EU producers must pay for emission certificates.

The second additional scenario, labelled'feasible' scenario, features a design of the CBA mechanism that is likely to bring larger economic benefits for the EU compared to the base scenario, and at the same time has realistic chances of being politically and socially acceptable by all stakeholders. It uses the current carbon price and keeps most design options in the Commission's proposal, except an expanded sector coverage, which is assumed to cover all sectors. The 'Maximum' scenario uses the high carbon price suggestion (EUR 250) and also full sector coverage. Both scenarios also come in a comprehensive version, featuring export rebates.

Given that the CBA mechanism is primarily a trade instrument, all scenarios will assume that EU member states set a common carbon tariff, and where applicable also grant common carbon rebates for exports for each industry. Moreover, in all scenarios, trade with the UK, all EFTA members[9] and Canada, New Zealand and South Korea is exempted from the CBA mechanism, as these countries have a domestic carbon pricing mechanism in place. For all other trading partners, the implicit carbon tariffs in Eq. (1) are imposed and the implicit carbon border rebates[10] in Eq. (2) are added to the pre-existing (bilateral) tariffs.

The carbon tariffs are calculated as implicit tariff equivalents of the carbon costs imposed on EU producers with the ETS. The calculation of this implicit price of the CO_2 emissions (p^{EUA})[11] resulting from the EU ETS (or an EU carbon tax), proceeds in two steps. First, the (scenario-specific) emission price is multiplied by the volume of

[8] The deeper issue here is that the production method is not part of the likeness concept in the GATT (Low et al., 2012).

[9] While EFTA members are part of the European ETS or linked to it (Switzerland), it is assumed that they do not impose carbon border taxes themselves.

[10] As the carbon border rebates have a negative sign, adding them to the existing tariffs reduces trade costs.

[11] EAU stands for Emissions Allowance Units.

Table 3 Additional scenarios of interest

Scenario	(6)	(7a)	(7b)	(8a)	(8b)
characteristics	WTO-safe scenario	Feasible scenario (carbon tax only)	Feasible scenario (comprehensive CBAM)	Maximum scenario (carbon tax only)	Maximum scenario (comprehensive CBAM)
Regime	Carbon tax only	Carbon tax only	Comprehensive CBAM (incl. export rebates)	Carbon tax only	Comprehensive CBAM (incl. export rebates)
CO_2 price	Current ETS price (€62)	Current ETS price (€62)	Current ETS price (€62)	EIB shadow price (€250)	EIB shadow price (€250)
Carbon benchmark	Avoided emissions	Embodied emissions	Embodied emissions	Embodied emissions	Embodied emissions
Within-industry coverage	As in the ETS	Full coverage	Full coverage	Full coverage	Full coverage
Sector coverage	Current ETS coverage	All sectors	All sectors	All sectors	All sectors

‘Full coverage’ in the characteristic ‘Within-industry coverage’ means that all plants in the relevant sectors are covered and that there are no free allowances so that the used CO_2 emissions are equal to the paid CO_2 emissions

Source: authors’ representation

emissions in each industry. For the embodied emissions approach, the volume of emissions is that of the respective trading partner. In principle, to benchmark against costs faced by EU producers in the ETS, the number of free allowances (EUA^f) has to be considered by deducting them from the emissions covered by the EU ETS/carbon tax. But this information is not available and is also not operational. Therefore, we assume that the firms in partner countries have to pay for all their CO_2 emissions. Second, the resulting 'CO_2 emission costs' at the industry level are divided by gross industry output (GO). The tariff equivalent of the implicit 'domestic' carbon price is assumed to define the size of the CBT (τ^{CBT}) to be imposed on imports from non-EU partners. Hence, the CBT on EU imports of industry k from trading partner j is defined as:

$$(1a - \text{embodied emissions})\ \tau_{j,k}^{CBT} = \begin{cases} \frac{p^{EUA} \cdot (CO2_{j,k})}{GO_{j,k}}, & \text{if industry } k \in \text{CBAM and partner } j \in \text{ targeted partner proposal} \\ 0 & \text{, otherwise.} \end{cases}$$

In contrast, when the implicit carbon tariffs are calculated according to the avoided emissions approach, as we do in one of the sensitivity analyses, the relevant CO_2 emissions ($CO2_k$), free allowances (EUA_k^f) and gross outputs (GO_k) are those of the EU and no partner-specific information is needed:

$$(1b - \text{avoided emissions})\ \tau_{k}^{CBT} = \begin{cases} \frac{p^{EUA} \cdot (CO2_k - EUA_k^f)}{GO_k}, & \text{if industry } k \in \text{CBAM proposal and partner} \in \text{ targeted partner} \\ 0 & \text{, otherwise.} \end{cases}$$

Equations (1a) and (1b) illustrate that correcting the CO_2 costs for the free allowances is only possible in those scenarios that apply the avoided emissions approach.

Table 4 shows a summary of the implicit bilateral carbon tariffs levied by EU member states in selected scenarios, including the base scenario. In the base scenario, the simple average tariff in each of the three 'CBAM sectors' is around 1%. More telling than simple averages are, however, weighted averages. The comparison of the two shows that the EU's major trading partners face higher tariffs than marginal trading partners. This pattern is strongly influenced by the relatively high carbon intensity of Russia, India and also China. Russia is also the country that faces the highest tariffs on average, for example, in the metals sectors amounting to more than 10%. This summary of the tariffs also helps to illustrate the differences among the different elements of the CBA mechanism scenarios.

For example, the described variation of carbon tariffs across partners is, by definition, only present if the embodied emissions approach is applied. This is why in scenario 2, which assumes the avoided emissions approach, there is a uniform tariff for each sector across all trading partners.

Differences in relative emission intensities (i.e. technology) can lead to high variance in the size of the carbon tariffs (see also Kuusi et al. 2020; Rocchi et al. 2018). For example, the maximum carbon tariff for the metals sector in the base scenario (10.7%) is almost ten times higher than the average one (1.3%). In the scenario which expands the sector coverage to all ETS sectors, the paper and mining industries also face sizeable carbon tariffs with significant tariff hikes against individual partners. Overall, the average tariffs indicate that the overall economic effects of the CBA mechanism might be small due to mild carbon tariffs, but also that trade with individual partner countries could be severely affected.

Table 4 Implicit carbon tariff rates, base scenario and variants

Sector	Simple average	Weighted average	Minimum	Maximum	Standard deviation
Base scenario (scenario 0)					
Chemical	0.93%	1.55%	0.17%	6.97%	0.84%
Mineral	0.95%	1.80%	0.17%	5.74%	0.87%
Metal	1.29%	3.40%	0.19%	10.72%	1.59%
Price sensitivity — high price (scenario 1b)					
Chemical	3.77%	6.25%	0.70%	28.10%	3.37%
Metal	5.19%	13.73%	0.77%	43.22%	6.41%
Mineral	3.82%	7.25%	0.69%	23.15%	3.53%
Avoided emissions approach (scenario 2)					
Chemical	0.252%				
Metal	0.188%				
Mineral	0.054%				
Sector coverage as in ETS (scenario 3)					
Agriculture	0.00%	0.00%	0.00%	0.01%	0.00%
Apparel	0.00%	0.00%	0.00%	0.02%	0.00%
Chemical	1.23%	1.70%	0.24%	6.97%	0.90%
Equipment	0.04%	0.05%	0.01%	0.24%	0.03%
Food	0.24%	0.26%	0.05%	0.72%	0.13%
Machinery	0.00%	0.00%	0.00%	0.00%	0.00%
Metal	1.29%	3.40%	0.19%	10.72%	1.59%
Mineral	2.90%	3.90%	0.61%	8.30%	1.66%
Mining	0.58%	0.28%	0.03%	35.41%	3.64%
Other	0.00%	0.00%	0.00%	0.01%	0.00%
Paper	0.53%	0.84%	0.10%	2.51%	0.38%
Service	0.00%	0.00%	0.00%	0.00%	0.00%
Textile	0.00%	0.01%	0.00%	0.02%	0.00%
Wood	0.02%	0.03%	0.00%	0.23%	0.03%

The non-tradable sector is, by definition, irrelevant for the trade part of the modelling exercise and is therefore not shown. Averages are averages over all partner countries. Averages refer to all countries which face tariffs. All tariffs were derived using data from 2014. By construction, sector-specific tariffs levied by the EU are identical for all partner countries, and therefore, simple and weighted mean, minimum and maximum are identical too. Tariffs in scenario 3 (sector coverage as in ETS) in the Chemical and Mineral sector differ from the base scenario. This is because the industries covered in the Commission's proposal for the CBA mechanism are defined at this more detailed industry level. Only then are these industries aggregated to the sectors used for the modelling. For details, see Appendix 1

Source: authors' calculations

3.2 Data

As this paper relies on the model from Larch and Wanner (2017), the main data sources are those of that model. At the core is the Global Trade Analysis Project (GTAP) 8 database (see Narayanan et al. 2010), which features 128 regions and 57 sectors. For the simulations, these very detailed sectors are aggregated to 14 tradable and 1 non-tradable sector. Real GDP is taken from the Penn World Table 9.1.[12] For estimating the social cost of carbon in the welfare function, the approach by Shapiro (2016) is utilized, together with estimates provided by the Interagency Working Group on the Social Cost of Carbon (2013).

The calculation of the implicit carbon tariffs across the different scenarios explained in Sec. 3.1 required several data sources. First, information on the ETS sector coverage, the amounts of emission allowances handed out for free ('free allowances') and those actually paid for are taken from the ETS Database (EEA 2020).[13] This information is only relevant (and therefore available) for the countries participating in the ETS (i.e. EU member states, Iceland, Lichtenstein and Norway) as was already mentioned in the context of the role of free emissions in the embodied and avoided emissions approach. This data is available at the level of so-called ETS categories, which we mapped into NACE Rev. 2 industries.[14] The ETS data is combined with information from the WIOD Environmental Accounts on CO_2 emissions at the industry level (NACE Rev. 2) (Corsatea et al. 2019).[15] Nicely, the CO_2 emission data from the Environmental Accounts match perfectly with the industry structure (consisting of 56 industries) in the World Input–Output Database (WIOD) Release 2016 (Timmer et al. 2015) and the country coverage (43 economies plus the Rest of the World) coincides as well. The WIOD Release 2016 provides the gross output data. Moreover, WIOD trade data is used for the calculation of weighted carbon tariffs in the process of collapsing the 56 WIOD industries to the 15 GTAP sectors used in Larch and Wanner (2017). One complication is that the country coverage of the WIOD Release 2016 is limited to 43 economies, while GTAP 8 contains 128 countries and regions. We solve this by calculating the implicit carbon tariffs of the countries not covered in the WIOD data by assuming the (sector-specific) average CO_2 emission intensity of six emerging countries in the WIOD data.[16] This imputation, however, does not affect the main results in any significant way as the share of these countries in total EU trade is negligible.

4 Model framework and results

4.1 Model framework

We use a structural gravity model to estimate the economic and environmental effects of a carbon border tax designed in the way described in Sec. 3 for all EU and EFTA countries as well as major extra-EU partner countries, in total 128 countries, for each industry. The structural gravity model is the workhorse framework

[12] The data is available at https://www.rug.nl/ggdc/productivity/pwt/?lang=en.

[13] The data is available at https://www.eea.europa.eu/data-and-maps/data/european-union-emissions-trading-scheme-16/eu-ets-data-download-latest-version.

[14] For details, see Appendix 1.

[15] The data is available at https://ec.europa.eu/jrc/en/research-topic/economic-environmental-and-social-effects-of-globalisation.

[16] These countries are Brazil, China, India, Indonesia, Russia and Turkey.

for trade policy analysis as it performs well empirically to explain bilateral flows and is consistent with a comparably large set of trade models (see Arkolakis et al 2012). For example, the gravity framework is consistent with the assumption of goods differentiated by place of origin combined with monopolistic competition (Anderson 1979; Anderson and van Wincoop 2003), a Heckscher-Ohlin framework (Bergstrand 1985; Deardorff 1998), a Ricardian framework (Eaton and Kortum 2002) and heterogeneous firms, which select into markets (Chaney 2008; Helpman et al. 2008), and with models allowing for sectors and input–output links (e.g. Costinot et al. 2012; Caliendo and Parro 2015). Most of the frameworks, however, do not account for any dynamics (exceptions are Eaton et al. 2016, and Anderson et al. 2020) and assume homothetic preferences (an exception is Fieler 2011), and therefore are less suited to allow for structural change. This is also true of the employed framework by Larch and Wanner (2017), which assumes constant spending shares, homothetic preferences and constant factor inputs in production. Furthermore, the models depend on strong functional form assumptions for the demand and production structure. Only recently, semi- and non-parametric approaches for counterfactual analysis were developed and introduced into the trade literature (see Adao et al. 2017; Allen et al. 2020). We believe that performing non-parametric counterfactual analysis for the evaluation of environmental policies in a trade context is a fruitful area for future research.

As accounting for emissions alongside the trade and welfare effects is crucial for evaluating the effects of carbon tariffs, we use the recent framework from Larch and Wanner (2017) which was explicitly developed to quantify the effects of carbon tariffs on trade, GDP, welfare and carbon emissions.[17] It is a multi-sector, multi-factor structural gravity model that allows the decomposition of the emission changes into scale, composition and technique effects, as famously introduced by Grossman and Krueger (1993) and formalised by Copeland and Taylor (1994). Note that the decomposition into scale, composition and technique effect is based on a total differential. Hence, the decomposition depends on the model structure and is a linear approximation of the non-linear effects. Impact factors and relationships that we did not account for in our model are therefore also not reflected in our decomposition. Further, the approximation works very well for small changes but will be a bit off for larger changes.

The model has 14 tradable sectors and one non-tradable sector. The trade costs are estimated using a structural gravity model that includes multilateral resistance terms.[18] Most importantly, the model includes energy as a production factor and treats the emissions as a proportional side output. Additionally, the utility function includes multiplicative damages from CO_2 pollution following Shapiro (2016).

[17] There are only a few structural gravity frameworks that take emissions into account (see, for example, Aichele 2013; Egger and Nigai 2012, 2015; Shapiro 2016; Shapiro and Walker 2018; Caron and Fally 2022). A summary of the Larch and Wanner (2017) model is presented in Appendix 2.

[18] Multilateral resistance terms account for the potential trade diversion effects that arise for third parties when country pairs lower their bilateral tariffs, as is the case with FTAs. Technically, they are captured by exporter and importer fixed effects in our sector-wise estimates.

Taking the abovementioned limitation into account, this framework nevertheless allows us to quantify the effects of the European CBA measures. Hence, considering its trade relationships in a framework with many countries seems crucial to us. Furthermore, country-specific environmental policies that specifically target global pollutants, such as CO_2 emissions, need to be seen in light of their effects on trading partners to properly quantify their effectiveness in terms of emission reductions. In other words, potential leakage effects need to be properly accounted for, which the suggested model framework ensures not only by incorporating trade and emissions in an integrated manner but also by using a multi-country framework featuring a very large number of countries. Sector differentiation enables the study to differentiate the impact by industries, which are also heterogeneous in terms of their dependence on energy as input.

For the baseline, we use the data from Larch and Wanner (2017). For the scenario analysis, we rely on the tariff equivalents for the carbon border tariffs, τ^{CBT}, obtained for the base CBA mechanism scenario and the different variants in the previous section. Note that by modelling the CBA mechanism in the form of exogenous tariff equivalents (which vary across scenarios), we implicitly assume that all adjustments on the producer side will take the form of quantitative changes to production and exports. Therefore, we have to assume that within the EU, the induced quantitative adjustments remain within the total amount of available emission allowances corresponding to EU production.[19]

4.2 Results and discussion

The counterfactual results for exports, real GDP, welfare and CO_2 emissions of the base scenario and the sensitivity analysis for changing individual parameters are shown in Table 5. The outcomes are reported for the EU as a group, all other third countries, the EFTA members and the world as a whole. The reported aggregate values for trade flows and emissions are obtained by summing trade flows and emissions of the respective groups for the baseline and counterfactual and then calculating the changes based on these aggregated values for the respective groups. For real GDP and welfare, we calculate the reported aggregate values as GDP-weighted averages of the country-specific changes. The effects for individual countries are reported in Appendix 3.[20]

[19] Given that so far the ETS did not suffer from any shortages in available allowances (but rather an oversupply) and that with the market stability reserve (MSR) there is a mechanism in place to counteract potential imbalances according to pre-defined rules, we believe that this modelling approach is adequate. Extending the analysis to capture the potential overall quantity constraint within EU ETS would, however, be an interesting avenue for future extensions.

[20] We chose the scaled equilibrium price in the agricultural sector (first sector in alphabetical order in our data) in Albania (first country in alphabetical order in our data) as the numéraire. Note that real GDP, welfare, and emissions are not affected by the choice of the numéraire, while nominal trade flows and output are. Hence, the results for trade flows and output have to be interpreted relative to the price change in agriculture in Albania.

Table 5 Economic and environmental effects of a European carbon border tax. Base scenario and alternative scenarios (sensitivity analysis)

	(0)	(1a)	(1b)	(2)	(3)	(4)
	Base scenario	Price scenarios		Carbon benchmark	Sector coverage	CBAM regime
	(CBAM proposal)	Moderate price (EUR 85)	High price (EUR 250)	Avoided emissions	ETS sectors	Comprehensive
(a) Exports						
EU	−0.0365	−0.0461	−0.0812	0.0005	−0.0402	0.0179
Non-EU	−0.1597	−0.2056	−0.4295	−0.0131	−0.2071	−0.1560
EFTA	0.0461	0.0612	0.1519	0.0066	0.0732	0.0459
World	−0.1161	−0.1492	−0.3063	−0.0083	−0.1480	−0.0945
(b) Real GDP						
EU	0.0228	0.0281	0.0446	0.0025	0.0302	0.0270
Non-EU	−0.0094	−0.0123	−0.0274	−0.0009	−0.0123	−0.0108
EFTA	0.0103	0.0135	0.0297	0.0011	0.0140	0.0082
World	−0.0011	−0.0019	−0.0090	0.0000	−0.0014	−0.0011
(c) Welfare						
EU	0.0242	0.0299	0.0487	0.0026	0.0322	0.0284
Non-EU	−0.0088	−0.0115	−0.0256	−0.0008	−0.0114	−0.0102
EFTA	0.0118	0.0154	0.0341	0.0012	0.0162	0.0097
World	−0.0003	−0.0009	−0.0066	0.0000	−0.0002	−0.0003
(d) CO_2 emissions						
EU	0.2429	0.3249	0.8162	0.0121	0.4243	0.2728
Non-EU	−0.1330	−0.1756	−0.4102	−0.0070	−0.2048	−0.1420
EFTA	0.1785	0.2337	0.5218	−0.0014	0.2892	0.1815
World	−0.0833	−0.1093	−0.2479	−0.0045	−0.1215	−0.0871

Numbers indicate changes to the baseline expressed in percent. The number 0.2429, for example, indicates a growth of the EU's CO2 emissions by 0.2429% in the base scenario. For the defining characteristics of the base scenario see Sec. 3

Source: authors' own simulations based on the model by Larch and Wanner (2017)

4.2.1 Base scenario — the European Commission's CBA mechanism proposal

As a first observation, the size of the effects is small. We find that global exports decline by 0.11% and total exports for the EU decline by 0.03%. This suggests that the concerns about green protectionism on the side of important emerging countries and the warning of the CBT 'jolting' world trade (Aylor et al. 2020) are unwarranted. In all likelihood, the introduction of a European CBT will not rock world trade. There are several reasons for these small effects. First of all, a large share of EU countries' trade is intra-EU trade, which is not directly affected by the carbon tariffs. Second, the carbon price in the base scenario is modest. This small drop in EU exports is noteworthy, given the huge debate about the effects of a carbon border tax. Third, in the form the CBA mechanism is suggested, it affects only three sectors directly (which account for about 13.1% of EU imports).

EU imports from third countries will become relatively more expensive as a result of the CBT. The effect is small as intra-EU trade and trade with EFTA partners are not directly affected by the measure. The pro-export effect for EU member states is counteracted by a general equilibrium effect that works via reduced real GDP and associated lower import demand from third countries. The net result is a small drop in the export volume of EU countries. The abovementioned cost imposed on third countries by the CBT is also the reason for the decline in exports in non-EU countries (−0.16%). And as they are exempted from the CBT, the EFTA members' exports increase slightly (+0.046%) as a result of both trade diversion effects and higher incomes in EU member states, many of which are important trading partners.

The global real GDP and welfare effects are also close to zero. Note that the difference between real GDP and welfare is that the latter also takes the negative effects of pollution on welfare into account following Shapiro (2016). Given the social costs of carbon, the difference between real GDP and welfare is not huge (see also Larch and Wanner 2017; and Shapiro 2016). The GDP effects for EU countries are slightly positive (+0.02%), while non-EU countries' GDP declines by 0.01%.

As the carbon tariffs are closely related to the European Green Deal (EGD) and one of its objectives is the reduction of carbon leakage, the effects on CO_2 emissions are of major importance. For the EU as a whole, CO_2 emissions are estimated to increase slightly (+0.24%). This outcome for emissions is almost uniform across member states, with Latvia, Slovenia and Slovakia as the only exceptions. This increase in EU emissions, however small it may be, is in contrast with a global decline in emissions, which amounts to less than 0.1% though.

As mentioned above, our quantitative model does not consider any dynamic effects. As suggested by Sampson (2016) and Anderson et al. (2020), dynamic forces have the potential to magnify the static gains substantially. Sampson (2016) finds that dynamic selection may triple the static gains from trade, while Anderson et al. (2020) report a dynamic path multiplier of 1.8. Taking into account dynamic effects will therefore very likely also lead to larger effects of the CBA mechanism on exports, GDP and emissions. Indeed, comparing the effects resulting from our base scenario with, for example, those in Bellora and Fontagné (2022) in the literature section (see Table 1), illustrates the potential importance of these dynamic effects. Their CGE model, the MIRAGE-VA, models energy inputs as direct substitutes for capital in the production function and features endogenous CO_2 prices in the ETS certificates and the CBA, including feedback effects between the two.[21] Their exporter-tax base scenario (scenario 2), which roughly corresponds to our 'ETS sectors' scenario, leads to a decrease in exports between 8.6% (intermediate goods) and 6% (final goods) which contrasts with our marginal decrease in exports of 0.04% (see model (3) in Table 5). Hence, our quantitative results are very likely a lower bound. Apart from the larger multipliers, the endogenous prices also mean that the

[21] In contrast to Bellora and Fontagné (2022), we do not explicitly model the EU ETS itself. For this reason, and also because our scenarios assume a fixed carbon border tariff, we cannot integrate feedback effects of this kind into our analyses.

Table 6 Sector level effects of a European carbon border tax, EU27. Base scenario

	Exports			Output			CO_2 emissions		
	Change in %	Sector share	Contribution in p.p	Change in %	Sector share	Contribution in p.p	Change in %	Sector share	Contribution in p.p
Total	*−0.037*	*1.00*	*−0.04*	*1.734*	*1.00*	*1.73*	*0.243*	*1.00*	*0.24*
Agriculture	−0.145	0.02	0.00	−0.072	0.02	0.00	−0.121	0.02	0.00
Apparel	−0.368	0.01	0.00	−0.246	0.01	0.00	−0.338	0.00	0.00
Chemical	0.459	0.06	0.03	0.606	0.05	0.03	0.573	0.10	0.05
Equipment	−0.186	0.06	−0.01	−0.133	0.05	−0.01	−0.195	0.01	0.00
Food	−0.139	0.05	−0.01	−0.067	0.05	0.00	−0.119	0.02	0.00
Machinery	−0.354	0.10	−0.03	−0.283	0.08	−0.02	−0.358	0.01	0.00
Metal	1.585	0.05	0.07	1.928	0.04	0.08	1.889	0.04	0.08
Mineral	0.475	0.03	0.02	0.608	0.04	0.02	0.597	0.30	0.18
Mining	−0.318	0.00	0.00	−0.296	0.00	0.00	−0.348	0.01	0.00
Other	−0.446	0.01	0.00	−0.331	0.01	0.00	−0.379	0.00	0.00
Paper	−0.101	0.02	0.00	−0.038	0.02	0.00	−0.100	0.02	0.00
Service	−0.140	0.58	−0.08	−0.125	0.38	−0.05	−0.173	0.35	−0.06
Textile	−0.332	0.01	0.00	−0.210	0.01	0.00	−0.275	0.00	0.00
Wood	−0.180	0.01	0.00	−0.118	0.01	0.00	−0.183	0.00	0.00
Non-tradables				3.294	0.24	0.78	0.062	0.12	0.01

effects on GDP differ not only in magnitude but may also have a different sign. For example, comparing the same scenarios as for exports, Bellora and Fontagné (2022) find a decrease in EU GDP of 0.7%, while we obtain a slight increase in real GDP of 0.03%.

The constellation where EU-wide emissions increase while emissions in third countries go down, potentially pointing to a 'carbon leakage reversal', is not exactly in accordance with the general objectives of the EGD and the EU's emission-reduction targets. Such a reversal may not seem desirable from an environmental perspective as it would imply increasing CO_2 emissions in the EU and would go against the spirit and objectives of the EGD. However, this carbon leakage reversal, overall, results in a reduction of global emissions, which is what ultimately matters for the world climate. The fact that global CO_2 emissions are slightly reduced while global GDP remains de facto unchanged is explained by different technologies in the EU and third countries. Hence, there is a trade-off between the specific objectives of the CBA mechanism and the EU's general environmental objectives as envisaged by the EGD.

Table 6 shows the sector-level effects of the base scenario in the EU member states. These show on a more granular level that exports, output and CO_2 emissions increase in all sectors covered by the CBA mechanism. On average, the metals sector benefits the most with a 1.6% increase in exports, a 1.9% increase in output and a 1.9% rise in emissions. Meanwhile, most other sectors see a slight decline in exports and output, as well as in emissions. Only the non-tradables sector, which also includes most activities, related to fuel combustion, sees a large increase in output. All of the sectors not covered by the CBA experience a decline in emissions. However, in the EU, these drops are overpowered by the increased emissions resulting from the increased output in the emission-intensive sectors, now protected by the CBA mechanism. This shows the relative importance of these sectors to the efforts to reduce emissions in the EU. Although they represent 14% of the total exports of all ETS sectors, they contribute 44% of all emissions.

How should we assess these outcomes given the two main objectives of the proposed CBA mechanism: the restoring of EU competitiveness and mitigating carbon leakage? At least at the economy-wide level, the proposed EU CBA mechanism is only of limited effectiveness when it comes to pushing exports. Although the effects induced by the CBT tend to be positive, they are small. Turning to the environmental effects, they too tend to be small but they have the desired effect at the global level, that is, to reduce emissions.

4.2.2 Sensitivity analysis and alternative scenarios

The first set of additional scenarios tests the price sensitivity of the CBA mechanism proposal. With the CBT imposed based on a CO_2 price of EUR 85 (scenario 1a in Table 5) as suggested by the IMF (2019), the effects on exports, real GDP, welfare and emissions are larger in magnitude than in the base scenario. Increasing the carbon price increases the economic effects of the CBA mechanism, but not proportionally. To illustrate this point, scenario 1b includes a carbon price of EUR 250, more than four times higher than that in the base scenario (EU 62). The higher carbon price leads to a decline in exports by a factor of 2.2 for the EU, and by a factor of 2.6 for the world. The reason for the less than proportional decrease in total exports is that only three sectors are directly affected by the tariff. While in the affected sectors within the EU exports increase, in all other sectors we see a decrease in exports. The effect of high carbon prices is more pronounced for emissions, which increase for the EU (+0.82%) and decline for the world (−0.25%) by factor 3 compared to the base scenario. The reason for the relatively stronger reaction of emissions is that the affected sectors are the most emission-intensive sectors.

Changing to the 'avoided emissions' approach (scenario 2) decreases the effects further, to almost negligible sizes. Unsurprisingly, this design option produces the smallest effects of all scenarios. The reason for this is lower carbon tariffs, which are now determined based on the comparatively lower emission intensities of EU producers. The embodied emissions approach is therefore superior since it leads to higher carbon tariffs, and consequently to larger effectiveness of the CBA. However, this assessment is also made without considering the legal aspects.

Extending the CBA mechanism to cover all ETS sectors (scenario 3) tends to increase the effects but does not lead to qualitative changes compared to our base scenario, although the CBA mechanism now encompasses significantly more sectors. EU exports decline by 0.04% while GDP rises by 0.03%. Both cases represent a 10% increase in effects compared to the base scenario. World exports take a harder hit and now decrease by 0.15%. Once again, the effect of the CBA mechanism is more pronounced for emissions. Extending sector coverage increases EU emissions by 0.42% and amplifies the decrease in world emissions by 46% compared to the base scenario, although the absolute terms, the effect is still very small (−0.12%). The main reason why expanding sector coverage brings smaller gains than expected is that the base scenario covers the three sectors which together contribute to almost half of all emissions by ETS sectors.

Turning to the comprehensive regime of the CBA mechanism (scenario 4), we find that the granting of export rebates (in addition to the carbon border tax) leads to similar quantitative changes in CO_2 emissions compared to the base scenario. In addition, it also causes a switch in the change of EU exports, which now increase by+0.02%. This is because the export rebates act like an export subsidy for EU exporters, leading to an increase in trade with non-EU countries. The EU's real GDP and welfare effects remain essentially unchanged compared to the base scenario. This finding differs from the findings in several studies which report larger GDP and welfare effects resulting from a comprehensive CBA mechanism (e.g. Branger and Quirion 2014; Böhringer et al. 2012a; Fischer and Fox 2012).

The combination of higher EU exports and higher production means that the increase in CO_2 emissions in the comprehensive CBA regime (0.27%) is slightly larger than in the base scenario. What is also important to note is that at the global level, the reduction in CO_2 emissions is higher despite comparable effects on global GDP and welfare. The reason for this is that with export rebates in place, more production shifts to the EU, in combination with comparably lower EU emission intensity.

Table 7 Economic and environmental effects of a European carbon border tax. Additional scenarios

	WTO safe bet	Reasonable scenario		Maximum scenario	
	(5) scenario	(6a) CBT-tax only	(6b) comprehensive CBAM	(7a) CBT-tax only	(7b) Comprehensive CBAM
(a) Exports					
EU	0.0016	0.0840	1.5148	0.4864	6.6664
Non-EU	−0.0250	−1.0212	−0.9599	−3.3929	−3.2564
EFTA	0.0157	0.4154	0.4468	1.6316	1.7959
World	−0.0156	−0.6302	−0.0845	−2.0205	0.2540
(b) Real GDP					
EU	0.0045	0.1166	0.2202	0.2969	0.7569
Non-EU	−0.0016	−0.0453	−0.0811	−0.1511	−0.3171
EFTA	0.0029	0.0824	0.0368	0.3169	0.1599
World	0.0000	−0.0038	−0.0039	−0.0363	−0.0419
(c) Welfare					
EU	0.0047	0.1186	0.2229	0.3025	0.7656
Non-EU	−0.0015	−0.0443	−0.0799	−0.1486	−0.3132
EFTA	0.0031	0.0847	0.0397	0.3229	0.1692
World	0.0001	−0.0026	−0.0023	−0.0330	−0.0367
(d) CO_2 emissions					
EU	0.0392	0.4443	0.9388	1.4571	3.8250
Non-EU	−0.0174	−0.2119	−0.3302	−0.6107	−1.1859
EFTA	0.0124	0.3959	0.4760	1.1912	1.6198
World	−0.0099	−0.1251	−0.1622	−0.3370	−0.5227

Numbers indicate changes to the baseline expressed in per cent. The number 0.0392, for example, indicates a growth of the EU's CO_2 emissions by 0.0392% in the WTO safe bet scenario. For the defining characteristics of the base scenario see Sec. 3

Source: authors' own simulations based on the model by Larch and Wanner (2017)

In addition to the 'sensitivity scenarios', where in each case only one element of the CBA mechanism was changed, we also perform several additional scenarios where we change several elements of the CBA mechanism (Table 7).

Most illustrative are the 'maximum' scenarios (scenarios 7a and 7b in Table 7) which combine the highest carbon price (EUR 250) with full sector coverage and full within-sector coverage. In the comprehensive CBA regime, the maximum scenario unleashes a veritable export push for the EU, with exports increasing by 6.67%. EU GDP also increases more strongly in both versions of the maximum scenario compared to the base scenario. Compared to the heightened effect on exports, the extra boost for GDP (+0.3% and+0.76% respectively) is more limited. Interestingly, the comprehensive version of the CBA mechanism emerges as the preferred option if judged by the effect on global emissions: global CO_2 emissions are reduced by 0.52%. The flip side of this is a 2.5% increase in EU CO_2 emissions.

What do the results mean for assessing the attractiveness of alternative configurations of the proposed CBA mechanism and higher carbon prices? In general, all scenarios achieve the economic objective of increasing export competitiveness, as well as the environmental objective of fighting carbon leakage — without having large, negative effects on GDP for all involved parties — but to various extents and not without trade-offs. The analysis of scenarios shows that the environmental effects of the CBA mechanism are more sensitive to changes in the carbon price than to sector coverage or other design options.

The comprehensive design of the CBA mechanism that includes export rebates emerges as the most feasible single design option to strengthen the EU's exports. The reason is simple: because the carbon tariff leads to the desired effects, i.e. strengthening of the EU's export competitiveness[22] and counteracting carbon leakage, and the export rebates magnify these effects, a mechanism that includes such export rebates is more attractive. However, all scenarios featuring export rebates provide less environmental benefits for the world compared to the base scenario. The reason for this is a combination of differences in technology across countries and the fact that EU producers will produce more in energy-intensive industries if they receive an export subsidy.

Free allocation of emissions permits effectively reduces carbon costs for companies and leads to a lower carbon tariff. However, its elimination only affects the model outcomes in scenarios that assume that the avoided emissions approach is used. Therefore, its relevance to the modelling results is less impactful.

Figure 1 focuses on the results for the EU and global outcomes for exports and CO_2 emissions across the scenarios. Exports and emissions have been chosen as they are most relevant for the CBA mechanism's main objectives. As the maximum of the vertical axis is a 1% change induced by the CBA mechanism, this shows that the aggregate results are small by any standard, which is especially true for the global outcomes. Hence, the results suggest that carbon prices ought to be quite high for a CBA mechanism to yield substantial results which may, in turn, be seen as support for a floor for carbon prices (see e.g. Rey 2021), and should also be accompanied by extending the sector coverage. However, even in more extreme configurations, the absolute size of the environmental effects is still limited to less than 0.4%. This points to the fact that the EU CBA mechanism by itself will not be the solution to the climate challenge, but it can be a useful part of a wider package of measures to fight climate change.

5 Conclusions

This paper translates the information contained in the European Commission's proposal on the numerous characteristics of the European CBA mechanism, scheduled to be introduced in 2023, into a model scenario. The key element of this model scenario is the implicit carbon tariff that the EU is going to levy in (presumably) three sectors for trade with extra-EU partners. The simulation results obtained from

[22] In this context, it should be mentioned that export competitiveness is a rather narrow definition of international competitiveness.

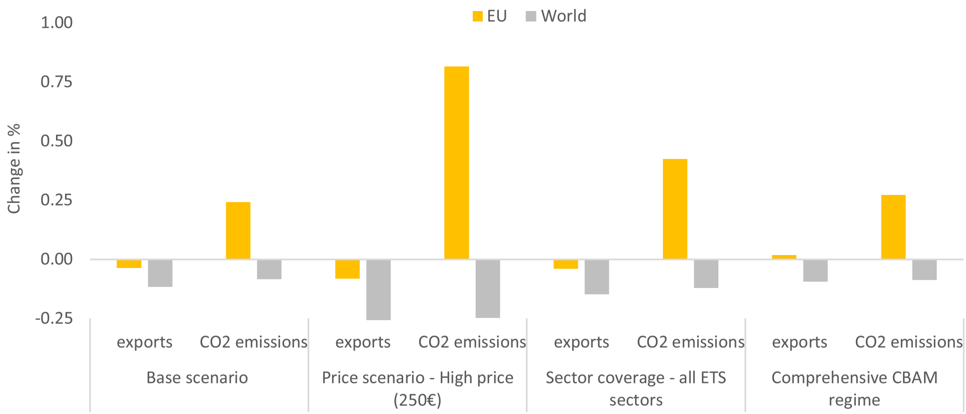

Fig. 1 Base scenario results for the EU and globally, exports and CO_2 emissions. Source: Results in Table 5

a multi-country, multi-sector gravity model for our base model suggest that both the economic effects and the environmental effects are somewhere between modest (exports and emissions) and negligible (GDP and welfare). The good news from an environmental perspective is that the European CBA mechanism will reduce global CO_2 emissions. Depending on the design features, this emission reduction is close to zero, which is for example the case in a very prudent scenario which is designed to avoid any clash with the EU's WTO obligations, amounts to 0.08% in the base scenario and reaches 0.34% in the 'maximum' scenario.

The order of magnitude of these changes in CO_2 emissions makes clear that the European CBA mechanism, on its own, lacks the potential to save the climate. Certainly, saving the world climate makes great demands on the CBA mechanism. Being a supplementary instrument to the domestic carbon pricing system of the EU, its role must be seen as much more modest. It serves two specific objectives, i.e. countering potential carbon leakage effects and restoring EU producers' export competitiveness. The former is achieved to some extent if the identified increase in CO_2 emissions in the EU economy is interpreted as a reversal of the suspected carbon leakage effect. Note, however, that such reverse carbon leakage implies a structural shift towards more CO_2-intensive industries and in turn a situation where EU member states' efforts at achieving the emission reduction targets become even more challenging. Regarding export competitiveness, the base scenario clearly shows that an increase in EU exports following the introduction of carbon tariffs cannot be taken for granted. The general equilibrium effects outweigh the export-promoting effect that comes along with the additional tariffs. One way to ensure a positive effect for EU exports is to opt for a comprehensive regime in the CBA mechanism, that is, to complement the carbon border tax with export rebates of domestic carbon costs for EU producers.

This brings us to the sensitivity of the results concerning changes in the characteristics of the CBA mechanism. The main insight from the sensitivity analysis is that no single design element of the CBA mechanism has the potential to boost either the economic or the environmental effects. Certainly, raising the price of CO_2, and hence the resulting carbon tariffs, yields larger effects across all dimensions but even a high price of CO_2 (EUR 250) will only have marginal effects on EU exports. It requires the combination of more elements, in particular, the granting of export rebates, to make high carbon prices achieve sizeable results. However, even in this case, there might be trade-offs between the EU-specific and global environmental performance of the CBA mechanism.

To summarize, the main reason why a European carbon border tax seems as an appropriate policy instrument is because it helps reduce global emissions, however small the impact may be. Since the economic costs for trading partners, in the form of negative GDP and welfare effects, are very small, the uproarious concerns about green protectionism appear to be misplaced in the context of the European CBA mechanism. There is no reason to believe that this measure will push the world trading system into turmoil.

Appendix 1 CO_2 emissions, ETS categories and industry correspondences

Verified emissions, paid emissions and free allocations in the ETS

The construction of the scenarios and the implied CO_2 tariffs relied on several data sources. The first of these data sources was the ETS database[23] from which the number of verified emissions of CO_2 equivalents within the ETS system were obtained. This is the sum of emissions by installations registered in the ETS that were verified (across all so-called categories). The ETS database also provides information on the number of free allowances granted to each participating country. The number of verified emissions is available at the level of each category, and the same is true for free emissions. In contrast, the ETS database does not hold information on the emissions paid at the category level, but only at the aggregate level (for all industrial sectors and aviation). Therefore, we need to calculate the number of paid emissions at the category level as the difference between verified emissions and free emissions.[24] The total volume of paid emissions across all ETS categories for the EU27 are shown in Fig. 2.

Correspondence between ETS categories industries and NACE industries

Most of the ETS categories (i.e. sectors) correspond one to one to an industry in the Standard Industry Classification (NACE), Revision 2. For example, the ETS categories ‘21 Refining of mineral oil’ and ‘22 Production of coke’ both match the NACE Rev.2 industry ‘Manufacture of coke and refined petroleum products’ (NACE 19) (see Table 8 below). The identification of the allowances that have to be paid for by EU companies at the ETS sector level is done in the same way as described above, as the difference between the verified emissions and the free allowances.

The identification of allowances must be done at an individual ETS sector level for each EU member state. This is important because excess free allowances in, say, the German ETS sector ‘Production of bulk chemicals’ (42), does not mean that an excess demand of allowances in the Finnish paper ETS sector ‘Production of pulp’ (35) does not have to be paid for in the latter.[25] In other words, we assume that an excess supply of free allowances in one ETS sector does not cancel out the excess demand of allowances in another ETS sector.

[23] Available at https://www.eea.europa.eu/data-and-maps/data/european-union-emissions-trading-scheme-14.

[24] The sum of free allowances and paid allowances equals the total number of allowances in each year. However, the number of total allowances does not coincide exactly with number of verified emissions because firms can carry over EAUs from 1 year to the next. Moreover, allowances can be sold and bought (auctioned) across ETS industries.

[25] Of course, in this example, the German firm that sells the allowances earns additional income, but we have no information on which firms in which sectors sell allowances, who they sell them to or whether they sell them at all.

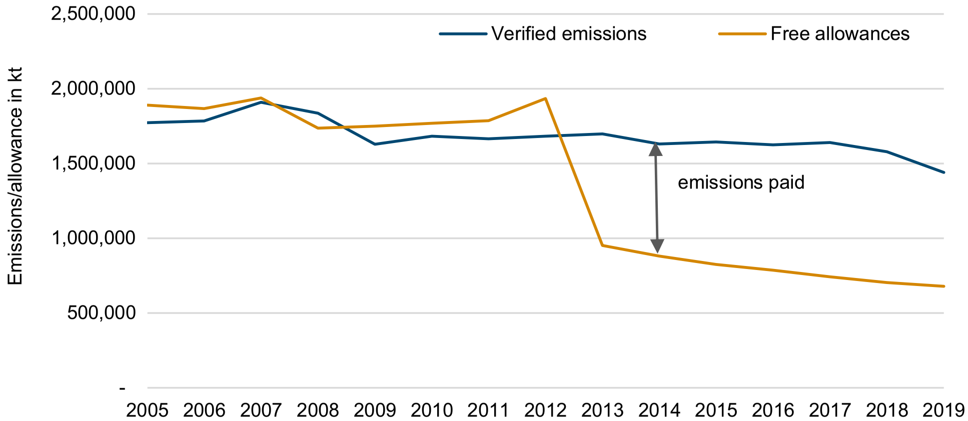

Fig. 2 Total verified emissions and free allowances in the European ETS system, EU27, 1995–2019. Note: emissions and free allowances in all ETS categories (including industrial installations and aviation). The peak in free emissions in 2012 is due to the inclusion of the aviation sector. Source: ETS Database. Available at: https://www.eea.europa.eu/data-and-maps/data/european-union-emissions-trading-scheme-14

Table 8 Assignment of ETS sector 'Combustion of fuels' (20) to NACE Rev.2 industries /WIOD industries, 2012

NACE industry code	NACE industry name	Verified emissions	Free allowances	Paid allowances
A01	Crop and animal production, hunting	0.04%	0.05%	0.04%
B	Mining and quarrying	0.21%	0.40%	0.15%
C10–C12	Food products, beverages and tobacco	2.91%	2.15%	3.20%
C13–C15	Textiles, wearing apparel and leather	0.01%	0.01%	0.01%
C16	Wood and of products of wood and cork	0.03%	0.05%	0.02%
C17	Paper and paper products	0.02%	0.04%	0.01%
C18	Printing and reproduction of recorded media	0.15%	0.05%	0.18%
C19	Coke and refined petroleum products	0.08%	0.16%	0.05%
C20	Chemicals and chemical products	7.10%	8.90%	6.42%
C21	Basic pharmaceutical products	1.68%	1.52%	1.75%
C22	Rubber and plastic products	0.07%	0.08%	0.06%
C23	Other non-metallic mineral products	0.05%	0.05%	0.05%
C24	Basic metals	3.91%	7.44%	2.59%
C25	Fabricated metal products	0.00%	0.01%	0.00%
C27	Electrical equipment	0.00%	0.00%	0.00%
C28	Machinery and equipment n.e.c	0.01%	0.01%	0.00%
C29	Motor vehicles, trailers and semi-trailers	0.10%	0.09%	0.10%
C30	Other transport equipment	0.10%	0.20%	0.07%
C31–C32	Furniture; other manufacturing	0.00%	0.00%	0.00%
C33	Repair and installation of machinery and eq	0.00%	0.00%	0.00%
D35	Electricity, gas, steam supply	83.37%	78.53%	85.17%
E37–E39	Sewerage; waste collection, treatment	0.01%	0.01%	0.00%
F	Construction	0.00%	0.00%	0.00%
H49	Land transport and transport via pipelines	0.09%	0.16%	0.06%
H52	Warehousing	0.04%	0.07%	0.03%
L68	Real estate activities	0.00%	0.00%	0.00%
O84	Public administration and defence	0.00%	0.00%	0.01%
P85	Education	0.00%	0.00%	0.00%
Q	Human health and social work activities	0.01%	0.02%	0.01%
A-Q	All NACE industries	100.00%	100.00%	100.00%

Emissions are assigned to NACE industries at the member states' specific level for the ETS category *'Combustion of fuels' (20).*

Source: ETS database. Available at https://www.eea.europa.eu/data-and-maps/data/european-union-emissions-trading-scheme-14

The ETS category ‘combustion of fuel’ (20) has no correspondence with a NACE industry. The bulk, about 75% of the emissions in this ETS category, is attributable to power stations (with a capacity of 20 MW or more) (Gores et al. 2019) and can therefore be assigned to the electricity sector *(D35 – Electricity, gas, steam and air conditioning supply)*. However, the ETS category ‘combustion of fuel’ also comprises industrial installations that are listed in Annex I of the ETS Directive. The guiding document to this Annex I (European Commission, 2010, p. 6) states that ‘… the activity ‘combustion of fuels’ can occur in all types of NACE categories, not only industrial ones. Examples of such non-industrial installations are combustion units in greenhouses, hospitals, universities and office buildings, booster stations in natural gas transport networks etc.’

Hence, firms across all NACE can potentially be covered by the ETS and therefore all NACE industries can at least be partially required to purchase emissions allowances. We have found a list of installations covered by the ETS system as of 2012 indicating both the primary NACE industry code and the ETS category ‘combustion of fuel’. We use this list to assign (at the level of individual member states) the CO_2 emissions from the ETS category ‘combustion of fuel’ to the different NACE industries. The result is listed in Table 7.

This procedure assigns more than 80% of verified emissions from the combustion of fuel to the NACE industry ‘Electricity, gas, steam and air conditioning supply’ (D35). Important shares also end up in the chemicals industry and the basic metal industry.

We omit the emissions under the category *‘99 Other activity opted-in under Art. 24’,* as these are very heterogeneous industries that individual member states decided to be included in the EU ETS. This choice of omitting this category is due to the impossibility to link them to any particular industry (see Gores et al. 2019). However, this is not an important exclusion, as these opt-in installations only accounted for 0.05% of the total emissions of stationary installations in 2014.

In this way, we can construct a correspondence between ETS sectors and NACE industries to be used for calculating the implicit carbon tariff equivalents (Table 11). This correspondence to NACE industries enables the linking of data from the ETS database to the WIOD’s International Input–Output Table (WIOT) (Timmer, et al. 2015) and the associated Socio-Economic Account (SEA) for CO_2 emissions developed by the Joint Research Centre associated with the European Commission (Corsatea et al. 2019).

As we use official data from the ETS database, Table 9 reflects the sectors covered by the ETS as reported by the European Commission.[26]

[26] According to the Commission website (https://ec.europa.eu/clima/policies/ets_en), emissions of greenhouse gases from the following industries are covered: (i) power and heat generation; (ii) energy-intensive industry sectors comprising oil refineries, steel works and production of iron, aluminium, metals, cement, lime, glass, ceramics, pulp, paper, cardboard, acids, and bulk organic chemicals; and (iii) commercial aviation (coverage is limited to flights between destinations within the European Economic Area).

Table 9 Correspondence between ETS sector and to NACE Rev.2 industries/WIOD industries, 2012

ETS code	ETS sector name	WIOD code	WIOD name
10	10 Aviation	H51	Air transport
20	*20 Combustion of fuels*		*See Table 7 for split*
21	21 Refining of mineral oil	C19	Coke and refined petroleum products
22	22 Production of coke	C19	Coke and refined petroleum products
23	23 Metal ore roasting or sintering	B	Mining and quarrying
24	24 Production of pig iron or steel	C24	Basic metals
25	25 Production or processing of ferrous metals	C24	Basic metals
26	26 Production of primary aluminium	C24	Basic metals
27	27 Production of secondary aluminium	C24	Basic metals
28	28 Production or processing of non-ferrous metals	C24	Basic metals
29	29 Production of cement clinker	C23	Other non-metallic mineral products
30	30 Production of lime	C23	Other non-metallic mineral products
31	31 Manufacture of glass	C23	Other non-metallic mineral products
32	32 Manufacture of ceramics	C23	Other non-metallic mineral products
33	33 Manufacture of mineral wool	C23	Other non-metallic mineral products
34	34 Production or processing of gypsum or plasterboard	C23	Other non-metallic mineral products
35	35 Production of pulp	C17	Paper and paper products
36	36 Production of paper or cardboard	C17	Paper and paper products
37	37 Production of carbon black	C20	Chemicals and chemical products
38	38 Production of nitric acid	C20	Chemicals and chemical products
39	39 Production of adipic acid	C20	Chemicals and chemical products
40	40 Production of glyoxal and glyoxylic acid	C20	Chemicals and chemical products
41	41 Production of ammonia	C20	Chemicals and chemical products
42	42 Production of bulk chemicals	C20	Chemicals and chemical products
43	43 Production of hydrogen and synthesis gas	C20	Chemicals and chemical products
44	44 Production of soda ash and sodium bicarbonate	C20	Chemicals and chemical products

Table 9 (continued)

ETS code	ETS sector name	WIOD code	WIOD name
45	45 Capture of greenhouse gases under Dir.2009/31/EC	C26	Computer, electronic and optical products
46	46 Transport of greenhouse gases under Dir.2009/31/EC	H49	Land transport and transport via pipelines

Table 10 Correspondence between NACE Rev.2 industries and GTAP sectors

WIOD industry code	WIOD industry name	GTAP sector	GTAP ID
A01	Crop and animal production, hunting and related service activities	Agriculture	1
A02	Forestry and logging		
A03	Fishing and aquaculture		
C13–C15	Manufacture of textiles, wearing apparel and leather products	Apparel	2
C20	Manufacture of chemicals and chemical products	Chemical	3
C21	Manufacture of basic pharmaceutical products and pharmaceutical preparations		
C22	Manufacture of rubber and plastic products		
C29	Manufacture of motor vehicles, trailers and semi-trailers	Equipment	4
C30	Manufacture of other transport equipment		
C10–C12	Manufacture of food products, beverages and tobacco products	Food	5
C26	Manufacture of computer, electronic and optical products	Machinery	6
C27	Manufacture of electrical equipment		
C28	Manufacture of machinery and equipment n.e.c		
C24	Manufacture of basic metals	Metal	7
C25	Manufacture of fabricated metal products, except machinery and equipment		
C19	Manufacture of coke and refined petroleum products	Mineral	8
C23	Manufacture of other non-metallic mineral products		
B	Mining and quarrying	Mining	9
D35	Electricity, gas, steam and air conditioning supply	Non-tradables	10
E36	Water collection, treatment and supply		
E37–E39	Sewerage; waste collection, treatment and disposal activities; materials recovery; remediation activities and other waste management services		
F	Construction		
O84	Public administration and defence; compulsory social security		
P85	Education		
Q	Human health and social work activities		

Table 10 (continued)

WIOD industry code	WIOD industry name	GTAP sector	GTAP ID
C31–C32	Manufacture of furniture; other manufacturing	Other	11
C33	Repair and installation of machinery and equipment		
C17	Manufacture of paper and paper products	Paper	12
C18	Printing and reproduction of recorded media		
G45	Wholesale and retail trade and repair of motor vehicles and motorcycles	Service	13
G46	Wholesale trade, except of motor vehicles and motorcycles		
G47	Retail trade, except of motor vehicles and motorcycles		
H49	Land transport and transport via pipelines		
H50	Water transport		
H51	Air transport		
H52	Warehousing and support activities for transportation		
H53	Postal and courier activities		
I	Accommodation and food service activities		
J58	Publishing activities		
J59_J60	Motion picture, video and television programme production, sound recording and music publishing activities; programming and broadcasting activities		
J61	Telecommunications		
J62_J63	Computer programming, consultancy and related activities; information service activities		
K64	Financial service activities, except insurance and pension funding		
K65	Insurance, reinsurance and pension funding, except compulsory social security		
K66	Activities auxiliary to financial services and insurance activities		
L68	Real estate activities		
M69_M70	Legal and accounting activities; activities of head offices; management consultancy activities		
M71	Architectural and engineering activities; technical testing and analysis		
M72	Scientific research and development		
M73	Advertising and market research		

Table 10 (continued)

WIOD industry code	WIOD industry name	GTAP sector	GTAP ID
M74_M75	Other professional, scientific and technical activities; veterinary activities		
N	Administrative and support service activities		
R_S	Other service activities		
T	Activities of households as employers; undifferentiated goods- and services-producing activities of households for own use		
U	Activities of extraterritorial organizations and bodies		
C13-C15	Manufacture of textiles, wearing apparel and leather products	Textile	14
C16	Manufacture of wood and of products of wood and cork, except furniture; manufacture of articles of straw and plaiting materials	Wood	15

For the base scenario and all other scenarios, except for the ETS sector coverage scenario, it is assumed that the CBA mechanism covers only the NACE industries C20 (Chemicals and chemical products), C23 (Other non-metallic mineral products) and C24 (basic metals), in line with the industry coverage of the European Commission's proposal for the CBA mechanism.

Correspondence between WIOD industries and GTAP sectors

The implicit CBT and implicit carbon border rebates that were calculated at the level of WIOD industries are aggregated to the level of GTAP sectors. For WIOD industries with a one-to-one correspondence to the GTAP sectors (e.g. mining), the calculated implicit carbon tariffs/rebates remain unchanged (and are hence identical across member states for any industry). For GTAP sectors that comprise several WIOD industries, a weighted average tariff (export rebate) is calculated using the respective country's industry-level imports (exports) as weights (in the embodied emissions approach) or the member states' industry-level imports (exports) as weights (in the avoided emissions approach).

Table 10 shows the correspondence between WIOD industries and GTAP sectors.

There is only one WIOD industry that needs to be assigned to two different GTAP sectors: the textiles and apparel industries (C13–C15). The issue is solved by applying the carbon tariff/export rebate calculated at the WIOD industry level to both the 'apparel' and 'textile' GTAP sectors.

Appendix 2. The multi-sector, multi-factor gravity model of Larch and Wanner (2017)

To better understand the results, we provide in this Appendix a brief description and the main equations of the structural gravity model with energy production which we use for our quantification.

Demand. The model features L tradable goods sectors ($l \in \mathcal{L}$) in each of the N countries, and these goods are differentiated by country of origin (Armington 1969). In addition, there is one homogeneous, non-tradable goods sector S. The utility function of the representative consumer in country j is given by:

$$U^j = \left(U_S^j\right)^{\gamma_S^j}\left[\prod\nolimits_{l\in\mathcal{L}}\left(U_l^j\right)^{\gamma_l^j}\right]\left[\frac{1}{1+\left(\frac{1}{\mu^j}\sum_{i=1}^N E^i\right)^2}\right], \tag{1}$$

where U_S^j is the utility from the non-tradable good and U_l^j the utility from all tradable goods, which are combined using a constant elasticity of substitution (CES) sub-utility function:

$$U_l^j = \left[\sum_{i=1}^{N} \left(\beta_l^i\right)^{\frac{1-\sigma_l}{\sigma_l}} \left(q_l^{ij}\right)^{\frac{\sigma_l-1}{\sigma_l}} \right]^{\frac{\sigma_l}{\sigma_l-1}}, \tag{2}$$

where β_l^i is a distribution parameter, q_l^{ij} is the amount of goods from country i in tradable sector l that is consumed in country j, and σ_l is the elasticity of substitution in sector l. γ_S^j and γ_l^j's are Cobb–Douglas coefficients, which fulfil $\gamma_S^j + \sum_{l\in\mathcal{L}}\gamma_l^j = 1$. The last term in Eq. (1) captures the damages from CO_2 pollution following Shapiro (2016), where μ^j translates pollution into social costs, and E^i is the CO_2 emissions in country i.

The total income of the representative consumer in country j is given by:

$$Y^j = \sum_{f\in\mathcal{F}} v_f^j V_f^j + \omega^j r\overline{R^W} + \sum_{i=1}^{N}\sum_{l\in\mathcal{L}} \left(\tau_l^{ij} - 1\right) X_l^{ij}, \tag{3}$$

with $V_f^j = V_{Ef}^j + V_{Sf}^j + \sum_{l\in\mathcal{L}} V_{lf}^j$, where V_{Ef}^j, V_{Sf}^j and V_{lf}^j are the sectoral factor usages $f \in \mathcal{F}$ for energy production, non-tradable and tradable goods production, respectively, of the sectoral mobile but international immobile factors unskilled and skilled labour, capital, land and natural resources with corresponding factor prices of factor f in country j denoted by v_f^j. $\overline{R^W}$ denotes the world resource endowment, r is the international resource price and ω^j is the resource endowment share of country j. The last term captures tariff revenues of country j, with τ_l^{ij} denoting one plus the ad valorem tariff rate and X_l^{ij} the value of exports from country i to country j in sector l.

Utility maximization subject to the budget constraint $Y^j = p_S^j q_S^j + \sum_{l\in\mathcal{L}} \sum_{i=1}^{N} p_l^{ij} q_l^{ij}$ leads to the demand function. Note that p_S^j denotes the price for the non-tradable good, q_S^j the quantity of the non-tradable goods consumed, p_l^{ij} the price in country j for goods from sector l from country i and q_l^{ij} the number of goods from sector l from country i consumed in country j. Expenditure in tradable sector l in country j can be written as $\mathfrak{X}_l^j = \gamma_l^j \mathfrak{X}^j = \sum_{i=1}^{N} p_l^{ij} q_l^{ij}$, where $\mathfrak{X}^j$ denotes the total expenditure of country j. Expenditure in the non-tradable sector S can be expressed as $\mathfrak{X}_S^j = \gamma_S^j \mathfrak{X}^j = p_S^j q_S^j$. Assuming balanced trade, it holds that $Y^j = \mathfrak{X}^j = \mathfrak{X}_S^j + \sum_{l\in\mathcal{L}} \mathfrak{X}_l^j$. Demand in country j for non-tradables is given by $q_S^j = \mathfrak{X}_S^j / p_S^j$. Demand for tradables is given by:

$$q_l^{ij} = \left(\frac{\beta_l^i p_l^{ij}}{P_l^j}\right)^{-\sigma_l} \left(\frac{\beta_l^i \mathfrak{X}_l^j}{P_l^j}\right), \tag{4}$$

where P_l^j is the sectoral price index, given by

$$P_l^j = \left[\sum_{i=1}^{N} \left(\beta_l^i p_l^{ij} \right)^{1-\sigma_l} \right]^{\frac{1}{1-\sigma_l}}. \tag{5}$$

Trade costs T_l^{ij} are of the iceberg type, leading to a consumption price of $p_l^{ij} = T_l^{ij} \tau_l^{ij} p_l^i$, where p_l^i is the factory-gate price. The value of exports can then be stated as:

$$X_l^{ij} = p_l^i q_l^{ij} T_l^{ij} = \left(\tau_l^{ij} \right)^{-\sigma_l} \left(\frac{\beta_l^i p_l^i T_l^{ij}}{P_l^j} \right)^{1-\sigma_l} \mathfrak{X}_l^j. \tag{6}$$

Goods market clearing ensures $Y_l^i = \sum_{j=1}^{N} X_l^{ij}$. Real GDP in country j is given by Y^j divided by the consumer price index given by $\left(p_S^j \right)^{\gamma_S^j} \prod_{l \in \mathcal{L}} \left(P_l^j \right)^{\gamma_l^j}$. Welfare in addition takes into account the negative effects of emissions as defined in Eq. (1).

Production. The sectoral Cobb–Douglas production functions for the tradable sectors and the non-tradable sector are given by:

$$q_l^i = A_l^i \left(E_l^i \right)^{\alpha_{lE}^i} \prod_{f \in \mathcal{F}} \left(V_{lf}^i \right)^{\alpha_{lf}^i}, \tag{7}$$

$$q_S^i = A_S^i \left(E_S^i \right)^{\alpha_{SE}^i} \prod_{f \in \mathcal{F}} \left(V_{Sf}^i \right)^{\alpha_{Sf}^i}, \tag{8}$$

where A_l^i and A_S^i are the productivity parameters, α_{lE}^i and α_{SE}^i the cost shares of energy and α_{lf}^i and α_{lS}^i are the cost shares of the other factors, with $\alpha_{lE}^i + \sum_{f \in \mathcal{F}} \alpha_{lf}^i = 1$ and $\alpha_{SE}^i + \sum_{f \in \mathcal{F}} \alpha_{Sf}^i = 1$.

The production function for energy (where emissions are one-to-one linked as a side output) is given by:

$$E^i = E_S^i + \sum_{l \in \mathcal{L}} E_l^i = A_E^i \left(R^i \right)^{\xi_R^i} \prod_{f \in \mathcal{F}} \left(V_{Ef}^i \right)^{\xi_f^i}, \tag{9}$$

with $\xi_R^i + \sum_{f \in \mathcal{F}} \xi_f^i = 1$. R^i denotes the usage of the internationally freely tradable input resource in country i and the E subscript denotes the energy sector.

For energy, we take energy prices as given and there is an endogenous, completely elastic, supply of energy at the given price. For all other factors, we assume fixed endowments. The equations described can be used to solve for the equilibrium amount and prices and to perform counterfactual analysis and the decomposition.

Decomposition. Total emissions from production in multiple tradable sectors and one non-tradable sector can be written as: $E^i = \left(\alpha^i_{SE} Y^i_S + \sum_{l \in \mathcal{L}} \alpha^i_E Y^i_l\right)/e^i$. Defining total nominal income without tariff revenues $\widetilde{Y}^i \equiv Y^i_S + \sum_{l \in \mathcal{L}} Y^i_l$, sectoral production shares $\kappa^i_S \equiv Y^i_S/\widetilde{Y}_i$ and $\kappa^i_l \equiv Y^i_l/\widetilde{Y}_i$, a country's production-share-weighted average energy cost share $\overline{\alpha}^i_E \equiv \alpha^i_{SE}\kappa^i_S + \sum_{l \in \mathcal{L}} \alpha^i_{lE}\kappa^i_l$ and total emissions in terms of this energy cost term, the real value of production and the real energy price can be stated as:

$$E^i = \overline{\alpha}^i_E \frac{\widetilde{Y}^i}{P^i}\left(\frac{e^i}{P^i}\right)^{-1}. \tag{10}$$

Taking the total differential leads to:

$$dE^i = \underbrace{\frac{\partial E^i}{\partial\left(\frac{\widetilde{Y}^i}{P^i}\right)} d\left(\frac{\widetilde{Y}^i}{P^i}\right)}_{\text{scale effect}} + \underbrace{\frac{\partial E^i}{\partial \overline{\alpha}^i_E} d\overline{\alpha}^i_E}_{\text{composition effect}} + \underbrace{\frac{\partial E^i}{\partial\left(\frac{e^i}{P^i}\right)} d\left(\frac{e^i}{P^i}\right)}_{\text{technique effect}} \tag{11}$$

where the scale effect is given by:

$$\frac{\partial E^i}{\partial\left(\widetilde{Y}^i/P^i\right)} = \frac{\overline{\alpha}^i_E}{e^i/P^i} > 0 \text{ and} \frac{\partial E^i}{\partial\left(\widetilde{Y}^i/P^i\right)} \frac{\widetilde{Y}^i/P^i}{E^i} = 1, \tag{12}$$

the composition effect is given by:

$$\frac{\partial E^i}{\partial \overline{\alpha}^i_E} = \frac{\widetilde{Y}^i}{e^i} > 0 \text{ and} \frac{\partial E^i}{\partial \overline{\alpha}^i_E} \frac{\overline{\alpha}^i_E}{E^i} = 1, \tag{13}$$

and the technique effect is given by:

$$\frac{\partial E^i}{\partial\left(\frac{e^i}{P^i}\right)} = \frac{\overline{\alpha}^i_E \widetilde{Y}^i/P^i}{\left(e^i/P^i\right)^2} < 0 \text{ and} \frac{\partial E^i}{\partial\left(e^i/P^i\right)} \frac{\left(e^i/P^i\right)}{E^i} = -1 \tag{14}$$

Appendix 3. Additional results

The main text reported the results forthe EU, non-EU countries, EFTA and the World as a whole. Table 11 presents theresults from the base scenario for EU member states and selected othercountries.

Table 11 Country-specific results (selected), base scenario

Country	Exports	GDP	Welfare	CO_2 emissions
EU27	−0.0365	0.0228	0.0242	0.2429
Austria	0.0273	0.0238	0.0253	0.1886
Belgium	0.0262	0.0274	0.0289	0.2095
Bulgaria	−0.0405	0.0418	0.0422	0.3476
Cyprus	−0.0511	0.0102	0.0115	0.0070
Czech Republic	0.0180	0.0280	0.0284	0.2536
Germany	−0.0286	0.0219	0.0234	0.2731
Denmark	0.0074	0.0138	0.0153	0.1554
Estonia	−0.0072	0.0159	0.0163	0.0170
Finland	−0.1569	0.0350	0.0364	0.3689
France	−0.0302	0.0178	0.0193	0.1631
Greece	−0.1255	0.0288	0.0302	0.2479
Croatia	0.0152	0.0307	0.0310	0.2265
Hungary	0.0124	0.0215	0.0218	0.3461
Ireland	0.0070	0.0195	0.0209	0.0262
Italy	−0.0912	0.0236	0.0251	0.2278
Lithuania	−0.0124	0.0265	0.0269	0.2907
Luxembourg	0.0560	0.0232	0.0247	0.0421
Latvia	−0.0085	0.0090	0.0094	−0.0088
Malta	0.0073	0.0024	0.0037	−0.0028
Netherlands	0.0305	0.0206	0.0221	0.3257
Poland	−0.0413	0.0305	0.0308	0.3029
Portugal	−0.0404	0.0186	0.0200	0.1843
Romania	−0.0674	0.0280	0.0283	0.4564
Slovakia	0.0293	0.0374	0.0377	0.3975
Slovenia	0.0441	0.0259	0.0263	0.1535
Spain	−0.0902	0.0245	0.0260	0.1930
Sweden	−0.0386	0.0282	0.0297	0.2896
G20				
Argentina	−0.0532	−0.0004	0.0008	0.0421
Australia	−0.1234	−0.0115	−0.0115	−0.0614
Brazil	−0.2172	−0.0175	−0.0163	−0.1427
Canada	0.0095	0.0024	0.0024	0.0753
China	−0.1935	−0.0083	−0.0082	−0.0722
India	−0.3256	−0.0264	−0.0238	−0.1623
Indonesia	−0.1866	−0.0149	−0.0136	−0.0178

Table 11 (continued)

Country	Exports	GDP	Welfare	CO_2 emissions
Japan	−0.0770	−0.0038	−0.0035	−0.0503
South Korea	−0.0002	0.0034	0.0046	−0.0090
Mexico	−0.0839	−0.0070	−0.0060	−0.0504
Russia	−1.4284	−0.1156	−0.1156	−1.2079
Saudi Arabia	−0.2152	−0.0392	−0.0382	−0.1011
South Africa	−0.4332	−0.0419	−0.0398	−0.0810
Turkey	−0.6252	−0.0629	−0.0620	−1.0185
UK	0.0418	0.0080	0.0095	0.1430
USA	−0.0337	−0.0001	0.0001	0.0191
Other Europe				
Albania	−0.1608	−0.0093	−0.0079	−0.0970
Belarus	−0.7639	−0.0443	−0.0439	−0.6716
Georgia	−0.1594	−0.0025	−0.0011	−0.0237
Morocco	−0.5543	−0.0379	−0.0358	−0.2989
Norway	0.0413	−0.0018	−0.0003	0.3315
Switzerland	0.0670	0.0221	0.0236	0.0318
Ukraine	−1.0179	−0.0666	−0.0662	−0.7129
Tunisia	−0.4606	−0.0422	−0.0401	−0.1976
Rest of Europe*	−0.4007	−0.0287	−0.0274	−0.3243
World	−0.1161	−0.0011	−0.0003	−0.0833

Rest of Europe includes Andorra, Bosnia and Herzegovina, Faroe Islands, Gibraltar, Guernsey, Holy See (Vatican City State), Isle of Man, Jersey, North Macedonia, Monaco, Montenegro, San Marino and Serbia

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