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Working Paper The Potential of Carbon Border Adjustments to Foster Climate Cooperation

CESifo Working Paper, No. 11429

Provided in Cooperation with: Ifo Institute – Leibniz Institute for Economic Research at the University of Munich

Suggested Citation: Beaufils, Timothé; Wanner, Joschka; Wenz, Leonie (2024) : The Potential of Carbon Border Adjustments to Foster Climate Cooperation, CESifo Working Paper, No. 11429, CESifo GmbH, Munich

This Version is available at: https://hdl.handle.net/10419/307359

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Impressum:

CESifo Working Papers ISSN 2364-1428 (electronic version) Publisher and distributor: Munich Society for the Promotion of Economic Research - CESifo GmbH The international platform of Ludwigs-Maximilians University's Center for Economic Studies and the ifo Institute Poschingerstr. 5, 81679 Munich, Germany Telephone +49 (0)89 2180-2740, Telefax +49 (0)89 2180-17845, email office@cesifo.de Editor: Clemens Fuest https://www.cesifo.org/en/wp An electronic version of the paper may be downloaded • from the SSRN website: www.SSRN.com

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The Potential of Carbon Border Adjustments to Foster Climate Cooperation

Abstract

The European Union (EU) is implementing a Carbon Border Adjustment Mechanism (CBAM) at its borders, which will require exporters of basic materials to surrender emission permits when exporting to the EU market. Since it makes foreign producers compete under a carbon price, the EU CBAM may motivate some trade partners to implement their own carbon pricing mechanisms, thereby encouraging the creation of a coalition of countries with ambitious carbon pricing policies protected by a joint CBAM. Such geostrategic potential of the EU CBAM has been identified in previous literature, but the conditions under which it could be realised remain largely unknown. Here, we present a modelling framework to simulate the potential of CBAMs to motivate the creation of climate coalitions. We use a fully interlinked New Quantitative Trade model to evaluate the pay-offs of a dynamic club negotiation model. Compared to previous research, our approach allows for a more granular definition of climate policies and requires relatively little input data and numerical power. This allows us to explore the formation and stability of climate coalitions under a broader range of CBAM implementation options. Our results highlight that the potential of a CBAM-based climate coalition strongly depends on the exact CBAM design. In its current version, the EU CBAM would only trigger the formation of a modest coalition. Future extensions of the EU CBAM could motivate the adoption of carbon pricing in all countries except China, India and Russia. Meanwhile, export rebates shrink its coalition-building potential.

JEL-Codes: C680, F180, Q560.

Keywords: Carbon Border Adjustment, climate policy, international trade, climate cooperation, climate clubs.

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October 20, 2024

The authors are grateful for the comments and suggestions received at the 25. Göttinger Workshop, at the Paris-Saclay Conference on Trade and Environment 2024 and at SURED 2024. Beaufils acknowledges funding from the German Federal Ministry of Education and Research through the Ariadne-Kopernikus project. Wanner gratefully acknowledges funding from the DFG under project 518604731.

1 Introduction

On October 1st 2023, the Carbon Border Adjustment Mechanism (CBAM) of the European Union (EU) entered its transitional phase (European Commission, 2023). Starting from January 1st 2026, exporters of steel, iron, aluminium, cement, fertilisers, electricity and hydrogen to the EU will have to surrender emission permits at the border of the EU, effectively paying the carbon price imposed on European industries through the European Emission Trading Scheme (EU ETS). The EU CBAM is introduced as an anti-carbon leakage instrument, aiming at avoiding the relocation of emission-intense production to countries with less stringent climate policies (Grubb et al., 2022). It is set to substitute the free allowances currently granted to emission-intense, trade-exposed sectors, which are hardly compatible with net-zero emission targets (Jakob, 2021). From a theoretical point of view, the EU CBAM has the potential to help the EU accelerate its climate mitigation effort while protecting its domestic industry from carbon leakage (Jakob et al., 2022).

A rapidly growing literature examines the efficiency of the EU CBAM as an anti-carbon leakage instrument. Ex-ante modelling exercises and theoretical works overall converge on the potential benefits of CBAMs in terms of reducing carbon leakage and maintaining competitiveness (Zhong and Pei, 2024; Böhringer et al., 2022; Sogalla, 2023; Korpar et al., 2022). However, legal, technical and administrative constraints limit the realistic policy space, such that the EU CBAM 2026 regime will only target a limited number of products and mostly cover direct emissions, thereby reducing its efficiency (Cosbey et al., 2019). Further coverage extensions to other products (horizontal coverage) and indirect emissions (vertical coverage) are envisaged. We here analyse the effectiveness and consequences of the EU CBAM under different implementation options. Crucially, we also account for the endogenous policy responses of other countries, which are not captured in most previous analyses.

While the EU CBAM is introduced as a unilateral policy, it may de facto affect the EU trade partners' policies: not only will it force industries in exporting countries to compete under the EU carbon price, but the EU CBAM might give an incentive to the EU trade partners to implement their own domestic carbon price in order to collect domestically the fiscal revenue otherwise collected by the EU (Beaufils et al., 2023b). The EU CBAM could then provide a stepping stone for the formation of a climate club of countries with a common carbon market protected by a CBAM (Tagliapietra and Wolff, 2021; Nordhaus, 2015; Winchester, 2018; Overland and Huda, 2022).¹ Alternatively, the EU CBAM might also be perceived as a protectionist trade policy and trigger antagonist political reactions, such as retaliating trade measures (Jakob et al., 2022; Böhringer et al., 2016).

Despite its political relevance, the question of the potentially cooperative outcomes of the EU CBAM is still largely open. In particular, the current literature corpus is limited regarding the spatial resolution (Overland and Huda, 2022) and the consideration of different implementation designs (Zhong and Pei, 2024).

First, despite the existence of multi-regional input-output (MRIO) data at high spatial resolution (Lenzen et al., 2013, 2017; Aguiar et al., 2022), CGE modellers usually aggregate countries into larger regions in order to limit computing times (e.g. 9 regions in Böhringer et al. (2016); Winchester (2018), 15 in Farrokhi and Lashkaripour (2023) and 16 in Clora et al. (2023)). Such regional aggregation overlooks the substantial heterogeneity in the countries' exposure to the EU CBAM (Beaufils et al., 2023b; Zhong and Pei, 2022; Perdana and Vielle, 2022; Magacho et al., 2023), thereby underestimating the variety of possible policy responses to the EU CBAM (Overland and Huda, 2022).

Second, most research focuses on a single policy scenario, which might be far from the design of the EU CBAM (Clora et al., 2023). Past research has shown that the efficiency of the EU CBAM strongly depends on specific implementation choices, such as the number of sectors covered and the emissions accounted for (Zhong and Pei, 2024), making the case for a broader mapping of the policy space. Similarly, the recycling of the fiscal revenue created by the EU CBAM might considerably change the incentive structure for other countries to join a CBAM-based climate coalition (Beaufils et al., 2023b) and has been overlooked in the modelling exercises available in the literature.

Both limitations are usually imposed by the high dimensionality of the option space (both in terms of CBAM implementation and policy responses) and by the numerical complexity of the Computable General Equilibrium (CGE) models typically used (Böhringer et al., 2016). In this paper, we introduce a two-stage modelling framework to address these two shortcomings of previous analyses.

Our approach builds on a relatively simple New Quantitative Trade model which we (i) extend by a trade policy module and (ii) complement by an agent-based model simulating the trade partners' policy response. The trade model comprises international and intersectoral linkages (Caliendo and Parro, 2015) and entails an endogenous MRIO-based emission accounting module, allowing the implementation of a larger variety of trade and climate policies compared to available models. Different from previous environmental extensions of Caliendo and Parro (2015) (see e.g. Duan et al.,

¹Note that the tariffs in Nordhaus (2015)'s original climate club proposal are not carbon tariffs, i.e. are not linked to the carbon content of trade flows. Instead, he suggests uniform punitive tariffs on all imports from non-members.

2021; Shapiro, 2021; Caron and Fally, 2022; Mahlkow and Wanner, 2023), we separately account for combustion and process emissions explicitly, more accurately capturing the emissions associated with the products covered by the EU CBAM (Bednar-Friedl et al., 2012). The model is conceptually simpler than the CGE models typically used in the literature, increasing the model's traceability while reducing the data requirements and numerical complexity, thereby allowing the exploration of a broader scope of policy scenarios with a higher regional resolution. The agent-based model simulates the iterative formation of a CBAM-based climate coalition, with flexible assumptions on the decision-making criteria of the countries.

The manuscript is organised as follows. Section 2 details the modelling approach. Section 3 introduces the calibration procedure and the data sources. Section 4 uses the model to examine the effects of the EU CBAM on emissions and incomes within the EU and abroad, and its potential to trigger the formation of a CBAM-based climate coalition. The section concludes by examining four potential extensions of the EU CBAM. Section 5 discusses the modelling strategy and the results presented in the paper and draws perspectives for future research. The last section (6) summarises the main findings of this paper.

2 Methods

Our analysis of the potential effects of the EU CBAM on international cooperation relies on the combination of two models, drawing respectively from trade economics and agent-based modelling. First, we estimate the income and emission effects of different EU CBAM implementation options for the EU and its trade partners. These analyses are conducted based on a New Quantitative Trade model, i.e. a quantitative general equilibrium model, extended from Caliendo and Parro (2015), which is introduced in section 2.1. Second, we simulate the possible response of the EU trade partners to the EU CBAM, through an agent-based model described in section 2.2.

2.1 A quantitative trade model for climate policies

We use a New Quantitative Trade model to evaluate the impacts of the EU CBAM on incomes and emissions using different implementation options. The model extends Caliendo and Parro (2015) with a climate policy module that includes a detailed emission accounting model. The first subsection (2.1.1) introduces the variables used in the model. The second subsection (2.1.2) describes the trade model from Caliendo and Parro (2015). Subsection 2.1.3 describes the extension of the model to the EU CBAM. Additional notes for implementing the model are provided in the supplementary materials (S.3).

2.1.1 Definitions

As a general convention, we note the country and sector of origin of commodities (supplier) as subscripts and the country and sector of destination as a superscript (user). For instance, z_{ir}^{js} denotes the transaction value from sector *i* in country *r* to sector *j* in country *s*, in basic price (i.e. excluding taxes, subsidies and intermediate margins). We note variables summed over one or multiple dimension(s) by removing the corresponding index/indices. For instance, the value of products *i* used by sector *j* in country *s* is denoted z_i^{js} , with $z_i^{js} = \sum_r z_{ir}^{js}$. We note counterfactual variables with a prime (') and relative changes from baseline values with a hat: let *z* be the baseline value of a variable, its counterfactual value is denoted *z'* and its value relative to the baseline is denoted by \hat{z} , with $\hat{z} = \frac{z'}{z}$.

We build on an MRIO table, covering m sectors in n countries. We assume that each sector produces a unique continuum of goods, such that referring to the sector i in country r refers to both the products of that sector and the aggregate of firms producing them. We aggregate final consumption (including government expenditures) and investments into a single final demand item per country: y_{ir}^s is the value of product i produced in country r and consumed final users in country s. We note value added created by sector i in country r, v_{ir} . Such value added comprises all incomes, including wages, profits, retail and transportation margins as well as taxes less subsidies. We calibrate the baseline equilibrium from a balanced MRIO table, where the monetary value of the inputs (including primary inputs, \bar{x}^{ir}) of each sector matches the monetary value of its production (\bar{x}_{ir}), in basic prices. With our notations, the balancing condition is expressed as:

$$\bar{x}_{ir} = \sum_{j,s} z_{ir}^{js} + \sum_{s} y_{ir}^{s}$$

$$= \sum_{j,s} z_{js}^{ir} + v_{ir}.$$
(1)

We denote the ad-valorem tax (if larger than 1) or subsidy (if lower than 1) imposed by country s on the use of input i imported from country r by τ_{ir}^s . ζ_{ir}^s is the ad-valorem tax or subsidy applied to product i from country r exported to country s. Note that we use this formalisation for both domestic (i.e. r = s) and trade policies (i.e. $r \neq s$).

We name baseline expenditures on product *i* in country $s(x_i^s)$ the sum of the intermediate use of *i* in $s(z_i^s)$ and of the final use of *i* in $s(y_i^s)$ in purchaser's prices, i.e. including the taxes and subsidies applied to product *i* in country *s*:

$$x_i^s = \sum_r \tau_{ir}^s \zeta_{ir}^s \left(z_{ir}^s + y_{ir}^s \right)$$

=
$$\sum_r \tau_{ir}^s \zeta_{ir}^s \bar{x}_{ir}^s.$$
 (2)

The trade share of country r for supplying product i in country $s(\pi_{ir}^s)$ is defined from the trade flows in purchaser's prices:

$$\pi_{ir}^s = \frac{x_{ir}^s}{x_i^s}.$$
(3)

The share of value added in the production function of sector j in country s is denoted γ^{js} :

$$\gamma^{js} = \frac{v_{js}}{x_{js}}.\tag{4}$$

The share of the intermediate input i in the production function of sector j in country s, γ_i^{js} , is:

$$\gamma_i^{js} = \frac{z_i^{js}}{x_{js}}.$$
(5)

We introduce the final demand consumption share of product *i* in country *s*, α_i^s as:

$$\alpha_i^s = \frac{y_i^s}{y^s}.\tag{6}$$

2.1.2 Basic trade model

Our core contribution concerning the trade model lies in combining it with a detailed emission accounting module and an agent-based strategic policy module. Therefore, we keep the description of the basic trade model to the essential minimum. Every country produces one unique differentiated variety in every sector. Producers combine labour and intermediates from all sectors in an upper-tier Cobb-Douglas production function. Intermediate inputs from different countries are combined into a constant elasticity of substitution (CES) input bundle. Consumers buy final products from different countries according to the same CES aggregator. Any trade flow faces iceberg-type trade costs. Firms operate in a perfectly competitive environment and all goods and labour markets are assumed to clear.

Following Dekle et al. (2007, 2008), the equilibrium conditions of the model can be expressed in relative changes, delivering a (slightly extended) representation of the model by Caliendo and Parro (2015).² This model entails six base equations introduced in this section (eq. I-VI). We then extend the model with a detailed carbon accounting and climate policy module, which are introduced in later subsections of the document (eq. VII- IX).

²Note that Caliendo and Parro (2015) derive their model from a Ricardian trade micro-foundation following Eaton and Kortum (2002) rather than our assumption of nationally differentiated varieties following Armington (1969). The representation of the trade equilibrium is unaffected by this choice (see Arkolakis et al., 2012). On the emission side, combustion emissions are unaffected, while process emissions are directly linked to produced physical quantities that do not behave independently of the trade micro-foundation (for a detailed discussion, see Watabe et al., 2024).

The production cost change in sector j in country s, \hat{c}_{js} , depends on the price change of the intermediate inputs i in country s, \hat{p}_i^s , and on the change of total value added in country s, v_s^3 :

$$\widehat{c}_{js} = \left(\widehat{v}_s\right)^{\gamma^{js}} \prod_i \left(\widehat{p}_i^s\right)^{\gamma_i^{js}}.$$
(I)

The price change for input *i* in country *s* is derived from the production cost changes in origin countries (\hat{c}_{ir}) , the input tariffs and subsidy changes $(\hat{\zeta}_{ir}^s)$ and sector-specific trade elasticities θ_i (which are directly linked to the sectoral elasticities of substitution across varieties from different origins):

$$\widehat{p}_{i}^{s} = \left(\sum_{r} \pi_{ir}^{s} \left(\widehat{\tau}_{ir}^{s} \widehat{\zeta}_{ir}^{s} \widehat{c}_{ir}\right)^{-\theta_{i}}\right)^{-\frac{1}{\theta_{i}}}.$$
(II)

The adjustment of the trade shares $(\hat{\pi}_{ir}^s)$ depends on the cost change in exporting country r (including tariffs and subsidies) relative to the price index change in importing country s:

$$\widehat{\pi}_{ir}^{s} = \left(\frac{\widehat{\tau}_{ir}^{s}\widehat{\zeta}_{ir}^{s}\widehat{c}_{ir}}{\widehat{p}_{i}^{s}}\right)^{-\theta_{i}}.$$
(III)

The counterfactual expenditure on product *i* in country *s*, $x_i^{s'}$, is:

$$x_i^{s'} = \sum_j \gamma_i^{js} \sum_r \frac{\hat{\pi}_{js}^r \pi_{js}^r}{\hat{\tau}_{js}^r \zeta_{js}^r \zeta_{js}^r \zeta_{js}^r} x_j^{r'} + \alpha_i^s y^{s'}, \tag{IV}$$

where α_i^s is country s's final expenditure share on goods from sector i and $y^{s'}$ is country s's total counterfactual consumption.

The net fiscal revenue from the input taxes, tariffs and subsidies in country s, $\kappa_{\tau}^{'s}$, derives from the sectoral expenditures *including output tariffs and subsidies* on each product j from country r and is expressed as:

$$\kappa_{\tau}^{'s} = \sum_{i,r} \left(\hat{\tau}_{ir}^{s} \tau_{ir}^{s} - 1 \right) \frac{\hat{\pi}_{ir}^{s} \pi_{ir}^{s}}{\hat{\tau}_{ir}^{s} \tau_{ir}^{s}} x_{i}^{s'}.$$
(7)

Conversely, the net revenue of output taxes and subsidies $(\kappa_{\eta}^{'s})$ is calculated from the sum of exports of all products j to each country r:

$$\kappa_{\eta}^{'s} = \sum_{j,r} \left(\widehat{\zeta}_{js}^{r} \zeta_{js}^{r} - 1 \right) \frac{\widehat{\pi}_{js}^{r} \pi_{js}^{r}}{\widehat{\tau}_{js}^{r} \widehat{\zeta}_{js}^{r} \widehat{\zeta}_{js}^{r}} x_{j}^{r'}.$$

$$\tag{8}$$

The counterfactual final consumption value in country $s, y^{s'}$, is the sum of the counterfactual value added $(v_s \hat{v}_s)$, the net fiscal cost and revenues of input and output tariffs and subsidies $(\kappa_{\tau}^{'s} \text{ and } \kappa_{\eta}^{'s})$ and the (exogenous) trade deficit (d_s) :

$$y^{s'} = v_s \widehat{v}_s + \sum_{i,r} \left(\widehat{\tau}_{ir}^s \tau_{ir}^s - 1\right) \frac{\widehat{\pi}_{ir}^s \pi_{ir}^s}{\widehat{\tau}_{ir}^s \tau_{ir}^s} x_i^{s'} + \sum_{j,r} \left(\widehat{\zeta}_{js}^r \zeta_{js}^r - 1\right) \frac{\widehat{\pi}_{js}^r \pi_{js}^r}{\widehat{\tau}_{js}^r \widehat{\zeta}_{js}^r \widehat{\zeta}_{js}^r} x_j^{r'} + d_s. \tag{V}$$

The change in value added (\hat{v}_s) in country *s* depends on the sum of the value added produced in each sector of the economy:

$$\widehat{v}_s = \frac{1}{v_s} \sum_j \gamma^{js} \sum_r \frac{\widehat{\pi}_{js}^r \pi_{js}^r}{\widehat{\tau}_{js}^r \zeta_{js}^r \zeta_{js}^r \zeta_{js}^r} x_j^{r'}.$$
(VI)

 $^{^{3}}$ We aggregate all value added in a single primary factor, such that the value added change is here equivalent to the wage change, see eq. VI.

The model is solved by introducing an exogenous variation in tariffs and subsidies (noted $\hat{\tau}_{ir}^s$ when applied to inputs and $\hat{\zeta}_{ir}^s$ on outputs) and by iterating through the equations until a new equilibrium is reached.

2.1.3 Climate policy module

We model the climate policy as the combination of a Domestic Carbon Price (DCP), Free Allowances (FA), Import Adjustments (IA) and Export Rebates (ER). The DCP applied is modelled as a domestic input tax on fossil fuel use (denoted $(\hat{\tau}_f)_{ir}^s$) and a domestic output tax on process emissions $((\hat{\zeta}_p)_{ir}^s)^4$. IA are input tariffs applied by country s on imports of commodity i from country r, $(\hat{\tau}_{ia})_{ir}^s$. ER are output subsidies that compensate the cost of the DCP and of IA on exported products, $(\hat{\zeta}_{er})_{ir}^s$. All taxes, tariffs and subsidies are defined as ad-valorem rates in the trade model (see 2.1.2). Fuel and process emission intensities are kept constant in real terms, but the ad-valorem rates and the embedded emissions are endogenously updated when solving the model (eq. VII to IX, table S. 1).

Ad-valorem emission intensities Our model distinguishes between the CO_2 emissions from the combustion of fuels and the direct emissions from industrial processes. While process emissions represent only about 10% of the total fuel combustion emissions (Gütschow et al., 2021b), this rate is higher for the sectors covered by the EU CBAM: 34% for aluminium, 45% for iron and steel and 50% for cement production (Gütschow et al., 2021b). Fuel combustion emissions correspond to energetic uses and can relatively easily be replaced by alternative or more efficient energy sources, using existing technologies. Instead, process emissions are associated with electrochemical reactions that can hardly be mitigated with current technologies (Bednar-Friedl et al., 2012). Here, we model the fuel combustion emissions proportional to the quantity of fuel use and the process emissions proportional to the output quantity.

We denote the real emission intensity of using a unit of fuel *i* by \bar{e}_i - which we assume constant - and the emission intensity per monetary unit of the fuel *i* used in country *s* by e_i^s . For a given fuel price level p_i^s , the real and nominal intensities are related by the following equation:

$$e_i^s = \frac{\bar{e}_i}{p_i^s}.\tag{9}$$

It follows that, in the counterfactual equilibrium, the ad-valorem carbon intensity of fuel *i* in country $s e_{i}^{s}$ is proportional to the inverse of the price index change of the fuel *i* in that country, \hat{p}_{i}^{s} :

$$e_i^{\prime s} = \frac{e_i^s}{\hat{p}_i^s} \tag{10}$$

Similarly, we denote as ϵ_{ir} the emissions embodied in one unit of product *i* produced in country *r*. The counterfactual ad-valorem emission intensity of the imports of a monetary unit of product *i* produced in country *r* and used in country *s*, ϵ_{ir}^{s} , is linked to the price of product *i* in importing country *s*, \hat{p}_{i}^{s} :

$$\epsilon_{ir}^{\prime s} = \frac{\epsilon_{ir}}{\hat{p}_i^s}.\tag{11}$$

As for fuel emissions, the real process emission intensity relates to the production of product *i* in country *r*, \bar{e}_{ir} , assumed constant. We denote by e_{ir} the baseline nominal emission intensity, per value unit:

$$e_{ir} = \frac{\bar{e}_{ir}}{c_{ir}}.$$
(12)

The counterfactual nominal intensity of process emissions (e'_{ir}) derives from the baseline emission intensities e_{ir} and the cost change \hat{c}_{ir} :

$$e_{ir}' = \frac{e_{ir}}{\hat{c}_{ir}}.$$
(13)

⁴Note that both equations apply to the use of domestic products when r = s and to traded products when $r \neq s$.

Policy layers Given a carbon price level λ'_r , country r can apply an ad-valorem tax on the use of fuel i $((\hat{\tau}_f)_i^r)$, on the domestic process emissions i $((\hat{\zeta}_p)_{ir})$ and on the emissions embodied in the imports of product i from country s (import adjustment, $(\hat{\tau}_{ia})_{is}^r$). Using the notations previously introduced, the three components are defined as:

$$\begin{cases} (\widehat{\tau}_{f})_{is}^{r} = \left(1 + \lambda_{r}^{\prime} \frac{e_{i}^{r}}{\widehat{p}_{i}^{r}}\right); \\ (\widehat{\tau}_{ia})_{is}^{r} = \left(1 + \lambda_{r}^{\prime} \frac{e_{is}^{r}}{\widehat{p}_{i}^{r}}\right); \\ (\widehat{\zeta}_{p})_{ir}^{s} = \left(1 + \lambda_{r}^{\prime} \frac{e_{ir}}{\widehat{c}_{ir}}\right). \end{cases}$$
(VII)

Rebates Additionally, country r can introduce export rebates to compensate for the effect of the climate policy on the exported production of regulated sectors. We denote again by ϵ_{ir} the (nominal) emission intensity embodied in the production of one unit of output from the sector i of country r.

The cost effect of the climate policy on the production of *i* in country *r* is proportional to the value of carbon tax paid on indirect emissions, $\lambda'_r \frac{\epsilon_{ir}}{\epsilon_{ir}}$. Under this assumption, the rebates that compensate the indirect cost of the climate policy on exports to country *s*, $(\hat{\zeta}_{er})^s_{ir}$, are:

$$(\widehat{\zeta_{er}})_{ir}^s = \left(1 + \lambda_r' \frac{\epsilon_{ir}}{\widehat{c}_{ir}}\right)^{-1}.$$
 (VIII)

Composition of the tariffs and subsidies layers The domestic fuel tax $(\hat{\tau}_f)_i^r$ and the import adjustments $(\hat{\tau}_{ia})_{is}^r$ apply on inputs to production processes, while the domestic process tax $(\hat{\zeta}_p)_{ir}$ and the export rebates $(\hat{\zeta}_{er})_{ir}^s$ apply on production outputs. The resulting input policy layer applied by country r on the use of product i from country s in country r, $\hat{\tau}_{is}^r$, and the output policy layers applied on products i from r and used in country s, $\hat{\zeta}_{ir}^s$, are defined as the multiplication of the respective input and output policy layers:

$$\begin{cases} \widehat{\tau}_{is}^r &= (\widehat{\tau}_f)_i^r (\widehat{\tau}_{ia})_{ir}^s \\ \widehat{\zeta}_{ir}^s &= (\widehat{\zeta}_p)_{ir} (\widehat{\zeta}_{fa})_{ir}^s. \end{cases}$$
(IX)

In addition to the climate policy, the model can include any other policy layer, such as retaliatory measures against the climate policy.

All the policy layers can be defined with different combinations of horizontal (sectors covered) and vertical (layers of supply chains used for computing the embodied emissions) coverages, except the fuel tax coverage that should be set identically to all fuel layers. The next paragraph describes the implementation of different coverages for the policy instruments.

Sectoral coverage The different layers of the climate policies may cover a subset of sectors \overline{J} only. In the case of output layers (process tax and export rebates, respectively), the layer selectively applies to a subset of sectors, \overline{J} , by setting the process tax to non-covered sectors \overline{J} to 1. The input layers (import adjustments and fuel tax) apply to all the products *i* used in country *r*, without discriminating between the sectors using these inputs. In the case of import adjustments, it is reasonable to assume that the border adjustment applies to all imported products, without discriminating against the actual user of such products. However, the fuel tax layer might be applied to the selected subset of sectors only by introducing a regulated fuel sector to the \overline{J} selected subset of sectors. The characteristics of such a regulated fuel sector are detailed in the supplementary materials (S.1).

Embodied emissions The computation of the embodied emissions in products traded from/to the countries applying the climate policy to/from the unregulated countries depends on the number of supply chain layers considered. Following usual MRIO conventions, fuel and process emissions are propagated along the supply chains in proportion to the transaction values, in basic prices (Beaufils et al., 2023a). The detail of the embodied emissions accounting module is provided in the supplementary materials (S.2).

2.2 Agent-Based Model

In the second part of the analysis, we simulate the potential effects of the EU CBAM on climate cooperation. This simulation is based on an agent-based model, which mimics negotiation rounds to form a potential climate coalition.

The model is similar to the approach used in Farrokhi and Lashkaripour (2023) and Böhringer et al. (2016), but our proposition supports additional decision criteria. The first part of this section (2.2.1) introduces the model in plain words. The second part (2.2.2) provides a formal description.

2.2.1 Description of the model

The model builds on conditional commitments to a climate coalition: countries joining the coalition pledge to implement a domestic carbon price aligned with the EU ETS and to apply a CBAM on imports from non-coalition countries. The model can support varying assumptions regarding the design of the climate club, the fiscal recycling of the tax revenue and the decision rationale of the countries.

At each iteration, all countries publicly declare their commitment to forming a coalition. Given the current state of the coalition, each country then opts separately on whether to:

- 1. commit to the coalition;
- 2. do nothing.

All countries then share their decisions publicly again. If at least one country has changed its stance on the coalition compared to the previous step, all countries are given another chance to review their decision; thus triggering a new iteration of decisions. Rounds of declaration/decisions are repeated until a stable (or cyclical) state is eventually reached.

2.2.2 Mathematical formulation

We consider a set of *n* countries, denoted r_1, \ldots, r_n . At the beginning of each iteration *i*, countries share their current status: in the coalition or neutral. We note $\Omega_i^+ = \{r_1, \ldots, r_{n^+}\}$ the subset of countries willing to join the coalition and $\Omega_i^= = \{r_1, \ldots, r_{n^-}\}$ the subset of neutral countries⁵. Together, the ensemble of the two subsets Ω_i^+ and $\Omega_i^=$ form the *public state* of the system at the beginning of the *i*-th iteration: $\Omega_i = \{\Omega_i^+, \Omega_i^=\}$. We note W^{Ω} the vector of the countries' real incomes in the state Ω , estimated through the general equilibrium model introduced in section 2.1.

In each iteration, each country r conditionally decides on a group to join. We note the decision of country r to join the coalition or remain neutral at the *i*-th iteration as $\delta_{i,r}$. $\delta_{i,r}$ is defined as a tuple $(\delta_{i,r}^{\Omega^+}, \delta_{i,r}^{\Omega^-})$, where $\delta_{i,r}^{\Omega^+}$ (resp. $\delta_{i,r}^{\Omega^-}$) is 1 if country r chooses to join the coalition (resp. remain neutral), and 0 otherwise. We define two *r*-conditional states, corresponding to the two possible decisions for country r: joining the coalition (Ω_i^{r+}) or becoming neutral $(\Omega_i^{r=})^6$. country r decides by comparing the hypothetical outcomes by choosing either of these conditional states:

$$\delta_{i,c} = g_c(W^{\Omega_i^{c+}}, W^{\Omega_i^{c-}}), \tag{14}$$

where g_c is the welfare function of country c, derived from the hypothetical equilibrium estimated with the trade model (2.1). In the rest of the manuscript, we assume that such welfare function is monotonically increasing with the real income level. In future research, this welfare function can be arbitrarily adjusted to integrate different elements in the countries' decision (see 5.3).

Once every country has independently chosen a conditional state, all decisions are simultaneously made public, therefore defining a new *public state*:

$$\Omega_{i+1} = \left(\left\{ \delta_{i,c}^{\Omega^+} \right\}_c, \left\{ \delta_{i,c}^{\Omega^-} \right\}_c \right).$$
(15)

Equations (14) and (15) are iterated until reaching an iteration j, such as:

$$\exists i < j, \ \Omega_i = \Omega_j. \tag{16}$$

- In case j = i + 1, the new *public state* is identical to the previous *public state*, meaning that all countries "confirm" their decision from iteration *i* in iteration *j*: this is a *stable state*.
- In case $j \neq i + 1$, the model has reached a state that had already been visited in an earlier iteration. However, this state was not stable since some countries chose to change their decision in the last exploration of that state

⁵All countries are in one and only one group: $\Omega^+ \cup \Omega^= \{r_1, \ldots, r_n\}$

⁶Since country r was necessarily in one of those two states in the *public state*, one of these two *conditional states* is necessarily identical to the *public state*.

(equation 15). If all equations are deterministic, such a case implies that there is no *stable state*. Still, this case does not rule out the existence of a stable subcoalition, i.e. a subset of countries applying the policy while others do not permanently impose it.

3 Data, calibration and scenarios

This part describes the calibration of the model with MRIO and elasticities data. Section 3.1 describes the data sources used. Section 3.2 explains the process for calibrating the emission intensities. Section 3.3 details the scenarios used in the analysis.

3.1 Data

The model is calibrated using MRIO data from the World Input-Output Database (WIOD) 2016 release, for the year 2014 (Timmer et al., 2015). The database distinguishes between 56 sectors and covers 43 countries and one Rest of the World (RoW) region. Trade elasticities are taken from Fontagné et al. (2022). Emission intensities are derived from the PRIMAP databases (Gütschow et al., 2021b,a) using the Multi-Scale Mapping method described in Beaufils et al. (2023a). The corresponding mapping table is provided in the Supplementary Materials (S. 5).

3.2 Estimation of the emission intensities

We denote by E_f^s the emissions caused by the burning of fossil fuel f in country s. In every country s, the real emission intensity of fossil fuel f, \bar{e}_f corresponds to the total emissions from fuel use f in country, E_f^s , divided by the quantity of fuel f used in country by non-fuel sectors in the baseline equilibrium, \tilde{Q}_f^{s7} . The quantity of fuel used by non-fuel sectors derive from the value of the gross production of the non fuel sectors $((\bar{x}_{js})_j \notin F)$, their fuel input shares γ_f^{js} and the domestic price of the fuel p_f^s :

$$\tilde{Q}_f^r = \frac{1}{p_f^s} \left(\sum_{j \notin F} \gamma_f^{js} \bar{x}_{js} \right), \tag{17}$$

in which the gross production \bar{x}_{js} (in basic prices) derives from the expenditures in purchaser's price as follows:

$$\bar{x}_{js} = \sum_{r} \frac{\pi_{js}^{r}}{\tau_{js}^{r} \zeta_{js}^{r}} x_{j}^{r'}.$$
(18)

Following equation 10, the baseline nominal emission intensity is:

$$e_f^s = E_f^s \left(\sum_{j \notin F} \gamma_f^{js} \bar{x}_{js} \right)^{-1}.$$
(19)

Similarly, the baseline nominal process emission intensity of products of p in country r, e_{pr} is the ratio between the emissions of that process, E_{pr} and the output of sector p in country r, \bar{x}_{pr} :

$$e_{pr} = \frac{E_{pr}}{\bar{x}_{pr}}.$$
(20)

3.3 Policy scenarios

The range of climate policy options spans an immense variety of implementation options, both in terms of sectors covered (horizontal coverage) and in terms of layers of emissions included in the estimation of the embodied emissions (vertical coverage). The first part of the analysis focuses on a central scenario that mimics the interaction between the

⁷The use of fuel by other fuel sectors is not covered by the carbon price - and thus not considered when estimating emission intensities. Note that the emissions that are caused by the fuel sectors (e.g. through oil refining) are still embodied in the total emissions E_f^s and the emission intensity \bar{e}_f , but the responsibility for these emissions is allocated to the downstream users of fuels.

EU ETS and the EU CBAM currently planned (denoted EU CBAM). The modelling of the EU ETS and EU CBAM are described in 3.3 and 3.3. The second part of the analysis examines extension options for the EU ETS, presented in 3.3. Section 3.3 details the countries applying the policies.

EU ETS The EU ETS covers emissions from emission-intense industries. The emission price derives from the auctions of a decreasing quota of emission allowances. The most trade-exposed, emission-intense sectors receive free allowances to reduce their exposure to carbon leakage. In our central scenario, we model the EU ETS as a fixed carbon price of 100 USD per tCO₂, applied to all CO₂ emissions from emission-intense sectors (see table S. 2). Since the EU CBAM replaces them, we do not model the free allowances here. We also use this representation of the EU ETS as a benchmark for comparing the different EU CBAM implementations.

EU CBAM We complement this EU ETS with an EU CBAM, which covers the direct fuel and process emissions from the aluminium, iron and steel, cement and fertilisers products. The detailed lists of MRIO sectors and emission categories are provided in the appendix (tables S. 3 and S. 4, respectively).

CBAM extensions The second part of the analysis examines four possible extensions of the EU CBAM. The *wide* CBAM covers the direct fuel and process emissions from all the sectors covered by the EU ETS. The *deep* CBAM accounts for all the upstream emissions related to imports of aluminium, iron and steel, cement and fertiliser to the EU. The *comprehensive* CBAM applies to all the emissions associated with the imports to the EU covered by the EU ETS. Fourth, *export rebates* deduct the carbon price to the EU ETS products exported by EU countries.

Regional coverage Beyond the 27 EU member states, non-EU countries applying the EU ETS (Switzerland, Norway, Iceland) will also apply the EU CBAM (European Commission, 2023). The United Knigdom (UK) also announced the implementation of a comparable CBAM (Department for Energy Security, 2023). We do not distinguish the EU and UK CBAMs in what follows and show the effects of the EU CBAM on an "EU" region that includes all the countries mentioned above. Some countries have an ETS in place, which should in principle be taken into account for computing the CBAM adjustment (World Bank, 2024). However, these ETS are either applied at the subnational level (Quebec, California) or have a relatively low price (Korea, China). For simplicity, we ignore these ETS in the baseline state.

4 Results

In the following section, we apply the modelling framework introduced in Section 2 to assess the effects of the EU CBAM on the EU economy and abroad, as well as its potential to trigger the formation of a climate coalition. First (4.1), the results are presented in absence of policy responses from the trade partners (i.e. using only the trade model described in 2.1). Second (4.2), the EU trade partners' strategic responses are endogeneized to estimate the potential of the EU CBAM to trigger the formation of a climate coalition (i.e. using the agent-based model described in 2.2). Third, we assess the impact of possible extensions of the EU CBAM (4.3).

4.1 Static analysis

Figure 1 shows the income and emission effects of an EU ETS without any anti-leakage instrument (blue dots) and an EU ETS combined with the EU CBAM (orange triangles). In the absence of an anti-leakage instrument, the EU ETS reduces the emissions in the EU by 7%. The emission reduction comes at a moderate cost, with a 0.025% reduction of the aggregated EU real incomes. The EU ETS also causes emission increases in the rest of the world. For most of the trade partners, the EU CBAM has a negligible effect on real incomes (below 0.01%), except for the two closest trade partners of the EU, Turkey and Russia. Russia is a major fuel supplier of fossil fuels to the EU: a decrease in fuel use in the EU leads to relatively large income losses in Russia.⁸ Conversely, Turkey depends on imports from the EU. The EU ETS increases production prices in the EU, thereby affecting the terms of trade for Turkey. In the EU, the negative effect of the price increase is partly compensated by the ETS fiscal revenue. The absence of such compensating measures explains the relatively higher negative impact of the EU ETS on Turkey compared to the EU.

The introduction of the EU CBAM (orange triangles) has a negligible effect on the EU emissions, and a positive effect on the EU real income compared to the EU ETS alone. The EU CBAM impact is qualitatively homogeneous for all trade partners, with a simultaneous decrease in emissions and income (EU CBAM data points are on the lower left of the comparable EU ETS figures). In agreement with the effect of the EU ETS, the impact of the EU CBAM is stronger for close trade partners, such as Turkey and Russia.

⁸Note that we calibrate the model to a baseline equilibrium before the Russian attack on Ukraine. The war and Western trade sanctions have led to a reduction in trade between the EU and Russia which will make Russia less directly affected by the EU CBAM.



Figure 1: Assessment of the impact of the EU ETS and EU CBAM on emission and income levels. The blue dots figure the income (x-axis) and emission effects (y-axis) of applying a carbon price of 100 USD per tCO₂ on the EU industrial emissions (EU ETS scenario). The red triangles correspond to a policy combining a domestic carbon price with a CBAM applied to imports to the EU. The results are provided in percentage deviation from the baseline equilibrium, which is assumed without a climate policy.

In quantitative terms, the EU ETS reduces by 239 Mt the CO_2 emissions in the EU (Figure 2, panel A). Such emission decrease is partially compensated by emissions in other countries, mainly driven by China and the Rest of the World (ROW), such that the overall emission reduction is 180MtCO₂. We estimate a carbon leakage rate of 25%, as the ratio between the emission level change for trade partners and the change for the EU.

In the EU, the EU CBAM causes a slight emission increase compared to the EU ETS scenario (234 MtCO₂). At the same carbon price, EU emissions could previously be partly reduced by pushing emission-intensive production abroad and importing the respective goods back into the EU. With a CBAM in place, more of the emission-intensive production remains in the EU, leading to higher EU emissions. However, the reduction of the leakage effect from 25% to 17% leads to a global abatement level 14 MtCO₂ larger than the EU ETS alone (194 MtCO₂, fig. 2, panel B). There are two key reasons why a CBAM can expected to reduce rather than eliminate leakage. First, it only removes the outside countries' climate policy-induced competitive advantage in the EU market. On other markets, EU producers still face the competitive disadvantage due to the EU ETS carbon price. Second, a CBAM does not tackle carbon leakage via international energy markets: lower EU demand for fossil fuels lowers international fuel prices and hence drives up fuel demand (and emissions) outside of the EU. Our finding of the CBAM lowering leakage without bringing it down to zero is consistent with other recent contributions in the literature (see e.g. Sogalla, 2023; Korpar et al., 2022).

The first step of our analysis highlights the relative efficiency of the EU CBAM as an anti-leakage instrument. Our model also reproduces the burden-shifting effect of the CBAM, as the reduction of the carbon leakage translates into income losses for the EU trade partners.

While the EU CBAM extends the coverage of the EU carbon price to polluters in non-EU countries, the fiscal revenues of the EU CBAM are recycled within the EU. If the EU trade partners were to implement their carbon pricing policy, the fiscal revenue of the carbon tax could be used domestically. In the next section, we evaluate whether the EU CBAM could motivate the formation of a climate coalition beyond the EU.



Figure 2: Comparative contributions to climate change mitigation under an EU ETS (panel A) and an EU CBAM (panel B). The black, left bar shows the global volume of CO_2 emissions in the baseline scenario. The red bar on the right shows the global emissions in the counterfactual scenario, i.e. with the climate policy being applied. The green and yellow bars show the contribution of each individual country to the difference in emissions between the baseline and counterfactual scenario. Green bars show emission reductions and yellow bars show emission increases. The ratio between the emission reduction in the EU and the emission increase in the rest of the world corresponds to the carbon leakage.

4.2 Strategic responses to the EU CBAM

Figure 3 pictures the agent-based model introduced in Section 2.2. Each panel of the figure describes the successive conditional decisions of the corresponding country. In each step, countries compare the potential outcome of joining the coalition (applying the EU ETS policy and an EU CBAM on non-coalition countries, green dot) to the option of staying neutral (orange cross) and take the decision that would yield the largest income. We assume that countries make myopic decisions. They know which countries have announced their intention to apply the policy in the previous step and assume that these intentions will not change in the current step. The black markers show the countries' relative real income once all decisions are aggregated. Note that these aggregated markers often differ from the respective coloured expectations. The assumption that other countries would not change their intention is violated as soon as any other country decides to change its stance on the coalition, thus creating a mismatch between a countries' income expectations (coloured lines and markers) and the actual realisation (black lines and markers).

For instance, in the first step of the process, Japan suffers negligible income losses due to the EU CBAM (time step 1, black cross). Because the introduction of an ETS on domestic emissions is costly, Japan initially decides not to respond to the EU CBAM (step 2, orange cross). However, at the beginning of the second step, the real income loss seems much larger than anticipated for Japan (step 2, black cross). The mismatch between Japanese expectations and actual outcomes derives from the other countries' simultaneous decisions. In the first step, both Korea and Taiwan expect a large gain from applying the EU ETS and EU CBAM. Because both countries are major trade partners to Japan, they can extract a substantial fiscal rent from their trade with Japan covered by the CBAM (black dots in step 2 for Japan and Korea). This CBAM rent extraction translates into major losses for Japan (black dot step 2), which could be limited if Japan were to collect the fiscal revenue from the carbon tax domestically. This is eventually what happens in the third step: now that the Japanese main trade partners are in the coalition, the decision space for Japan yields opposite expectations than in the previous step, such that Japan eventually decides to join the coalition (black dot, step 3).

Conversely, Japan joining the coalition largely reduces the income expectations of Korea and Taiwan (black dots, step 3). Because Japan is now part of the coalition, the CBAM fiscal rent has vanished along with the positive effect on Korean and Taiwanese incomes. Nevertheless, both Taiwan and Korea have no intention of leaving the coalition for the next step. If they were to do so, they would allow Japan to extract the fiscal rent from their bilateral trade flows, further



Figure 3: **Description of the construction process of a climate coalition.** Panels show the steps in the decision-making of each country and the "rest of the world (RoW)". (x-axis). The y-axis represents the relative income effect in each conditional state. In each step of the model, countries choose between joining the coalition (applying a 100USD/tCO₂ on industrial emissions and a CBAM on non-coalition countries) or staying neutral. The expected income resulting from any of these choices is indicated by a green dot (for joining the coalition) or an orange cross (staying neutral). In each step, countries chose the higher income option. The black markers show the income effect from the current coalition once the decisions of the previous step are put together. The marker is a dot for the countries currently declared in the coalition and a cross for the countries outside of the coalition. Note that the EU is assumed to commit to its climate policy, such that no alternative policy options are considered. The countries applying the policy in the final state are denoted by a thicker frame.



Figure 4: **Comparative contributions to climate change mitigation under an EU CBAM with endogenous policy responses.** The red bar on the right shows the global emissions in the counterfactual scenario, i.e., with the applied climate policy. The green and yellow bars show how much countries contribute to the difference in emissions between the baseline and counterfactual scenario. Green bars show emission reductions and yellow bars show emission increases. The ratio between the emission reduction in the countries applying the climate policy (left of the grey vertical dashed line) and the emission increase in the rest of the world corresponds to the carbon leakage.

reducing their income (orange crosses step 4). Therefore, despite lower income expectations than in the initial state, both countries commit to the coalition.

In each step, all other countries have a lower payoff when joining the coalition (green dots) than when staying neutral (orange crosses), thus deciding to stay neutral.

At the end of step 4, all countries have confirmed their decision from the previous step, as either a commitment to or an abstention from the coalition would be income-reducing. The final state of the coalition - the EU, Taiwan, Korea and Japan - is thereby a Nash equilibrium, i.e. a stable coalition (Nash, 1950).

The coalition induced by the EU CBAM leads to an overall 475 MtCO₂ emission reduction (fig. 4). While the abatement level within the EU stays comparable to the scenario neglecting the response from trade partners (230 MtCO₂, compare with 234 MtCO₂ in fig. 2), Japan, Korea and Taiwan applying the EU climate policy leads to more than a doubling of the global emission abatement. The coalition-level emission leakage remains at a similar level (19%) as in the scenario without endogenous policy responses (17%, fig. 2). In the unilateral EU policy case, most emissions leak to the ROW aggregate, followed by China. Once Japan, Korea, and Taiwan join the coalition, the largest leak of carbon emissions flows into China — an intuitive shift given the new East Asian focus of the larger coalition. From the EU perspective, the coalition-building effect of the EU CBAM leads to an emission reduction in the rest of the world almost as large as within the EU (230 Mt₂ emission reduction). We can interpret this additional abatement level as a *negative carbon leakage* of -98%.

4.3 Extending the EU CBAM

In this section, we evaluate four potential extensions of the EU CBAM. First, we consider the extension of the EU CBAM to a larger number of products (horizontal dimensions): we call *wide* CBAM an EU CBAM covering all the industries in the EU ETS. Second, we evaluate a *deep* extension of the EU CBAM, which is an EU CBAM that accounts for all upstream emissions embodied in the imported products currently covered by the EU CBAM. Third, we consider a *comprehensive* CBAM, which combines the horizontal coverage of the *wide* CBAM and the vertical coverage of the *deep* CBAM. Fourth, we evaluate the introduction of *Export Rebates* (ER) in the EU CBAM design. ER are export subsidies compensating the emission price paid in the EU.

4.3.1 Unilateral policy

| CBAM implementation | Emission reduction | Global | Carbon |
|---------------------|----------------------|--------------------|---------|
| | in the EU | emission reduction | leakage |
| | (MtCO ₂) | $(MtCO_2)$ | (%) |
| None (EU ETS) | 239 | 180 | 25 |
| EU CBAM | 234 | 194 | 17 |
| wide CBAM | 238 | 211 | 11 |
| deep CBAM | 231 | 208 | 12 |
| comprehensive CBAM | 238 | 216 | 9 |
| CBAM with ER | 225 | 198 | 12 |

Table 1: Effect of different CBAM implementations on emissions in the European Union and at the global level.

Abstracting from possible policy response of the EU trade partners, all the implementation options of the EU CBAM yield between 230 and 240 Mt of CO₂ emissions reduction in the EU (table 1), except for Export Rebates, which only abate 225 MtCO₂ in the EU. When accounting for carbon leakage and emission changes in the rest of the world, the range of emission reduction widens between different implementation options. While an EU ETS without an anti-leakage instrument only abates 180 MtCO₂ globally (25% leakage), a comprehensive CBAM reduces the leakage rate to 9%, reaching an overall mitigation level of 216 MtCO₂. A comprehensive CBAM combines a horizontal (*wide* CBAM) and a vertical (*deep* CBAM) extension. Taken in isolation, these implementation options yield similar effects, both in terms of global emission mitigation (211 MtCO₂ and 208₂ emission reduction, respectively) and carbon leakage (11 and 12%, respectively).

The vertical and horizontal extensions of the EU CBAM lead to an increase of the income in the EU compared to the current EU CBAM (fig. 5). In absolute terms, the more ambitious CBAM implementations could even increase the EU real incomes compared to the baseline without climate policy: the wide CBAM option (purple square) increases the aggregated incomes in the EU by 0.002% and the comprehensive CBAM increases EU incomes by 0.007%. In the rest of the world, the extensions of the CBAM are all associated with a decrease in incomes (down to -0.015% for a comprehensive CBAM) and in emission levels compared with the basic EU CBAM.

The introduction of Export Rebates has opposite effects, both in the EU and in the rest of the world (yellow hexagons). Export rebates use some of the fiscal revenue of the EU climate policy for subsidising consumption in other countries. This policy instrument therefore reduces the income of the EU by an additional 0.007 percentage point and increases the incomes in the rest of the world by 0.003 percentage point. Still, export rebates are effective at reducing the carbon leakage associated with the EU climate policy (table 1).

4.3.2 Coalition building potential

When accounting for the policy responses of the EU trade partners to the EU CBAM, different extensions of the EU CBAM yield diverging outcomes (table 2). Overall, the extensions with the most negative effect on the trade partners' incomes (see fig. 5) are associated with larger coalitions. A *deep* extension of the EU CBAM adds two additional economies to the coalition compared to the current EU CBAM, Indonesia and Canada. Both of these countries are found joining a coalition with a *wide* CBAM too, but such a *wide* CBAM would additionally bring the commitment of Australia, Brazil, Mexico and the *Rest of the World* aggregated region, more than tripling the abatement level reached with the current EU CBAM. Even though both extension options had similar income and emission effects on the aggregated level (5), the slightly different incentive structures they create for other countries yield major differences in the resulting coalition.



Figure 5: Assessment of the effect of different EU CBAM implementation options on emissions and real incomes in the EU and in the rest of the world. The orange triangles indicate the emission reduction (y-axis) and the real income change (x-axis) associated with implementing the EU CBAM, in the EU and outside of the EU. The coloured markers indicate the comparative outcomes with different extension options: a CBAM covering all the sectors included in the EU ETS (wide CBAM - purple squares), a CBAM covering all upstream emissions of the products covered by the EU CBAM (deep CBAM, pink diamonds), a comprehensive CBAM covering all upstream emissions of all the industries covered by the EU ETS (green pentagons) and an EU CBAM with export rebates relieving the EU exports from the carbon tax (yellow hexagons). All policy instruments assume a carbon price of 100 USD/tCO₂ and no policy response of the EU trade partners.

The combination of the *deep* and *wide* extensions of the CBAM - i.e. the *comprehensive* option - results in the broadest coalition. Such comprehensive CBAM would motivate the adoption of carbon pricing in 12 of the 15 regions covered in our analysis. Russia, China and India would be the only countries staying outside of the coalition. In contrast, the introduction of export rebates appears to reduce the coalition-building potential of the EU CBAM, as only Taiwan consistently joins the EU-led climate coalition in that case, while Japan and Korea are indecisive (see Figure S.1 in the Supplementary Materials).

| CBAM | Countries | Overall emission reduction |
|----------------|---------------------|-----------------------------------|
| implementation | in the coalition | $(MtCO_2)$ |
| EU CBAM | EU, TWN, KOR, JPN | 455 |
| | EU, AUS, BRA, CAN, | |
| wide CBAM | IDN, JPN, KOR, MEX, | 1 463 |
| | TWN, ROW | |
| deep CBAM | EU, CAN, IDN, JPN | 526 |
| | KOR, TWN | |
| comprehensive | EU, AUS, BRA, CAN | |
| CBAM | IDN, JPN, KOR, MEX | 1 681 |
| | TUR, TWN, USA, ROW | |
| CBAM | EU, TWN | 337 |
| with ER | (JPN, KOR)* | |

Table 2: Overview of the coalitions triggered by different EU CBAM implementation options. The asterisk (*) highlight countries that do not consistently join the coalition, indicating scenarios where no stable coalition arises.

In comparison, Farrokhi and Lashkaripour (2023) find that the EU alone would not be able to trigger the formation of a climate coalition under an optimal setting, but that the commitment of both the United States and the EU would be sufficient to reach commitment from all the countries. Our approach differs from Farrokhi and Lashkaripour (2023) by departing from their optimality condition. They let countries freely chose both the optimal level of carbon pricing and of import tariffs. Instead, we reduce the countries' policy choices to the binary decision of whether to join the coalition. Our results also differ from Böhringer et al. (2016), in which the EU CBAM motivates China and Russia to commit to climate policies. Compared to our analysis, Böhringer et al. (2016) allow countries to retaliate against the CBAM and model the climate policy as a global emission target, in line with the Kyoto Protocol targets, such that a larger coalition-building potential of a CBAM is strongly dependent on implementation details: all five options considered lead to distinct coalitions and to widely different emission abatement levels.

5 Discussion

In this section, we discuss the key assumptions underlying the trade model (5.1, the underlying calibration (5.2), the coalition-building model (5.3), the underlying mechanism (5.4) and the range of policy scenarios modelled (5.5).

5.1 Trade model

Our general equilibrium model largely builds on Caliendo and Parro (2015). In comparison with CGE models usually applied for studying the effects of the EU CBAM, our modelling framework abstracts from many potentially important mechanisms (Bekkers et al., 2023). We aggregate all countries' final use into a single representative agent, thereby not considering domestic distributional problems. We model a single counterfactual equilibrium, leaving technological change and investment trajectories out of the model. We model production with Cobb-Douglas functions, at the risk of overestimating substitution options and we assume the primary inputs fully flexible domestically and immobile internationally. Despite these simplifications, the results we obtain for the abatement levels, carbon leakage and income effects are well in the range of CGE-based estimations (Böhringer et al., 2022).

In turn, these simplifications increase the traceability of our analysis, reduce the calibration and computation effort and permit the modelling of a wide range of policy options. In addition, a growing literature has extended the original Caliendo and Parro (2015) model, which can be used in further research for enriching our modelling approach (e.g. Duan et al., 2021; Caron and Fally, 2022; Mahlkow and Wanner, 2023).

5.2 Baseline calibration and data limitations

Our analysis builds on MRIO data from 2014 (Timmer et al., 2016). In the meantime, the world economy underwent major changes, including a global pandemic and trade sanctions between major economies (e.g. between the United States and China or between the EU and Russia). While the availability of MRIO data for the most recent years at high sectoral and regional detail is limited, some more recent MRIO tables are already available (Aguiar et al., 2022) and can readily be exploited in future work using the methodological framework introduced here.

More generally, the sectoral aggregation of MRIO tables is a challenge for analysing the effects of the EU CBAM. In our model, we use emission data at the process level (Gütschow et al., 2021b,a) to model the EU CBAM below the MRIO sector level. Practically, such emission data allow isolating product-specific emissions, which permit estimating the carbon intensity of the products covered by the CBAM more precisely. However, such process-level emission intensities (e.g. steel production emissions) are still aggregated at the sector level (e.g. basic metals) when applying the taxes and tariffs: the specific products targeted by the EU CBAM are diluted into the larger MRIO sectors, which might cause us to misfeature some product-specific characteristics. Additionally, our methods isolate direct emissions. Indirect emissions are still estimated at the sector level, which might lead to overestimate the coverage of the CBAM - and thus the efficiency of this policy instrument. Similarly, the analysis presented here (Section 4) is still relatively aggregated on the regional level. More spatially disaggregated MRIO data (Lenzen et al., 2017; Aguiar et al., 2022) can partially overcome these limitations. Using more detailed economic data (e.g. bilateral trade data at the product level) is a promising avenue but is difficult to integrate with a general equilibrium consideration.

5.3 Coalition-building

In section 2.2, we introduce an agent-based model to simulate the formation of a climate coalition as a response to the EU trade policy. Such a coalition-building game with myopic, welfare-optimising agents aligns with the related literature (Böhringer et al., 2016; Nordhaus, 2015; Farrokhi and Lashkaripour, 2023). Any stable coalitions resulting

from the algorithm is a Nash equilibrium (Nash, 1950), but such Nash equilibrium is not necessarily unique, nor optimal. The space of possible coalitions follows a power law with the number of players (with N regions, 2^N coalitions are possible). Mapping all the Nash equilibria for any policy option would be numerically challenging (and largely irrelevant). Instead, our approach allows finding a plausible coalition derived from given initial conditions.

Still, our analysis of alternative implementation options for the EU CBAM (Section 4.3) highlights that neighbouring initial conditions might lead to substantially different stable states. Further research is needed to assess whether alternative design options for the coalition-building game - e.g. modelling successive instead of simultaneous decisions, or using stochastic processes (Young, 1993) - would lead to different outcomes.

Similarly, in the current game, countries are myopic: they do not form anticipations on the other countries' decisions. As a consequence, countries might make decisions that eventually decrease their pay-off (see for instance the Korean decision to join the coalition in fig. 3). Introducing forward-lookingness into the model would be numerically challenging, as the number of hypothetical states would grow exponentially. Instead, game-theory approaches use simpler pay-off functions, which appear complementary to our approach (Heitzig and Kornek, 2018).

5.4 Underlying mechanism

The agent-based model simulates the policy response of other countries to the EU CBAM. The fundamental mechanism we capture here is the competition for a CBAM rent. The countries imposing the CBAM extract a fiscal revenue from their imports. From the point of view of a trade partner outside of the coalition, joining the coalition allows (i) re-anchoring the fiscal revenue from its own emissions and exported to the coalition countries (ii) extracting the CBAM rent from its trade with non-coalition countries. The first channel explicitly depends on the countries within the coalition, while the second relies on the baseline trade relations. In the analysis of the EU CBAM (Section 4.2), the countries joining the coalition (Japan, Korea, Taiwan) are not major trade partners of the EU. Instead, the interaction between Japan and Korea hints towards the second channel dominating the formation of the coalition. Indeed, additional simulations show that Japan, Korea and Taiwan would form a CBAM-based coalition in Asia is reduced. Still, CBAM are complex regulatory instruments, whose implementability has long been disputed (Cosbey et al., 2019). The EU CBAM being the first of its kind, it creates a precedent and a standard that can be replicated elsewhere. Such diffusion effect has already been highlighted for carbon pricing (Linsenmeier et al., 2023).

Section 4.3 shows that combining Export Rebates (ER) with the EU CBAM strongly reduces the size of the potential coalition. ER act as subsidies on trade partner's consumption. On the one hand, this increases the policy cost for the coalition countries (see figure 5). On the other hand, the ER do not apply to other countries within the coalition. Losing access to the ER increases the relative cost for countries wanting to join the coalition. However, our modelling framework does not entail technological change, such that it underestimates the potential benefits of subsidising clean production (Carolyn Fischer, 2016; Schwerhoff et al., 2018).

5.5 Policy space

The coalition-building game assumes that countries face a dual choice, between applying the exact same policy as the EU or doing nothing 2.2. However, the actual policy space for responding to the EU CBAM is much larger. Instead of adopting the EU CBAM, countries could adopt different carbon pricing instruments, with potentially different carbon prices than the EU (as modelled in Farrokhi and Lashkaripour (2023)) or adopt trade sanctions against coalition members (see Böhringer et al. (2016)). Reciprocally, the EU can introduce a variety of CBAM implementations (see 4.3) or introduce additional policies to limit the impact of the CBAM on other countries (Beaufils et al., 2023b). Similarly, many design options are possible for the coalition. The climate club proposal by Nordhaus (2015) entails punitive tariffs against non-coalition members. Countries could decide on whether to join the coalition based on non-economic criteria.

In principle, our modelling framework can be used for modelling variety of policy options with arbitrary assumptions on the countries' rationality. For instance, the trade model can be extended to support heterogeneous carbon pricing instruments and revenue recycling options. The countries' welfare function in the agent-based model (eq. 15) can follow any functional form, e.g. including climate change damages (Kotz et al., 2024), weights based on countries' geopolitical proximity (Bailey et al., 2017) or bounded rationality assumptions. Our framework could also accommodate an arbitrary number of policy options for countries Ω (Section 2.2), including retaliation. This large option space opens opportunities for future research. Interactions with various scientific disciplines and policymakers will help derive relevant settings to explore within the framework introduced here.

6 Conclusion

This paper introduces a two-stage model to evaluate the potential of the EU CBAM to trigger the formation of a climate coalition. First, our numerical analysis highlights that the EU CBAM has the potential to reduce the carbon leakage associated with the EU ETS by one-third compared to a scenario without an anti-leakage policy, from 25% to 17%. Such limited efficiency of the EU CBAM aligns with existing literature on the EU CBAM (Böhringer et al., 2022) and our model reproduces the characteristic features of the EU CBAM, such as the burden-shifting effect captured in figure 1.

Second, we show that the EU CBAM can have knock-on effects on climate policies in the rest of the world. In its current form, the EU CBAM can ground a stable climate coalition of the EU with Korea, Taiwan and Japan. We find that extending the scope of an EU CBAM has the potential to motivate climate policies in most countries around the world, with the exception of China, Russia and India (comprehensive CBAM scenario).

Overall, our results highlight the importance of the multilateral dimension of the EU CBAM. In the most ambitious implementation option, the EU CBAM only halves the carbon leakage caused by the EU carbon price. Nonetheless, even in the most conservative implementation option, accounting for the policy response of the EU trade partners at least doubles the abatement potential of the EU CBAM.

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Supplementary materials

S.1 Regulated fuel sector

Restricting the application of the fuel tax to a subset of intermediate sectors requires introducing a set of so-called *regulated fuel sectors*, denoted \bar{f} . The regulated fuel sector acts as a domestic monopoly fully supplying the sectors paying the fuel input tax. In detail, the regulated fuel sector holds the following properties:

• The regulated fuel sector \bar{f} in country r supplies exclusively the sectors covered by the carbon price \bar{J} :

$$\begin{cases} \forall i \in \bar{J} \quad \gamma_{\bar{f}}^{ir} = \gamma_{f}^{ir}; \\ \forall i \in \tilde{J} \quad \gamma_{\bar{f}}^{ir} = 0; \end{cases}$$

$$(21)$$

• The non-regulated fuel sector \tilde{f} in country r supplies the sectors not covered by the carbon price \tilde{J} :

$$\begin{cases} \forall i \in \bar{J} \quad \gamma_{\bar{f}}^{ir} = 0; \\ \forall i \in \tilde{J} \quad \gamma_{\bar{f}}^{ir} = \gamma_{f}^{ir}; \end{cases}$$
(22)

• The non-regulated fuel sector \tilde{f} fully supplies the regulated fuel sector \bar{f} and the regulated fuel sector \bar{f} does not supply the non-regulated fuel sector \tilde{f}^9 :

$$\begin{cases} \gamma_{\tilde{f}}^{\bar{f}r} = 1; \\ \gamma_{\bar{f}}^{\bar{f}r} = 0; \end{cases}$$

$$(23)$$

• Only the regulated sector \overline{f} in country r provides the domestic supply of regulated fuel:

$$\begin{cases} \pi_r^{\bar{f}r} = 1; \\ \forall s \neq r, \quad \pi_r^{\bar{f}s} = 0. \end{cases}$$

$$(24)$$

Equations 21 to 24 define regulated fuel sectors \bar{f} that are entirely supplied by the non-regulated fuel sectors \tilde{f} and that supplies all regulated sectors. By setting the fuel input tax on the intermediate sector only $(\tau_{\bar{f}r}^s = \tau_{fr}^s; \tau_{\bar{f}r}^s = 1)$, the climate policy is only directly applied to the regulated sectors, while the indirect price effect is transmitted to the global fuel market through the non-regulated fuel sector \tilde{f} . The regulated fuel sector also ensures that regulated fuel users in country r do not buy unregulated fuels on the world market.

S.2 Computation of the embodied emissions

The computation of the embodied emissions in products traded from/to the regulated zone Ω to/from the unregulated zone $\overline{\Omega}$ depends on the number of supply chain layers considered. The direct emission intensity of the product j produced in country s, φ'_{js} , combines the process emission intensity of product j in country s, (direct process emissions, e_{js}) and the emission intensity from direct fuel use, φ'_{js}^{f} . The fuel emission intensity is proportional to the value of fuel f used by the sector j in country s, multiplied by the emission intensity of the fuel f in country s, e_{f}^{s} . The fuel share in quantity derives from the nominal expenditure share of fuel f in the production function of js, γ_{f}^{js} , divided by the fuel price change in country s, \hat{p}_{f}^{s} . The intensity of embodied emissions of rank 1 is then obtained by summing the emission intensities of all fuels available and the direct process emissions:

$$\varphi_{js}' = \sum_{f} \frac{\gamma_f^{js}}{\hat{p}_f^s} e_f^s + e_{js}.$$
(25)

⁹ This property ensures that the regulated fuel market is fully coupled with the non-regulated fuel market: following equation II, the price index of the regulated fuel equals the price index of the non-regulated fuel market, multiplied by the potential carbon tax on fuel use. Furthermore, the size of the non-regulated fuel market is unaffected by the introduction of a regulated fuel sector. A direct consequence of this property is that the fuel sector is excluded from the subset of sectors covered by the carbon price \bar{J} , i.e. emissions are only priced when fuels are being burned in the rest of the economy. This also rules out any double counting of emissions when trading fuels.

We denote the contribution of input *i* from country *r* to the embodied emissions of one unit of output of product *j* produced in country *s* by $(\eta'^1)_{js}^{ir}$. At each supply chain stage, we assume that the emissions embedded in products are proportional to the value shipped (in basic price), no matter the destination. $(\eta'^1)_{js}^{ir}$ then corresponds to the direct emission intensity of input *i* in country *r* multiplied by the real input share of *ir* in the production function of industry *j* in country *s*, β_{ir}^{js} :

$$(\eta'^{1})_{js}^{ir} = \beta'^{js}_{ir} \varphi'_{ir}.$$
(26)

The real input share of the input *i* from country *r* in the production function of *j* in *s*, $\beta_{ir}^{'js}$ depends on the price index of the input *i* in country *s*, \hat{p}_i^s , and the nominal input share of *ir* in *js*, is obtained by dividing the nominal value by the price index change of input *i* in country *s*, $\gamma_{ir}^{'js}$:

$$\beta_{ir}^{'js} = \frac{\gamma_{ir}^{'js}}{\hat{p}_i^s}.$$
(27)

Finally, the counterfactual input share derives from the fixed expenditure share of js in i, γ_i^{js} , multiplied by the counterfactual trade share of country r in providing i to country s, net of taxes and subsidies:

$$\gamma_{ir}^{'js} = \frac{\widehat{\pi_{ir}^s} \pi_{ir}^s}{\widehat{\tau_{ir}^s} \widehat{\tau_{ir}^s} \widehat{\zeta_{ir}^s}} \gamma_i^{js}.$$
(28)

The indirect embedded emission intensity from all direct suppliers to sector j in country s, $\eta_{js}'^1$, is then the sum of the emission intensities of the inputs from all the regulated sectors $i \in \Theta$ in unregulated countries $r \in \overline{\Omega}$ in the case of Import Adjustments, or regulated countries $r \in \Omega$ in the case of export rebates:

$$(\eta_{js}^{'1}) = \sum_{i \in \Theta} \sum_{i,r} (\eta^{'1})_{js}^{ir}.$$
(29)

The procedure can be extended to any rank of supplier k: for this purpose, we introduce the matrix of real input shares, B', the array of rank 1 emissions H'^1 and the array of emission intensities Φ' . With these notations, equation 29 becomes:

$$H^{'1} = B'\Phi'. \tag{30}$$

The emission intensity of indirect inputs of rank k, H'^k , is then:

$$H^{'k} = (B')^k \Phi'. (31)$$

In the matrix form, setting the coefficients corresponding to non-covered sectors and countries in the array Φ allows discriminating between the sectors and countries that should and should not be included in the calculation of the emission intensities.

Accounting for all the indirect emissions related to the production of j in s is done by using the Leontief inverse L', defined from the matrix of real input shares B' and the identity matrix I:

$$L' = (I - A')^{-1}.$$
(32)

Coefficient $l_{ir}^{'js}$ captures the real quantity of input *i* from country *r* required directly and indirectly to produce one unit of input *j* in country *s*. The emission intensity embodied indirectly in product *j* from *s*, $\eta_{js}^{'\infty}$, is then:

$$\eta_{js}^{\prime \infty} = \sum_{i,r} (l_{ir}^{\prime js} - 1)\varphi_{ir}^{\prime}.$$
(33)

Finally, applying import adjustments without export rebates with a comprehensive vertical coverage leads to double counting the emissions from supply chains looping through the regulated economy (Beaufils et al., 2023a). In that specific case, we use the Throughflow Based Accounting (TBA) method defined in (Beaufils et al., 2023a) to avoid

| Vertical coverage (Ranks of supply chains covered) | Embodied emissions ϵ_{ir}' |
|--|---|
| Direct coverage | φ_{js}^{\prime} (25) |
| Rank n coverage | $\eta_{js}^{'k}$ (31) |
| Comprehensive coverage | $\eta_{js}^{\prime\infty}$ (33) |
| Comprehensive coverage <i>with import adjustments and in absence of export rebates</i> | $\varphi_{js}' + \eta_{js}^{'*\infty}$ (eq. 34) |

Table S. 1: Overview of the equation used to compute the embedded emissions in imports and exports under different vertical coverage settings. Each row corresponds to different options of vertical coverage, i.e. different layers of supply chains considered. The equations defining the different variables are denoted in parentheses.

applying the adjustments multiple times to a single source of emissions. The TBA requires defining a matrix B'^* , where all input and output shares related to countries applying the climate policy are set to 0. The modified Leontief inverse L'^* describes the direct and indirect input requirements *in the absence of* the regulating countries, i.e. the supply chains that did not involve the regulated economy in earlier stages. Such modified embodied emission intensity, $\eta_{js}'^{*\infty}$ is finally defined as:

$$\eta_{js}^{\prime\infty} = \sum_{i,r} ((l^{\prime*})_{ir}^{js} - 1)\varphi_{ir}^{\prime}.$$
(34)

Table S. 1 summarises the relations required to compute the Import Adjustments and Export Rebates with different depths of emission accounting.

S.3 Implementation

This section entails practical notes for running the model.

Calibration in absence of trade deficits The trade model assumes constant trade deficits in nominal terms (eq. V). Fixing non-null trade deficits would force the model into unconditional transfers from the countries with a trade deficit to countries with a trade surplus. To minimise the influence of the initial deficit values on the final equilibrium, we first neutralise the trade balances before applying the policy shocks. This *neutralised* equilibrium is used as the baseline for running the model.

World revenue normalisation In addition to constant sectoral expenditure shares (eq. I) and constant trade deficit, we follow Caliendo and Parro (2015) and normalise world GDP to remain constant in the counterfactual equilibrium:

$$\sum_{s} \hat{v_s} v_s = \sum_{s} v_s. \tag{35}$$

Evaluation of the variables of interest The real income change of country s, \hat{y}_{real}^{s} , is derived from combining nominal income changes and the change in national price indices $\hat{\rho}^{s}$:

$$\hat{y}_{real}^{s'} = \frac{\hat{y}^s}{\hat{\rho^s}},\tag{36}$$

where the national price index changes are defined as:

$$\widehat{\rho^s} = \prod_i \left(\widehat{p_i^s}\right)^{\alpha_i^s}.$$
(37)

Similarly, real wage changes (\hat{w}_s^{real}) are derived from the price index changes $\hat{\rho}^s$ and the changes in value added \hat{v}_s :

$$\hat{w}_s^{real} = \frac{\hat{v_s}}{\rho^{\hat{s}}}.$$
(38)

The emissions caused by burning fuel f in sector i of country s, $E'_{f}{}^{is}$, derive from fuel input share in monetary terms (γ_{f}^{is}) , the gross production of the sector and the nominal fuel intensity $(e'_{f}{}^{s}$. see 10):

$$E_f^{'is} = \frac{e_f^s}{\hat{p}_f^s} \gamma_f^{js} \sum_r \frac{\hat{\pi}_{js}^r \pi_{js}^r}{\hat{\tau}_{js}^r \hat{\tau}_{js}^r \hat{\zeta}_{js}^r \zeta_{js}^r} x_j^{r'}.$$
(39)

The process emissions from the sector *i* in country *s*, $E_{p}^{'is}$ similarly derive from the gross production of the corresponding sector and the process-specific emission intensity ($e_{ir}^{'}f$. see 13):

$$E_p^{'is} = \frac{e_{is}}{\hat{c}_{is}} \sum_r \frac{\hat{\pi}_{is}^r \pi_{is}^r}{\hat{\tau}_{is}^r \hat{\tau}_{is}^r \hat{\zeta}_{is}^r \zeta_{is}^r} x_i^{r'}.$$
(40)

S.4 Additional figures

S.5 Mapping tables

| Sector covered by the EU ETS | | |
|--|--|--|
| Mining and quarrying | | |
| Manufacture of paper and paper products | | |
| Manufacture of coke and refined petroleum products | | |
| Manufacture of chemicals and chemical products | | |
| Manufacture of basic pharmaceutical products and pharmaceutical preparations | | |
| Manufacture of rubber and plastic products | | |
| Manufacture of other non-metallic mineral products | | |
| Manufacture of basic metals | | |
| Electricity, gas, steam and air conditioning supply | | |

Table S. 2: Sectors covered by the EU ETS.

| Product covered in the EU regulation | Sector in the MRIO table |
|--------------------------------------|--|
| (European Commission, 2023) | (Timmer et al., 2016) |
| Iron and steel | Manufacture of basic metals |
| Aluminium | Manufacture of basic metals |
| Fertilisers | Manufacture of chemicals and chemical products |
| Cement | Manufacture of other non-metallic mineral products |
| Electricity | Electricity, gas, steam and AC |
| Hydrogen | NA |

Table S. 3: Sectors covered by the EU CBAM. The first column shows the sectors explicitly covered by the EU CBAM regulation as implemented in 2023 (European Commission, 2023). The second column shows the equivalent sector in the MRIO table (Timmer et al., 2016). Note that Hydrogen is not considered here, as it was not traded in significant quantities in 2014.



Figure S.1: Coalition-building process under an EU CBAM with Export Rebates. In this scenario, the EU and Taiwan are committing to joining a climate club. At step 2, Korea decides to join the coalition, which triggers the decision of Japan to join the coalition too at step 3. In turn, the Japanese decision to join the coalition forces Korea out of it at step 4, which in turns motivate Japan to leave the coalition at step 5. Step 6 yields an identical situation as step 2: there is no stable coalition in this setting because of the strategic interaction between Japan and Korea.

| UNFCCC Category code | Emission type | Description |
|----------------------|-------------------|---|
| 1.A.1.a | Fuel emissions | Electricity and heat production |
| 1.A.2.a | Fuel emissions | Combustion for Iron and Steel production |
| 1.A.2.b | Fuel emissions | Combustion for non-ferrous metals (incl. aluminium) |
| 1.A.2.c | Fuel emissions | Combustion for chemicals (incl. fertilisers) |
| 1.A.2.f | Fuel emissions | Combustion for non-metallic minerals (incl. cement) |
| 2.A.1 | Process emissions | Cement production |
| 2.B | Process emissions | Production of chemicals (incl. fertilisers) |
| 2.C.1 | Process emissions | Iron and Steel production |
| 2.C.3 | Process emissions | Aluminium production |

Table S. 4: Emissions covered by the EU CBAM in our analysis. The nomenclature follows the United Nations Framework Convention on Climate Change (UNFCCC) guidelines (Gütschow et al., 2021b).

| Category Code | Economic sector | | |
|---------------|--|---|--------------------------------|
| 1.A.1.a | Electricity, gas, steam and AC | | |
| 1.A.1.b | coke and petroleum | | |
| 1.A.1.c | coke and petroleum | | |
| 1.A.2.a | basic metals | | |
| 1.A.2.b | basic metals | | |
| 1.A.2.c | chemicals | basic pharmaceutical products | |
| 1.A.2.d | paper and paper products | Printing and reproduction of recorded media | |
| 1.A.2.e | food products | | |
| 1.A.2.f | non-metallic mineral products | | |
| 1.A.2.g | motor vehicless | other transport equipment | |
| 1.A.2.h | computer, electronic and optical products | electrical equipment | machinery and equipment n.e.c. |
| 1.A.2.i | Mining and quarrying | | |
| 1.A.2.j | wood and of products of wood and cork | | |
| 1.A.2.k | Construction | | |
| 1.A.2.1 | textiles | | |
| 1.A.2.m | rubber and plastic products | fabricated metal products | furniture; other manufacturing |
| 1.A.3.a | Air transport | | |
| 1.A.3.b.i | Final demand | | |
| 1.A.3.b.ii | Land transport | | |
| 1.A.3.b.iii | Land transport | | |
| 1.A.3.b.iv | Final demand | | |
| 1.A.3.c | Land transport | | |
| 1.A.3.d | Water transport | | |
| 1.A.3.e | Land transport | | |
| 1.A.4.a | coke and petroleum | | |
| 1.A.4.b | Final demand | | |
| 1.A.4.c.i | Crop and animal production | Forestry and logging | |
| 1.A.4.c.ii | Crop and animal production | Forestry and logging | |
| 1.A.4.c.iii | Fishing and aquaculture | | |
| 1.A.5 | Public administration | | |
| 1.B.1.a | Mining and quarrying | | |
| 1.B.1.c | coke and petroleum | | |
| 1.B.2.a.i | Mining and quarrying | coke and petroleum | |
| 1.B.2.a.ii | Mining and quarrying | coke and petroleum | |
| 1.B.2.a.iii.1 | Mining and quarrying | coke and petroleum | |
| 1.B.2.a.iii.2 | Mining and quarrying | coke and petroleum | |
| 1.B.2.a.iii.3 | Land transport and transport via pipelines | | |
| 1.B.2.a.iii.4 | coke and petroleum | | |
| 1.B.2.a.iii.5 | coke and petroleum | | |
| 1.B.2.a.iii.6 | Mining and quarrying | coke and petroleum | |

| 1.B.2.b.i | Mining and quarrying | coke and petroleum |
|---------------|--|--------------------------------|
| 1.B.2.b.ii | Mining and quarrying | coke and petroleum |
| 1.B.2.b.iii.1 | Mining and quarrying | coke and petroleum |
| 1.B.2.b.iii.2 | Mining and quarrying | coke and petroleum |
| 1.B.2.b.iii.3 | coke and petroleum | |
| 1.B.2.b.iii.4 | Land transport and transport via pipelines | |
| 1.B.2.b.iii.5 | Electricity, gas, steam and AC | |
| 1.B.2.b.iii.6 | Mining and quarrying | coke and petroleum |
| 1.B.3 | Electricity, gas, steam and AC | - |
| 1.C | Mining and quarrying | |
| 2.A.1 | non-metallic mineral products | |
| 2.A.2 | non-metallic mineral products | |
| 2.A.3 | non-metallic mineral products | |
| 2.A.4 | non-metallic mineral products | |
| 2.B.1 | chemicals | |
| 2.B.10 | chemicals | |
| 2.B.2 | chemicals | |
| 2.B.3 | chemicals | |
| 2.B.4 | chemicals | |
| 2.B.5 | chemicals | |
| 2.B.6 | chemicals | |
| 2.B.7 | chemicals | |
| 2.B.8 | chemicals | |
| 2.B.9 | chemicals | |
| 2.C.1 | basic metals | |
| 2.C.2 | basic metals | |
| 2.C.3 | basic metals | |
| 2.C.4 | basic metals | |
| 2.C.5 | basic metals | |
| 2.C.6 | basic metals | |
| 2.C.7 | basic metals | |
| 2.D | coke and petroleum | |
| 2.E | computer, electronic and optical products | |
| 2.F | Repair and installation | Electricity, gas, steam and AC |
| 2.G.1 | electrical equipment | |
| 2.G.2 | computer, electronic and optical products | |
| 2.G.3 | Final demand | |
| 2.G.4 | Final demand | |
| 2.H.1 | paper and paper products | |
| 2.H.2 | food products | |
| 2.H.3 | Final demand | |
| 3 | Crop and animal production | Forestry and logging |

Sewerage and waste

Table S. 5: Mapping between UNFCCC emission categories and MRIO sectors.