

Institut für Physik und Astronomie

The climate coordination dilemma in an interconnected world

Instrumentalising interdependencies in the global trade network

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Abstract

Our world is interconnected on multiple levels. In the atmosphere, the greenhouse gas emissions of each country contribute to warming the planet, causing damage in every part of the world and requiring the negotiation of laborious international agreements. In society, international supply chains connect consumers, intermediates and producers globally, forming a complex network of economic interactions. Such trade interlinkages blur the responsibilities for emissions and enable industries to relocate their production to evade climate policies. On both dimensions, interdependencies restrain unilateral climate action and pose a coordination dilemma for mitigating climate change.

In October 2023, the European Union (EU) adopted a Carbon Border Adjustment Mechanism (CBAM) that will require importers of basic materials to surrender emission permits for the related emissions caused abroad. The EU CBAM will implicitly diffuse the EU carbon price through international trade and might motivate the adoption of climate policies in other countries. In my dissertation, I develop methods to model the global trade network and explore how the EU CBAM can promote climate cooperation by instrumentalising trade interdependencies.

My thesis builds on Multi-Regional Input-Output Tables (MRIOTs) representing the global economic network. The first two articles present methodological contributions to the development and analysis of MRIOTs and are complemented by data sets (Beaufils and Wenz 2021b; Beaufils and Wenz 2021a; Beaufils and Wenz 2021c) and two scientific software packages (Beaufils 2024; Beaufils 2023). The three last articles successively

build on this toolbox to explore the network effects of the EU CBAM and its potential consequences for climate cooperation.

While MRIOTs are built on historical data, the [first article](#) introduces the Scenario-based Projection of the International trade Network (SPIN) method that projects MRIOTs along economic scenarios to extend their availability to current and future states of the economy ([Beaufils and Wenz 2021d](#)). I evaluate this method by back-casting available MRIOT time series and simulating alternative recovery scenarios after the 2011 financial crisis.

MRIOTs are routinely used to disentangle the link between producers and consumers throughout the production network but usually overlook the role of intermediates. The [second article](#) develops the Throughflow Based Accounting (TBA) to overcome this shortcoming ([Beaufils, Berthet, et al. 2023](#)). Using the TBA framework, I evaluate the volume of carbon dioxide emissions associated with the supply chains starting from, traversing through and ending in Germany. My results show that one-third of the emissions associated with the German economy derive from its intermediate role in global value chains.

The [third article](#) directly builds on the TBA framework to evaluate the network effects of the EU CBAM ([Beaufils, Ward, et al. 2023](#)). I compare different implementation options of the EU CBAM and quantify the exposure of the EU trade partners. The results show vastly heterogeneous effects at the country level, with export-dependent developing countries being the most exposed to the EU CBAM. The [fourth article](#) extends this assessment by focusing on five African countries ([Beaufils, Gershon, and Jakob 2024](#)). I find diverse vulnerability patterns to the EU CBAM and discuss the introduction of a domestic carbon price on part or all emissions in these countries.

Building on the findings from the previous articles, the [fifth and last article](#) quantifies the potential of the EU CBAM to foster the formation of a climate coalition ([Beaufils, Wanner, and Wenz 2024](#)). Here, I develop a two-step modelling framework that endogenises the response of other countries to the EU CBAM. My results show the limited potential of the current EU CBAM for motivating climate policies abroad, but a more

ambitious implementation of the EU CBAM could trigger most countries to adopt carbon pricing.

Overall, my thesis illustrates a fundamental property of networks. While interdependencies hinder the agency of individual nodes, the action from a single node can propagate through the network and eventually shift the system state. For the climate coordination dilemma, interconnectedness challenges unilateral climate mitigation, but trade interdependencies can be instrumentalised to foster climate cooperation.

Zusammenfassung

Unsere Welt ist auf vielschichtige Weise miteinander vernetzt. In der Atmosphäre tragen die Treibhausgasemissionen eines jeden Landes zur Erwärmung des Planeten bei, die weltweit Schäden verursacht und die Aushandlung internationaler Abkommen erfordert. In Ökonomien verbinden internationale Lieferketten Verbraucher, Zwischenerzeuger und Produzenten weltweit und bilden ein komplexes Netz wirtschaftlicher Interaktionen. Diese gegenseitigen Abhängigkeiten stellen die Koordination zur Eindämmung des Klimawandels vor Herausforderung. Diese Handelsverflechtungen erschweren die Zuordnung der Verantwortung für Emissionen und ermöglichen es der Industrie, ihre Produktion zu verlagern, um sich der Klimapolitik zu entziehen. In beiden Dimensionen hemmen die Interdependenzen unilaterale Klimamaßnahmen und stellen ein Koordinationsdilemma zur Eindämmung des Klimawandels dar.

Im Oktober 2023 hat die Europäische Union (EU) ein europäisches CO₂ Grenzausgleichssystem (Carbon Border Adjustment Mechanism, CBAM) verabschiedet, das Importeure von Grundmaterialien verpflichtet, Emissionsrechte für die im Ausland verursachten Emissionen zu kaufen. Der EU-CBAM wird den EU-Kohlenstoffpreis implizit über den internationalen Handel verbreiten und könnte die Einführung von Klimapolitiken in anderen Ländern motivieren. In meiner Dissertation entwickle ich Methoden zur Modellierung des globalen Handelsnetzes und untersuche, wie der EU-CBAM die Klimakooperation durch die Instrumentalisierung von Handelsinterdependenzen fördern kann.

Meine Dissertation stützt sich auf multiregionale Input-Output-Tabellen (MRIOTs), die das globale Wirtschaftsnetzwerk darstellen. Die ersten bei-

den Artikel präsentieren methodische Beiträge zur Entwicklung und Analyse von MRIOTs und werden durch drei Datensätze (Beaufils und Wenz 2021b; Beaufils und Wenz 2021a; Beaufils und Wenz 2021c) und zwei wissenschaftliche Softwarepakete (Beaufils 2024; Beaufils 2023) ergänzt. Die drei letzten Artikel bauen auf diesem Instrumentarium auf, um die Netzwerkeffekte des EU-CBAM und ihre möglichen Folgen für die Klimakooperation zu untersuchen.

Während MRIOTs auf historischen Daten beruhen, stellt der **erste Artikel** die Methode der szenariobasierten Projektion des internationalen Handelsnetzes (SPIN) vor, die MRIOTs entlang wirtschaftlicher Szenarien projiziert, um ihre Verfügbarkeit auf aktuelle und zukünftige Zustände der Wirtschaft auszudehnen (Beaufils und Wenz 2021d). Ich bewerte diese Methode, indem ich verfügbare MRIOT-Zeitreihen zurückschreibe und alternative Konjunkturszenarien nach der Finanzkrise 2011 simuliere.

MRIOTs werden routinemäßig verwendet, um die Verbindung zwischen Erzeugern und Verbrauchern im gesamten Produktionsnetzwerk zu entflechten, übersehen aber in der Regel die Rolle der Zwischenerzeuger. Der **zweite Artikel** entwickelt die durchflussbasierte Bilanzierung (TBA), um diese Lücke der Forschung zu überwinden (Beaufils, Berthet u. a. 2023). Ich wende die TBA an, um das Volumen der mit den Lieferketten verbundenen Kohlenstoffdioxidemissionen zu bewerten, die von der deutschen Wirtschaft ausgehen, sie durchqueren und in ihr enden. Ich zeige, dass ein Drittel der mit der deutschen Wirtschaft verbundenen Emissionen auf ihre Rolle als Zwischenproduzent in globalen Wertschöpfungsketten zurückzuführen ist.

Der **dritte Artikel** baut direkt auf dem TBA-Konzept auf, um die Netzwerkeffekte des EU-CBAM zu bewerten (Beaufils, Ward u. a. 2023). Ich vergleiche verschiedene Umsetzungsoptionen des EU-CBAM und quantifiziere den Einfluss auf EU-Handelspartner. Im Ergebnis zeigen sich sehr heterogene Auswirkungen auf Länderebene, wobei exportabhängige Entwicklungsländer am stärksten vom EU-CBAM betroffen sind. Der **vierte Artikel** erweitert diese Bewertung, indem er sich auf fünf afrikanische Länder konzentriert. Ich identifiziere unterschiedliche Anfälligkeitsmuster für

den EU-CBAM und bewerte die Einführung eines nationalen Kohlenstoffpreises auf einen Teil oder alle Emissionen in diesen Ländern.

Aufbauend auf den Erkenntnissen aus den vorangegangenen Artikeln quantifiziert der **fünfte und letzte Artikel** das Potenzial der EU CBAM, die Bildung einer Klimakoalition zu motivieren (Beaufils, Wanner und Wenz 2024). Ich entwickle einen zweistufigen Modellierungsrahmen, der die Reaktion anderer Länder auf den EU-CBAM endogenisiert. Meine Ergebnisse verdeutlichen das begrenzte Potenzial des derzeitigen EU-CBAM, klimapolitische Maßnahmen im Ausland zu motivieren, aber eine ambitioniertere Ausgestaltung des EU-CBAM könnte jedoch die meisten Länder dazu bewegen, Kohlenstoffpreise einzuführen.

Insgesamt veranschaulicht meine Arbeit eine grundlegende Eigenschaft von Netzwerken. Während Interdependenzen die Handlungsfähigkeit einzelner Knoten einschränken, kann sich die Aktion eines einzelnen Knotens durch das Netzwerk ausbreiten und schließlich den Systemzustand verändern. Im Hinblick auf das Dilemma der Klimakoordinierung stellen diese Verflechtungen eine Herausforderung dar, können gleichzeitig jedoch auch zur Förderung der Klimakooperation instrumentalisiert werden.

“All models are wrong, but some are useful.”
Georges E. P. Box, 1987¹

¹(Box and Draper 1987)

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Introduction

I Mitigating climate change

The concentrations of Greenhouse Gases (GHG) in the atmosphere affect the radiative energy captured by the Earth System ([Arrhenius 1896](#)). Historical GHG emissions from human activities have already increased the Earth's average surface temperature by more than 1°C compared to the pre-industrial conditions ([NASA Global Climate Change 2024](#)). Such temperature increase modifies the climate system as a whole, including an increasing intensity and probability of extreme weather events (heatwaves, floods, droughts) and changes in local climate conditions ([IPCC 2021](#)). Mounting scientific evidence on the potentially catastrophic impacts of climate change on human societies and ecosystems stress the need for a massive and urgent decrease in GHG emissions ([IPCC 2022](#)).

In 2023, human activities released an estimated 35.8Gt of carbon dioxide (CO₂), the most common GHG, increasing by a small margin the record emissions from 2022 ([Liu et al. 2024](#)). Most carbon dioxide emissions (and most of the anthropogenic climate change) derive from the combustion of fossil fuels, formed over geological times by the degradation of organic matter underground ([Berner 2003](#)). In the last two centuries, the burning of fossil fuels supplied industrialised societies with cheap and abundant energy, shaping infrastructures, cultures and institutions ([Charbonnier 2020](#); [Fressoz 2024](#)). While the long-term benefits of limiting climate change largely outweigh the costs of climate action ([Kotz, Levermann, and Wenz](#)

2024), implementing climate policies raises challenges across multiple dimensions (IPCC 2023).

2 The dilemma of climate coordination

The atmosphere is a *global common*: it is shared by all countries and its degradation affects everyone around the globe. While reducing GHG emissions is costly, the benefits of climate mitigation are shared. Each country has thus an incentive to *free-ride*, i.e. to reap the benefits of the others' emissions reductions while keeping its own emissions unabated, eventually leading to a catastrophic climate change. This dilemma, sometimes called *tragedy of the commons* (Hardin 1968), can be overcome if countries build an institutional framework allowing collaboration (Ostrom 1999; Ostrom 2009; Edenhofer et al. 2015).

In 1992, the delegates of the United Nations (UN) member countries founded the United Nations Framework Convention on Climate Change (UNFCCC) to “*prevent dangerous anthropogenic interference with the climate system*” (UNFCCC 1992). In line with the UN founding principles (UN n.d.), the UNFCCC enshrines “*the sovereignty of States in international cooperation to address climate change*” (UNFCCC 1992). Countries set their abatement targets voluntarily (Nationally Determined Contributions) and decide unilaterally on how to reach them (UNFCCC 2015). The definition and achievement of global mitigation targets thus depend on each country's commitment, making each increment in global mitigation stringency the fruit of long and complex multilateral negotiations (Kuyper, Schroeder, and Linnér 2018).

The heterogeneity of climate targets and mitigation policies (Boehm et al. 2023) creates another dilemma. Around the world, industries compete within a complex network of economic interactions (Lenzen, Kanemoto, et al. 2012; Maluck and Donner 2015). If climate mitigation increases production costs, pollution-intense production might concentrate in the countries with the less ambitious climate policies, thereby undermining unilateral

climate policies (Copeland and Taylor 2004). Such risk of *carbon leakage* has been a major hurdle to implementing ambitious climate policies in the most committed countries (Jakob 2021; Grubb et al. 2022).

3 Contribution of this thesis

Coordinating the climate mitigation effort while accommodating heterogeneous mitigation paces is a pressing question for researchers and policy-makers. The dense interlinkage forming the global trade network is usually perceived as a constraint to climate policies. Instead, my thesis argues that *trade interdependencies can be instrumentalised to overcome the climate coordination dilemma*.

My dissertation relies on Multi-Regional Input-Output Tables (MRIOTs) and explores the plausible effects of the so-called EU Carbon Border Adjustment Mechanism (CBAM) for accelerating global climate mitigation. [Article 1](#) and [2](#) consist of methodological contributions for analysing and expanding MRIOTs and are complemented by a series of datasets (*Beaufils and Wenz 2021b*; *Beaufils and Wenz 2021a*; *Beaufils and Wenz 2021c*) and scientific software packages (*Beaufils 2023*; *Beaufils 2024*). Articles [3](#), [4](#) and [5](#) build on this toolbox to analyse the possible implications on the EU trade partners: [article 3](#) provides a global analysis and avenues to increase the international acceptability of the EU CBAM (*Beaufils, Ward, et al. 2023*); [article 4](#) focuses on African countries and highlight possible policy responses (*Beaufils, Gershon, and Jakob 2024*) and [article 5](#) quantitatively explores the potential of the EU CBAM for motivating climate policy adoption in other countries (*Beaufils, Wanner, and Wenz 2024*). [Figure 1](#) presents an overview of the thesis.

MRIOTs are representations of the global economy as weighted and directed networks of economic interactions (*Tukker and Dietzenbacher 2013*; *Mahajan et al. 2018*). These tables are built by compiling and harmonising national economic accounts from multiple countries in complex procedures (*Lenzen, Moran, et al. 2013*; *Geschke et al. 2019*). Because of limited

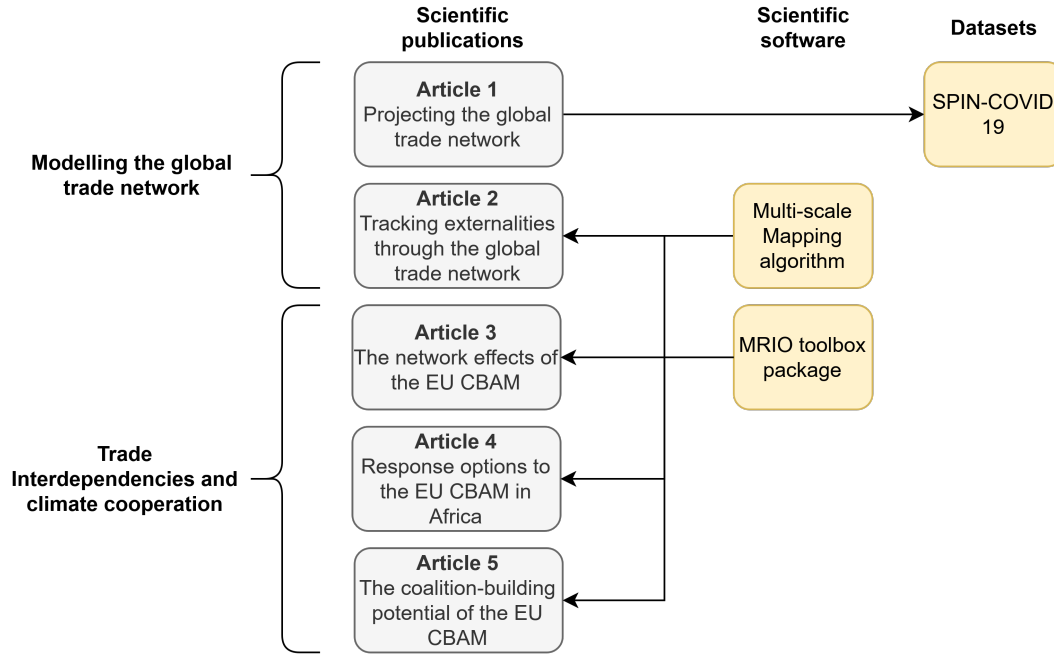


Figure 1: Overview of the thesis contribution. This thesis builds on five articles and contributes to an interdisciplinary corpus of scientific knowledge. **Article 1** develops a method for projecting the global trade network. **Article 2** introduces a framework to expand our understanding of the dilution of the responsibilities for emissions through international trade. Articles **3** and **4** explore the network impacts of a policy that the European Union is implementing, with a particular focus on developing countries. **Article 5** quantifies its potential for motivating the adoption of climate policies in other countries. Each article explores the role of interconnections in the global trade network. Together, the articles forming the dissertation explore how such interdependencies can be instrumentalised to overcome the climate coordination dilemma. The arrows indicate the relations between the thesis' articles and complementary scientific contributions.

data availability, MRIOTs are usually available with a few years' delay, such that existing tables might miss important developments in the global trade network. In the **first article** of the thesis, I introduce the Scenario-based Projection of the International trade Network (SPIN) method (*Beaufils and Wenz 2021d*) to partially overcome this challenge. The SPIN method combines well-established Input-Output techniques - namely the Leontief inverse (Leontief 1936) and a RAS-type balancing algorithm (Lahr and Mesnard 2004) - to project MRIOTs along simple macroeconomic trajectories. I evaluate the SPIN method by projecting historical MRIOTs (Lenzen, Moran, et al. 2013) along counterfactual scenarios of the world economy's development, showing that the SPIN method performs adequately for reproducing aggregate economic trends, at the cost of a limited precision at the coefficient level. In a supplementary dataset, I apply the SPIN method to illustrate alternative evolutions of the global economy (International Monetary Fund 2021) during the 2019 coronavirus pandemic (*Beaufils and Wenz 2021b*; *Beaufils and Wenz 2021a*; *Beaufils and Wenz 2021c*).

The **second article** focuses on the diffusion of responsibilities for externalities throughout the global trade network (*Beaufils, Berthet, et al. 2023*). GHG emissions occur at multiple stages of supply chains and MRIOTs are widely used to disentangle the allocation of social and environmental externalities within the global trade network (Minx et al. 2009; Wiedmann and Lenzen 2018; Wiedmann, Schandl, et al. 2015). Most of these assessments rely on so-called Production-Based (PBA) and Consumption-Based (CBA) Accounts (Peters 2008), focusing respectively on the agent producing externalities or on the downstream consumer at the end of the supply chain. Both frameworks overlook the role of intermediates. Here, I build on recent developments in the MRIO literature that re-interpret the so-called Hypothetical Extraction method (Hanaka, Kanemoto, and Kagawa 2022; Tokito, Kagawa, and Hanaka 2022) to introduce the Throughflow Based Accounting (TBA) framework. The TBA framework identifies the upstream externalities associated with all the supply chains starting from, traversing or ending in a given country. It encompasses both the PBA and CBA measures and extends them to measure the externalities associated

with imported products that eventually serve final consumption abroad. Using an MRIOT (Lenzen, Moran, et al. 2013) and GHG emission data for 2015 (Gütschow, Jeffery, and Günther 2021; Gütschow, Günther, Annika, et al. 2021), I apply this method to analyse the position of the German economy in the global trade network. I find that the TBA framework identifies one-third more emissions than the PBA and CBA approaches taken together, highlighting the role of Germany as a major economic hub in global supply chains.

The multiplication of intermediate agents in international supply chains raises questions about the allocation of responsibilities for emissions but simultaneously creates many entry points to enact mitigation policies (Tukker, Pollitt, and Henkemans 2020). Usual unilateral policies, such as carbon pricing, address the domestic emissions that are identified within the PBA framework. In the [third article](#), I discuss how the EU CBAM relates to the TBA framework (Beaufils, Ward, et al. 2023), based on an MRIOT (Lenzen, Moran, et al. 2013) and GHG data for 2016 (Gütschow, Jeffery, and Günther 2021; Gütschow, Günther, Annika, et al. 2021). The EU CBAM is a price adjustment on imports into the EU, based on the carbon emissions caused by these imports (EU 2023b). This article complements existing assessments of the EU CBAM (Böhringer, Fischer, et al. 2022; Zhong and Pei 2024) in three dimensions. First, I evaluate different implementation options for the EU CBAM and find that the current EU CBAM has limited coverage compared to the range of emissions caused by all the supply chains involving the EU. Second, most assessments of the EU CBAM have a scarce regional resolution, focusing on the EU main trade partners. In line with recent literature (Perdana and Vielle 2022; Zhong and Pei 2022), I perform the analysis of the article at a disaggregated spatial level and reveal that developing countries differ significantly in exposure to the EU CBAM, with some trade-dependent developing countries being the most affected. Third, I discuss the distributional burden that results from the EU CBAM and potential revenue recycling options to mitigate these impacts on the most vulnerable trade partners.

The **fourth article** expands the analysis of the EU CBAM with a focus on the exposure of African countries and their range of policy responses (*Beaufils, Gershon, and Jakob 2024*). Using an MRIOT (Aguilar et al. 2022) and emissions data for 2017 (Gütschow, Jeffery, and Günther 2021; Gütschow, Günther, Annika, et al. 2021), I analyse the vulnerability of five African countries based on alternative metrics and find that countries exhibit sensibly different exposure patterns. I then discuss how these countries could respond to the EU CBAM by introducing domestic carbon pricing measures. Under the EU CBAM, the price adjustment paid on imported products abounds to the EU budget, unless a carbon price is in place in the exporting country. Applying a carbon price on domestic or exported production would allow African countries to extract fiscal revenues that can help to cope with the social and economic challenges posed by the EU CBAM.

The responses of the EU trade partners to the EU CBAM are the core of the **fifth and last article** (*Beaufils, Wanner, and Wenz 2024*). The response mechanism discussed in the **third** and **fourth** articles provides a plausible avenue for the EU to motivate the adoption of climate policies in other countries. This proposition aligns with the *climate club* idea, in which a group of countries would voluntarily commit to adopting more stringent climate policies while imposing trade sanctions to non-compliant countries (Nordhaus 2015; Jakob et al. 2022; Tagliapietra and Wolff 2021). Here, I create and implement a two-stage modelling framework to evaluate whether the EU CBAM could provide a base for such a climate coalition. I combine a General Equilibrium (GE) model derived from Caliendo and Parro (2015) that is used for evaluating income and emission effects of climate policies, with an agent-based model simulating the building of a CBAM-based climate coalition. This article extends the existing literature (Böhringer, Carbone, and Rutherford 2016; Farrokhi and Lashkaripour 2023) by proposing a comparatively simpler model, which allows for modelling a wider set of policy options at a more disaggregated level. I calibrate the model using trade elasticities from the literature (Fontagné, Fouré, and Keck 2017), an MRIOT (Timmer et al. 2015; WIOD 2021) and emission data (Gütschow, Jeffery, and Günther 2021; Gütschow, Günther, Annika, et al. 2021) for

2017. In its current form, the EU CBAM motivates the adoption of more ambitious climate policies in Japan, Korea and Taiwan only. An EU CBAM with broader coverage could trigger the formation of a large climate coalition that would gather all countries except China, Russia and India.

As supplementary contributions, I implement two research software packages. First, I design the MRIO toolbox package for handling and manipulating MRIOTs in the Python programming language (*Beaufils 2024*). This package underlies the numerical analysis in articles 2, 3, 4 and 5. Second, using MRIOTs for analysing the relations between trade and externalities requires the extension of MRIOTs with so-called *satellite accounts* (Minx et al. 2009). Most MRIOT providers release satellite accounts for the most common externalities, but these extensions are often incoherent, insufficiently documented and a major source of divergence between MRIOTs (Moran and Wood 2014; Tukker, Wood, and Schmidt 2020). In the appendix to article 2, I introduce the Multi-Scale Mapping (MSM) algorithm to overcome this limitation (*Beaufils 2023*). The MSM method maps GHG emission data from harmonized GHG emission inventories (Gütschow, Jeffery, and Günther 2021; Gütschow, Günther, Annika, et al. 2021) with MRIOTs. The systemic use of the MSM method in articles 2, 3, 4 and 5 ensures consistent emission accounts across MRIOTs. Additionally, the MSM exploits the process-level information provided by the emission inventories, enabling differentiation between GHG emission sources beyond the usual MRIOT's sector level, as used in Articles 3, 4 and 5.

4 Overview of articles

My thesis builds on five distinct scientific publications: three published in peer-reviewed scientific journals, one under review for publication in a handbook and one in preparation for submission to a peer-reviewed journal. In each of these articles, I use established methods from different disciplines to build a coherent and transparent approach that contributes to extending an explicit set of scientific knowledge and techniques, thus forming a standalone contribution to the scientific literature. I present here a brief overview of each article and clarify my scientific contribution. **The next section** contains the full original manuscripts, each comprising an introduction, a method description, a result analysis and references.

ARTICLE I

A scenario-based method for projecting multi-regional input–output tables

T. Beaufigli, L. Wenz

A method to project MRIOTs along illustrative macroeconomic trajectories.

Leonie Wenz proposed the research idea. I implemented the method, conducted the analysis, prepared the figures and wrote the manuscript with contributions in each step from Leonie Wenz. All authors contributed to the development of the method, the performance assessment, the development of the illustrative study cases and the editing of the manuscript.

This article was awarded the 2023 Richard Stone’s award for the best article in Economic Systems Research.

This article has been published in *Economic Systems Research* (2021),

<https://doi.org/10.1080/09535314.2021.1952404>.

ARTICLE 2

**Beyond production and consumption:
using throughflows to untangle the virtual trade of externalities**

T. Beaufils, E. Berthet, H. Ward, L. Wenz

A method to decompose the externalities associated with the supply chains starting from, traversing or ending in a country.

All authors contributed equally to the development of the research idea, to the interpretation of the results and the editing of the manuscript. I developed the method with contributions from Hauke Ward and Leonie Wenz. I conducted the data preparation and numerical computations. I led the preparation of the figures and the writing of the manuscripts with contributions from all authors.

This article has been published in *Economic Systems Research* (2023),
<https://doi.org/10.1080/09535314.2023.2174003>.

ARTICLE 3

**Assessing different European Carbon Border Adjustment
implementations and their impacts on trade partners**

T. Beaufils, H. Ward, M. Jakob, L. Wenz

An analysis of different EU CBAM designs, their impact on trade partners and options to mitigate their distributional effects.

Hauke Ward proposed to apply the TBA framework to analyse the EU CBAM. All authors contributed equally to designing the study, interpreting the results and editing the manuscript. I collected and processed data, prepared the figures and wrote the manuscript with contributions from all authors.

This article has been published in *Nature Communications Earth & Environment* (2023),
<https://doi.org/10.1038/s43247-023-00788-4>.

ARTICLE 4

The EU Carbon Border Adjustment Mechanism as an incentive for carbon pricing in African countries

T. Beaufils, O. Gershon, M. Jakob

An analysis of the exposure of African countries to the EU CBAM and an assessment of possible policy responses.

All authors contributed equally to designing the study, interpreting the results and writing the manuscript. I implemented the methods, collected and processed data and prepared the figures with contributions from all authors.

This article has been accepted for publication in *The Palgrave Handbook of Carbon Trading in Africa*.

ARTICLE 5

The potential of carbon border adjustments to foster climate cooperation

T. Beaufils, J. Wanner, L. Wenz

An analysis of the efficiency and the coalition-building potential of the EU CBAM under different implementation options.

All authors contributed equally to designing the study, interpreting the results and editing the manuscript. Joschka Wanner and I developed the model and collected data, with contributions from Leonie Wenz. I implemented the model and processed data with contributions from Joschka Wanner. I prepared the figures and led the writing of the manuscript with contributions from all authors.

This article is in preparation for submission in

Journal of the Association of Environmental and Resource Economists.

Articles

Projecting the global trade network

1

This article has been published in *Economic Systems Research* as:

A scenario-based method for projecting multi-regional
input–output tables

T. Beaufils and L. Wenz (2021).

DOI: [10.1080/09535314.2021.1952404](https://doi.org/10.1080/09535314.2021.1952404)

ABSTRACT: Multi-regional input–output (MRIO) data are a powerful tool to analyze complex interdependencies in the international trade and supply network. Their field of application is however limited by the fact that MRIO datasets are only available for past years whereas the structure of the international trade network has been found to change profoundly over time. We here propose the SPIN method, a simple and flexible algorithm that can project MRIO tables into the future based on transparent scenarios of how gross domestic product and trade relations may evolve in that time. By combining well-established input–output techniques, namely the Leontief quantity model and an RAS-type algorithm, our method provides a straightforward mean to convert quantitative scenarios of the world economy into consistent MRIO tables. We illustrate the functioning of the SPIN method by projecting the evolution of the trade network after the 2008 financial crisis under different alternative scenarios of recovery.



A scenario-based method for projecting multi-regional input–output tables

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ABSTRACT

Multi-regional input–output (MRIO) data are a powerful tool to analyze complex interdependencies in the international trade and supply network. Their field of application is however limited by the fact that MRIO datasets are only available for past years whereas the structure of the international trade network has been found to change profoundly over time. We here propose the SPIN method, a simple and flexible algorithm that can project MRIO tables into the future based on transparent scenarios of how gross domestic product and trade relations may evolve in that time. By combining well-established input–output techniques, namely the Leontief quantity model and an RAS-type algorithm, our method provides a straightforward mean to convert quantitative scenarios of the world economy into consistent MRIO tables. We illustrate the functioning of the SPIN method by projecting the evolution of the trade network after the 2008 financial crisis under different alternative scenarios of recovery.

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Multi-regional input–output tables; global trade network; updating techniques; Leontief model; RAS algorithm

1. Introduction

The past 50 years have marked the globalization of the trade of goods and services. From 27% in 1970, the equivalent of almost 60% of the world gross domestic product (GDP) is now traded globally each year (World Bank, 2020). The fragmentation of production processes such that many different intermediary producers are involved has formed a densely interwoven trade and supply network that spans around the world. On one hand, economic integration can increase the efficiency of production at world scale (Winters, 2004), fuel the development of emerging countries (Brenton et al., 2015; Dollar & Kraay, 2004) and increase food security (Kornher & Kalkuhl, 2019). On the other hand, the internationalization of supply chains blurs the responsibilities for social and environmental externalities (Wiedmann & Lenzen, 2018) and may cause shortages when trade relations are disrupted, as occurred in the early stages of the Covid-19 pandemic (Beetz et al., 2020; Gereffi, 2020;

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Inaba et al., 2020; Tucker et al., 2020). The dependence on distant suppliers and export markets can render producers and countries vulnerable to shocks in other parts of the world (Kashiwagi et al., 2018; Wenz & Levermann, 2016; Willner et al., 2018). Economic shocks induced by natural, biological or man-made disasters can propagate along supply chains, thereby spreading and amplifying the initial damage. For example, the 2011 great floods in Thailand caused a long-term surge in global hard disk prices which lasted for several months (Haraguchi & Lall, 2015). Due to climate change, future supply chain disruptions from extreme weather events are likely to happen more often and at larger scale (Levermann, 2014). Consequently, a solid understanding of the global trade network and how it may likely evolve in the short- to medium-term is crucial for improving our societies' resilience and shaping international trade relations in a sustainable way.

Input–output (IO) tables depict the financial transactions between different sectors of a country, thereby providing insights into the tightly interwoven network of sectoral dependencies that form our modern economies (see (Miller & Blair, 2009) for a comprehensive introduction to IO tables). During the past two decades, several data sets linking multiple national IO tables into one coherent accounting framework have been developed, such as GTAP (Aguiar et al., 2016), EORA (Lenzen et al., 2012, 2013) and WIOD (Timmer et al., 2015). These so-called Multi-regional input–output (MRIO) databases allow the tracking of supply chains across sectors and countries and can be used as representation of the global trade network (Wiedmann et al., 2011). For example, MRIOs have been used to analyze critical trade and supply dependencies in the global food network (Bren d'Amour et al., 2016), to investigate the effect of the diffusion of technologies on carbon dioxide emissions (Ward et al., 2017) or to simulate the international propagation of external shocks along supply chains (Kashiwagi et al., 2018; Wenz & Levermann, 2016). Since many MRIO databases include environmental extensions, one broad field of application is global sustainability assessments that aim to allocate the responsibilities for social or environmental externalities such as greenhouse gas emissions (Wiedmann, 2009) or material resources use (Wiedmann et al., 2015).

The development of MRIOs is a complex task that requires dealing with inconsistent and incomplete data. Global MRIO products are therefore usually only available with a time lag of up to 5–10 years (Lenzen et al., 2012). However, the structure of the global trade network might change significantly over the course of just a few years (Maluck & Donner, 2015; Wenz & Levermann, 2016), which influences the phenomena listed above. The past five years alone have seen the United Kingdom leave the European Union, a trade conflict between the US and China and the Covid19 pandemic that has led to an abrupt contraction of the volume of goods traded internationally (World Trade Organization, 2020). These events will influence the evolution of the global trade network and shape its future structure. Assessments of the climate vulnerability or sustainability of the global trade network based on data that are at least five years old might hence lead to results that are outdated in the sense that they do no account for recent trends in the economy.

The evolution of the global economy is driven by numerous factors such as technological change, policy choices and exogenous shocks (e.g. pandemics, natural disasters). Naturally, it is impossible to predict the evolution of all these drivers and to project MRIO tables accordingly. However, a scenario-based approach that consistently projects MRIO tables based on transparent and empirically or theoretically well-grounded assumptions is possible and can yield valuable insights. We here propose such a method for simple scenario-based projections: the Scenario-based projection of the international trade

network (SPIN) method. The SPIN method combines the Leontief inverse (Leontief, 1936) and an RAS-type algorithm (Temurshoev et al., 2013), both of which are well-established and applied frequently in the literature, including in combination (Khan, 1993; Temursho et al., 2020; Valderas-Jaramillo et al., 2019).

Various approaches for updating and projecting MRIO data (see (Wiebe et al., 2018) for a comprehensive overview of existing approaches) have proven valuable for exploring the future based on diverse assumptions and economic foundations specific to their respective research contexts. An RAS-type algorithm permits updating a given IO table from one year to the next in accordance with available information for that next year (Bacharach, 1970). It has been widely extended in past years (Mahajan et al., 2018, pp. 475–504), also with regard to the handling of trade constraints (Temursho et al., 2020) and can provide baseline data for IO-based models. Trade gravity models (Distefano et al., 2019) and econometric approaches (Wang et al., 2015) can be used as alternatives to the RAS-type algorithm to forecast MRIO tables. The World Trade Model (Duchin, 2005; Duchin et al., 2016) exploits comparative advantage theory and has been applied to investigate the future of resource use (Springer & Duchin, 2014) and waste production (Duchin, 2019; Lin & Nakamura, 2019). Technology-focused models address the economy-wide effects of technological change (De Koning et al., 2016; Ward et al., 2017; Wiebe et al., 2018). Economically integrated models explore long-term trends in the global economy using elements from econometrics, endogenous growth theory and computable general equilibrium (CGE) techniques (Distelkamp & Meyer, 2019; Fontagne & Fouré, 2013; Jorgenson, 1982; Kratena et al., 2013; Los, 2001; Mercure et al., 2018; Rey, 2005).

Existing projection methods as outlined above rely on the exploitation of extensive input data (e.g. factor endowments, production elasticities), allowing for a precise but complex parametrization of the projections. Our method complements existing approaches by offering a straightforward and simple mean to project MRIO tables into the future from a network perspective without requiring expert knowledge. The projection procedure is based on a few inputs reflecting how GDP and trade relations may evolve. These inputs can be set at different levels of detail. Scenario-based investigations are made possible as different tables for the same year can be transparently projected, each reflecting a different scenario of how these economic key figures might change in the future. Tables projected with the SPIN method can be used to assess the properties of the global trade network under diverse trade evolution assumptions, for instance with respect to the propagation of economic damages along supply chains. As an example, we test and demonstrate the application of the method by use of – partly hypothetical – scenarios of how international trade relations could have evolved between 2009 and 2015.

This paper is organized as follow. The second section introduces the SPIN method. In the third section, we assess the performance of the method by projecting the evolution of the trade network after the 2008 financial crisis for alternative scenarios of recovery. First, we reproduce MRIO tables up to 2015 based on the observed evolution of GDP and trade relations, using either national or regionally aggregated constraints. Second, we provide projections for two hypothetical scenarios of recovery for international trade after the financial crisis. In the first scenario, overall international trade is homogeneously scaled up or down by 25%. The second alternative scenario assumes that trade between major emerging countries and the rest of the world does not recover from the financial crisis. We conclude by discussing possible limitations and avenues for future research in the fourth section.

2. Materials and methods

The SPIN method projects a recent MRIO table into the future in accordance with pre-defined scenarios of how GDP and aggregated trade relations will evolve during that time. It relies on a combination of the Leontief quantity model (Leontief, 1936) and an RAS-type algorithm (Junius & Oosterhaven, 2003; Lenzen et al., 2007; Temurshoev et al., 2013), each being central to one of the two main steps of the method (see Figure 1 for a schematic overview). In the first step, projections for local GDP and assumptions about international trade relations are used to define constraints on sectoral inputs and outputs. These constraints ensure that the projected table will be in line with the prescribed macroeconomic trajectories while conserving the balance between outputs and inputs of each sector. In the second step, a balancing procedure is applied that updates the base MRIO table such that the constraints are met while at the same time preserving the main properties of an MRIO table. This then creates a new table. The whole procedure can be applied iteratively to produce a time series of projected tables by using the table previously estimated as a base table for the forthcoming year. The method is therefore suitable to produce either a projection for a specific year (e.g. a table for 2015 based on a 2009 table), or a time series (e.g. all years from 2010 to 2015 based on the 2009 table).

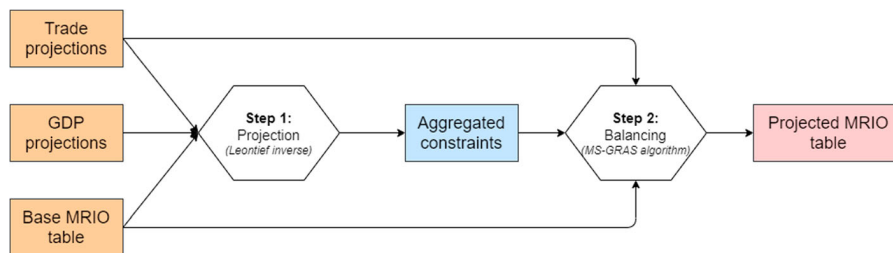
2.1. Notation and fundamental relations

As a general convention, we denote matrices with bold capital letters, arrays with bold lowercases and scalars with italic lowercases. An overview of all variable names and other notation used in the text is given in Table S1 of the Supplementary Materials.

2.1.1. Basic notation and conventions

Let $\mathbf{Z}$ be the MRIO base table to be projected into the future, describing the economic transactions (in USD/year) between m sectors in n regions. The diagonal blocks $((\mathbf{Z}_{rr})_{r \in [1, n]})$ describe the inter industry flows within each region whereas the non-diagonal blocks $((\mathbf{Z}_{rs})_{(r, s) \in [1, n]^2, r \neq s})$ contain information on the trade flows between different regions. More

Figure 1. Overview of the SPIN method.



Note: The SPIN method projects an MRIO table under prescribed trajectories of GDP and trade relations based on an existing MRIO table for an earlier year (inputs of the method; left-hand rectangles). It consists of two successive steps, namely the projection step and the balancing step (polygons, with intermediate outputs shown in the middle rectangle). The output is a projected MRIO table that can be used as a base table for a further iteration (right-hand rectangle).

generally, an element $z_{ir \rightarrow js}$ of $\mathbf{Z}$, denotes the economic flow from sector i in region r to sector j in region s . Each sector produces a unique commodity, assumed perfectly substitutable with another commodity from the same sector of another region. Under this assumption, we identify each sector i with the production of commodity i . MRIO tables also comprise information on final demand, i.e. the amount of each final commodity that is produced in a region and consumed in any other, typically distinguishing between private consumption, government consumption, investment, changes in stocks and inventories. Changes in stocks and inventories may correspond to short-term fluctuations, which are beyond the scope of the SPIN method, and tend to be zero over the medium to long term (ECB, 2003). For the sake of simplicity and to avoid negative coefficients in final demand, changes in stocks and inventories are hence assumed to be zero in both the base and projected tables.¹ The other contributions to final demand for commodities produced by sector i in region s and used in region r are aggregated into a single final demand scalar of positive value: $y_{is \rightarrow r}$. Each column $\mathbf{c}_r$ of the final demand matrix contains the final uses in region r , named domestic demand hereafter. Elements of $\mathbf{c}_r$ may either have been domestically produced ($\mathbf{y}_{rr}$), or imported from abroad ($(\mathbf{y}_{sr})_{s \neq r}$).

Similarly, MRIO tables comprise information on the allocation of value added (sometimes referred to as primary inputs) between sectors in each region. Value added is usually decomposed into wages, net taxes and subsidies, net consumption of capital and profits. In the basic setting of the method, we aggregate all contributions to value added associated with sector i in region r into a single scalar v_{ir} . Accordingly, we obtain a value-added array $\mathbf{v}$. The gross output $\mathbf{x}$ is then the total output of each sector and equals the total input:

$$\mathbf{x} = \mathbf{Z} \cdot \mathbf{e} + \mathbf{Y} \cdot \mathbf{e} = \mathbf{e}' \mathbf{Z} + \mathbf{v}, \quad (1)$$

where $\mathbf{e}$ is the row-wise sum operator, i.e. an array of ones, and $(\cdot)'$ is the transposition operator.

2.1.2. Trade notations

The MRIO framework distinguishes between trade in final commodities (commodities that are consumed in the destination region), and trade in intermediate commodities (commodities that are integrated in further production processes). Following our notation, trade in intermediate goods from region r to region s (or conversely imports of intermediate goods of region s that stem from region r) are depicted in the inter industry matrix:

$$t_{rs}^{in} = \sum_{i,j} z_{ir \rightarrow js}. \quad (2)$$

The exports ex_r^{in} and the imports im_r^{in} of intermediate commodities from/to region r are thus:

$$ex_r^{in} = \sum_{\substack{s \\ r \neq s}} t_{rs} \quad (3)$$

¹ An alternative solution consists in accounting for positive changes in stocks and inventories from the demand side (i.e. as part of final demand), and negative changes in stocks and inventories from the supply side (i.e. handled along with value added). This alternative could be implemented as described in Supplementary Materials S3.1.

and

$$im_r^{in} = \sum_{\substack{s \\ r \neq s}} t_{sr}. \quad (4)$$

Similarly, exports ex_r^{fi} and imports im_r^{fi} of final commodities are defined in relation to the coefficients of the final demand matrix:

$$ex_r^{fi} = \sum_{\substack{s, i \\ r \neq s}} y_{ir \rightarrow s} \quad (5)$$

and

$$im_r^{fi} = \sum_{\substack{s, j \\ r \neq s}} y_{js \rightarrow r}. \quad (6)$$

Straightforwardly, total exports/imports from/to region r are given by the sum of intermediate and final exports/imports:

$$ex_r = ex_r^{in} + ex_r^{fi}; \quad (7)$$

$$im_r = im_r^{in} + im_r^{fi}. \quad (8)$$

Trade between region r and region s can also be expressed in terms of trade balance δ and trade intensity λ . These parameters are linked to the respective trade flows from region r to region s (t_{rs}) and vice-versa (t_{sr}) by the following equations:

$$\begin{cases} \delta_{rs} = t_{rs} - t_{sr} \\ \lambda_{rs} = t_{rs} + t_{sr} \end{cases}. \quad (9)$$

2.1.3. Trade zones

We base the MRIO projection, inter alia, on assumptions about how trade relations may likely evolve in the future. The definition of trade inputs is highly flexible. Trade assumptions can be made at the level of countries but also on a more aggregated level for bigger trade zones such as the European Union. Many trade agreements, for instance, are negotiated between trade zones rather than countries (Maluck et al., 2018). In the SPIN method, trade relations are hence constrained with regard to aggregated trade zones, which can contain one or several regions.² The use of trade zones renders the method more flexible: the SPIN method can be applied to a wide variety of spatial scales, depending on the disaggregation of the inputs available. For instance, it is possible to consider the world as a single trade zone. In that case, trade relations of every country only need to be prescribed with regard to the rest of the world. Reciprocally, it is possible to consider each region

² Regions themselves can comprise several countries. For the sake of simplicity, we restrict the description of the method to regions corresponding to single countries. The case of regions composed of multiple countries is covered in section S3.2 in the Supplementary Materials.

as a different trade zone, and hence to prescribe trade between each pair of regions (see Section 3.1).

Trade from region r to trade zone $L = \{r_1, \dots, r_{n_L}\}$ composed of regions $r_1, \dots, r_{n_L}$ is straightforwardly defined as the sum of the trade flows from region r to each region of L :

$$t_{rL} = \sum_{\substack{s \in L \\ r \neq s}} t_{rs}. \quad (10)$$

Exports and imports in both intermediate and final commodities and trade balance and intensity definitions introduced at regional scale (Section 2.1.2) remain valid between regions and trade zones.

2.1.4. Relation to common macroeconomic aggregates

The SPIN method relies on the correspondences between an MRIO table and common macroeconomic aggregates. Annual GDP is typically defined either as the gross value added generated within some geographic boundaries within a year in basic prices, plus taxes less subsidies on products (income measure) or as the total amount of consumption and capital formation during that time, i.e. domestic final demand, plus exports and minus imports (expenditure measure) (United Nations et al., 2009, p. 332). In our framework, we account for taxes and subsidies on products as part of value added. Therefore, for region r , the income measure straightforwardly links GDP to value added (see Wenz et al., 2014 for a more detailed identification of GDP in the MRIO framework):

$$gdp_r = v_r. \quad (11)$$

On the expenditure side, GDP equals domestic use of final goods and services (c_r), plus the total trade balance δ_r , i.e. is the difference between all exports and all imports:

$$gdp_r = c_r + \delta_r. \quad (12)$$

This equation describes a straightforward relation between explicit inputs to the method, i.e. GDP and trade balance, and domestic demand. Since changes in stocks and inventories are not included in our formulation (Section 2.1.1), the volume of domestic demand c_r is necessarily positive:

$$c_r = gdp_r - \delta_r \geq 0. \quad (13)$$

This imposes as a direct consequence that trade balance cannot exceed GDP in our framework:

$$gdp_r \geq \delta_r. \quad (14)$$

In other words, a region cannot export more than it produces. The supply to an economy (imports plus value added) is necessarily larger (or equal) to its exports:

$$gdp_r + im_r \geq ex_r. \quad (15)$$

The limit case of exports equalizing primary supply (imports plus value added) implies that consumption of domestically produced final commodities is null. This corresponds to the unlikely situation of a region importing all its final consumption and exporting all its domestic production.

2.2. Method inputs

In the basic setting, the SPIN method requires three main inputs: a balanced MRIO table, a time series of trade relations for each region with regard to every trade zone and a time series of regional GDP values.³ All three inputs must be prescribed in the same monetary unit as the base matrix and it is possible to use either current or constant prices. Concerning the time dimension, trade and GDP inputs must be prescribed for each year to be projected. International trade relations time series can be expressed either in terms of exports and imports, or in terms of trade balance and trade intensity as defined in Equation 9. In order to be consistent with each other, GDP and trade relations inputs must comply two simple accounting rules. First, as detailed in Equation 14, exports from a region must be smaller than the inputs supplied to the same region, i.e. exports should not exceed the sum of GDP of imports. Second, a corollary of our definition of trade intensity and trade balance (Equation 9) is that the trade balance between two trade partners is necessarily lower in absolute value than the corresponding trade intensity. In terms of absolute trade flows, this is equivalent to saying that trade flows can only have positive values.

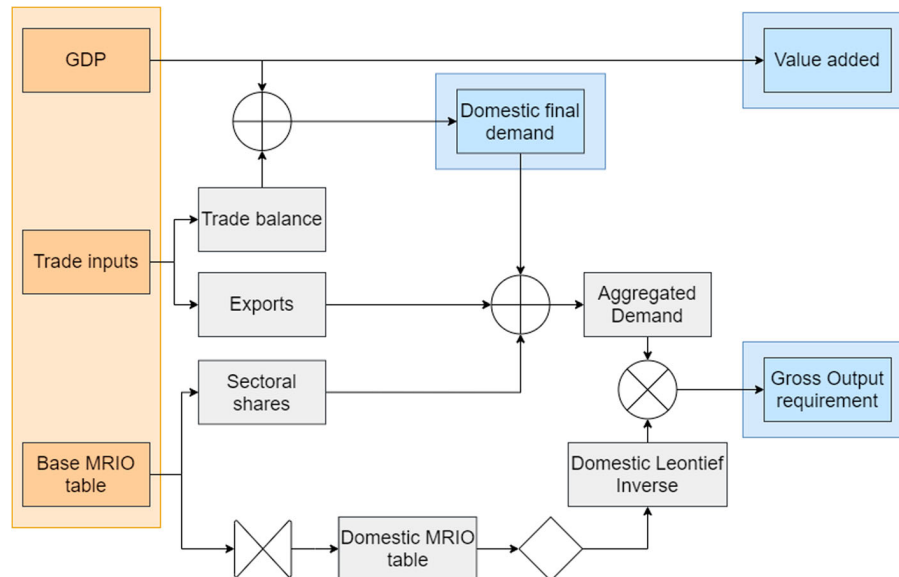
MRIO tables can be valued following different price concepts (Mahajan et al., 2018, pp. 181–209). The base MRIO table used as input to the SPIN method should be expressed in basic prices, i.e. excluding taxes, subsidies and trade and transport margins from the inter industry matrix. Similarly, trade constraints should be expressed in basic prices excluding transportation, assurances and duties costs (*Free on Board* valuation). Indeed, basic prices reflect production costs best, which is consistent with the use of the Leontief quantity model and in line with the recommendation of (Mahajan et al., 2018). In order to ensure the validity of Equation 11 and to ensure balance between inputs and outputs in the base MRIO table, net taxes and subsidies on products are handled along with value added.⁴ This convention also holds for the projected tables. Finally, the basic setting of the SPIN method preserves null elements from the base table through the projections, hence obstructing the creation of new connections during the projection process. This property can be overridden by setting very small values instead of null coefficients in the base table.⁵

A set of additional parameters can also be prescribed, such as the composition of regions and trade zones. Without any specification from the user, regions and trade zones are identified with each country represented in the base MRIO table. The user can also specify estimations for sectoral shares in domestic final demand (ϕ , Equation 17, Section 2.3) and in exports (θ , Equation 18, *id.*) and share of final commodities in imports (α , Equation 18, *id.*). In absence of any specification, these parameters are endogenously derived from the base table.

³ GDP can also be constrained at sub-regional scale, e.g. to distinguish between different countries within a region. This alternative is treated in section S3.2 of Supplementary Materials.

⁴ Note that the SPIN method is sign conservative: negative elements in the base table will remain negative in the projected tables, which may be an unrealistic assumption for long term projections. Section S3.1 in Supplementary Materials proposes an alternative setting for enhancing the flexibility of the method with regard to negatives.

⁵ The creation of new connections is not subjected to any explicit constraint in the SPIN method. These new connections may hence be technologically or technically implausible. However, since the balancing algorithm minimizes the cross-entropy between the base and the final table (Lenzen et al., 2007), pre-existing trade connections are more likely to keep being predominant in the projected matrix, even if null coefficients are transformed into small positive values. The structurally conservative properties of the SPIN method are assessed in Section 3.1. Additionally, the SPIN method relies on a variant of the RAS algorithm, that may not converge if the base matrix is too sparse (Miller & Blair, 2009, pp. 335–336). In that situation, setting very small values to null coefficients guarantees the convergence of the balancing procedure.

Figure 2. Projection step of the SPIN method.

Note: The projection step is applied to each region. From the base MRIO table, the domestic inter industry matrix is extracted to compute the domestic Leontief inverse. Combining GDP and trade projections yields the projected volume of domestic demand for each region. GDP constraints directly prescribe the availability of value added. Domestic demand and exports are allocated between domestic sectors using the sectoral shares endogenously derived from the base MRIO table. They are then summed up to the aggregated demand array. The Leontief model converts the aggregated demand into sectoral gross output for the projected table. Boxes in the left panel refer to the inputs of the SPIN method, standard boxes denote intermediate outputs that are successively computed and circled boxes the outputs of the projection step. Double triangle operator denotes that the variable is directly extracted from its predecessor whereas the diamond represents the computation of the Leontief inverse. Pluses in circles are summation operators and tilted crosses in circles are matrix multiplication operators.

2.3. Projection step

In the first step of the SPIN method, gross production of each regional sector of the projected table is computed based on the demand volumes of both domestic consumers and trade partners. That is, the so-called projection step builds on the macroeconomic relations exposed in Section 2.1.4 to derive, for each region, sectoral demand volumes from GDP and trade inputs. These demand estimations are then translated into gross production requirements using the Leontief inverse (Leontief, 1936). The thus derived gross production volumes then constitute the constraints of the subsequent balancing step. Figure 2 summarizes the operations of the projection step that are detailed in the following paragraphs.

2.3.1. Derivation of aggregated demand

For each region, a preliminary estimation of demand for commodities in the projected table is computed using the macro-economic relations embodied in Equation 12 and the prescribed exports volumes. Since Equation 12 and prescribed exports only entail scalar

values, the following procedure is applied to derive demand for each sector from the available information. The projected aggregated demand array for region r , $\mathbf{ad}_r$ is derived as an estimation of the demand for commodities produced by sectors of region r either to be consumed in the same region (domestic demand of locally produced final commodities, $\mathbf{y}_{rr}$) or to be exported to trade partners (exports to all trade zones, $\mathbf{ex}_r$):

$$\mathbf{ad}_r = \mathbf{y}_{rr} + \mathbf{ex}_r. \quad (16)$$

The three terms of this equation are arrays of dimensions (m), with m being the number of sectors per region. Each coefficient ad_{ri} corresponds to the estimated volume of commodities that sector i in region r will furnish to domestic final users and to its international trade partners in the projected table. Note that indirect demand stemming from local producers is not included here.

The export term of Equation 16 corresponds in volume to the sum of exports from region r to every trade zone, as prescribed in input of the method. The sectoral allocation of exports to each trade zone K is given by the array θ_{rK} , which contains the market shares of the sectors of r in exports to trade zone K . The array θ_{rK} is endogenously derived from the base table, assuming that the sectoral shares of exports will remain similar to the sectoral shares observed in the base table.⁶ This is a reasonable assumption given that the array θ_{rK} is simply a preliminary estimation of the export structure in the projected table: these shares will further be adjusted during the balancing process with regard to the balance between supply and demand. Using the endogenous sectoral shares in exports, the export array for region r becomes:

$$\mathbf{ex}_r = \sum_K \theta_{rK}^* ex_{rK}, \quad (17)$$

where the $*$ superscript indicates that data are extracted from the base table.

The derivation of final demand for locally produced commodities follows a similar reasoning. The volume of domestic final demand is related to GDP and trade balance by Equation 12. The domestic consumption term of the aggregated demand array only concerns consumption of domestically produced commodities. Imported final commodities are hence excluded from this quantity:

$$\mathbf{y}_{rr} = \boldsymbol{\varphi}_r^* \cdot \left(gdp_r - \delta_r - \alpha_r^* \sum_s im_{rs} \right), \quad (18)$$

where α_r^* is the share of final commodities in imports to region r and the array $\boldsymbol{\varphi}_r^*$ represents the relative market shares of domestic sectors in the domestic final demand of region r . As for the sectoral shares in exports θ_{rK}^* , the share of final commodities in imports α_r^* and the sectoral shares in domestic final demand $\boldsymbol{\varphi}_r^*$ are endogenously derived from the base table.⁷ Again, these shares only represent preliminary estimations of the final demand composition in the projected table. These estimated shares are further adjusted during the

⁶ Unless the sectoral allocation of exports is exogenously prescribed.

⁷ Again, shares of final commodities in imports and sectoral allocation of domestic final demand can also be exogenously prescribed.

balancing procedure. Inserting Equations 17, 18 into Equation 16, the projected aggregated demand for sectors of region r is finally:

$$\mathbf{ad}_r = \boldsymbol{\varphi}_r^* \cdot \left(gdp_r - \delta_r - \alpha_r^* \sum_s im_{rs} \right) + \sum_K \boldsymbol{\theta}_{rK}^* ex_{rK}. \quad (19)$$

2.3.2. Application of the Leontief inverse

The regional production array is then deducted from the aggregated demand array and the technological structure, using the Leontief quantity model (Leontief, 1936). The Leontief inverse makes explicit the direct and indirect dependencies interlinking the sectors forming the inter industry network (Miller & Blair, 2009, pp. 10–41). The Leontief inverse is generally used to obtain the sectoral production volumes required to fulfill a given demand for commodities, under the assumption of constant technologies. In our approach, both regional final demand and regional trade relations are derived exogenously from the inputs of the method. Hence, we apply the Leontief quantity model at regional scale. For each region r , we define the domestic Leontief inverse $\mathbf{L}_r$ from the domestic inter industry matrix $\mathbf{Z}_{rr}$ of the base table:

$$\mathbf{L}_r^* = (\mathbf{I} - \mathbf{Z}_{rr}^* \cdot (\hat{\mathbf{x}}_r^*)^{-1})^{-1}, \quad (20)$$

where $\mathbf{I}$ is an identity matrix of consistent dimensions and $\wedge$ represents the diagonalization operator. In each region, the exogenous demand previously estimated is represented by the array of aggregated demand $\mathbf{ad}_r$. Hence, the sectoral production array $\mathbf{x}_r$ required to fulfill the estimated demand in the projected table is:

$$\mathbf{x}_r = \mathbf{L}_r^* \cdot \mathbf{ad}_r. \quad (21)$$

In each region, the sectoral production array $\mathbf{x}_r$ represents how much each sector in region r has to produce such that demand derived from the method inputs is met, using the technologies of the base table. Analogously to the assumptions of sectoral compositions of exports and domestic demand, the assumption of constant technologies only holds for the first step of the method. The input coefficients driving the input mix of each sector are further adjusted during the second step of the procedure.

2.4. Balancing step

In the second step, the balancing step, the base MRIO table is adjusted such that regions meet the output volume $\mathbf{x}_r$ defined during the projection step, while ensuring the equilibrium between inputs and outputs and the consistence with regard to GDP and trade constraints. This operation is achieved by adjusting the technological structure and the sectoral allocation of trade, final demand and value added while minimizing the overall changes with regard to the base table. This operation is resolved using a tailored RAS-type algorithm, referred to as Multi-Scale GRAS (MS-GRAS) algorithm hereafter. The MS-GRAS balances the MRIO table in two successive sub-steps. First, regional economies are adjusted with regard to aggregated trade and GDP constraints using a GRAS algorithm (Junius & Oosterhaven, 2003; Lenzen et al., 2007; Temurshoev et al., 2013). Second, international trade flows are reconciled at the scale of trade zones, using the sectoral export and import constraints previously detailed at regional scale.

Figure 3. Simple example MRIO table to describe the balancing step of the SPIN method.

	Trade zone	K		L		Final demand			
Trade zone	Region	r_1	r_2	s_1	s_2	r_1	r_2	s_1	s_2
K	r_1	$Z_{r_1 r_1}^*$	$Z_{r_1 r_2}^*$	Z_{KL}^*		$Y_{r_1 r_1}^*$	$Y_{r_1 r_2}^*$	Y_{KL}^*	
	r_2	$Z_{r_2 r_1}^*$	$Z_{r_2 r_2}^*$			$Y_{r_2 r_1}^*$	$Y_{r_2 r_2}^*$		
L	s_1	Z_{LK}^*		$Z_{s_1 s_1}^*$	$Z_{s_1 s_2}^*$	Y_{LK}^*		$Y_{s_1 s_1}^*$	$Y_{s_1 s_2}^*$
	s_2			$Z_{s_2 s_1}^*$	$Z_{s_2 s_2}^*$			$Y_{s_2 s_1}^*$	$Y_{s_2 s_2}^*$
Value added		$v_{r_1}^*$	$v_{r_2}^*$	$v_{s_1}^*$	$v_{s_2}^*$				

Note: Simple example table displays four regions (r_1, r_2, s_1, s_2) that are grouped in two trade zones (**K** and **L**). The MS-GRAS algorithm (second step of the SPIN method) balances the table in two sub steps. First, the domestic inter industry matrices ($Z_{r_i r_j}^*$ and $Z_{s_i s_j}^*$; on the diagonal) are balanced. Then, international trade blocks are adjusted consistently. The latter consists of both, trade block within a trade zone (i.e. $Z_{r_i r_j}^*$ and $Z_{s_i s_j}^*$ for $i \neq j$) and trade blocks between trade zones (i.e. the anti-diagonal blocks Z_{KL}^* and Z_{LK}^*). Elements of the final demand matrix (Y^* ; upper right quadrant) are combined with the corresponding matrices of the inter industry table Z^* (marked with the same shade) for the balancing step (see Figures 4 and 5). Regional value added arrays ($v_{r_i}^*$ and $v_{s_j}^*$; bottom left quadrant) are subjected to balancing together with the inter industry matrices $Z_{r_i r_i}^*$ and $Z_{s_j s_j}^*$ (see Figure 4). The sectoral composition of the regional economies is not shown in this simplified MRIO.

Figures 3–5 illustrate the main principles of our algorithm by means of a simple MRIO table consisting of two trade zones K and L , comprising two regions each, r_1, r_2 , and s_1, s_2 . This simplified example table is pictured in Figure 3.

2.4.1. Sub-step 1: domestic balancing

During the first sub-step of the balancing step, regional economies are separately balanced, in coherence with both GDP and trade constraints and with the production volumes derived in the projection step. Domestic blocks are formed by aggregating different elements from the base MRIO table:

- The inter industry matrix Z_{rr}^* for region r
- A vertical array of exports ex_{rK}^* for each trade zone K , where an element ex_{irK}^* denotes the total volume of exports from sector i in r to regions of trade zone K .
- A horizontal array of intermediate imports im_{rK}^{*in} from each trade zone K , where an element im_{irK}^{*in} denotes the total volume of intermediate imports from regions of trade zone K to sector i in region r . Note that final demand imports are not included in this array, but rather in the domestic final demand array.
- The value-added array v_r^* , corresponding to the primary inputs, i.e. value-added, associated with each domestic sector in region r .
- A final demand array, corresponding to domestic final demand c_r^* , where demand for locally produced commodities is detailed at sector scale and imported commodities are aggregated by trade zone.

Figure 4. Example of a domestic IO table to describe sub-step 1 of the MS-GRAS algorithm.

Regions	r	Exports to trade zone K	Exports to trade zone L	Final demand	Row-wise constraints
r	Z_{rr}^*	$\mathbf{ex}_{rK}^* = \mathbf{Z}_{rK}^* \cdot \mathbf{e} + \mathbf{Y}_{rK}^* \cdot \mathbf{e}$	$\mathbf{ex}_{rL}^* = \mathbf{Z}_{rL}^* \cdot \mathbf{e} + \mathbf{Y}_{rL}^* \cdot \mathbf{e}$	$\mathbf{y}_{rr}^*$	$\mathbf{x}_r$
Imports from trade zone K	$\mathbf{im}_{rK}^{*in} = \mathbf{e}' \cdot \mathbf{Z}_{Kr}^*$	0	0	$\mathbf{im}_{rK}^{*fi} = \mathbf{e}' \cdot \mathbf{Y}_{Kr}^*$	$\mathbf{im}_{rK}$
Imports from trade zone L	$\mathbf{im}_{rL}^{*in} = \mathbf{e}' \cdot \mathbf{Z}_{Lr}^*$	0	0	$\mathbf{im}_{rL}^{*fi} = \mathbf{e}' \cdot \mathbf{Y}_{Lr}^*$	$\mathbf{im}_{rL}$
Value Added	$\mathbf{v}_{r1}^*$	0	0	0	$\mathbf{gdp}_r$
Column-wise constraints	$\mathbf{x}_r'$	$\mathbf{ex}_{rK}$	$\mathbf{ex}_{rL}$	$\mathbf{c}_r = \mathbf{gdp}_r - \delta_r$	

Note: The first sub-step of the MS-GRAS algorithm subjects the domestic table of each region to a GRAS algorithm. The row and column totals (upper right and bottom left quadrant) that the balanced table should meet correspond to outcomes of the first step of the SPIN method (projection step, see Section 2.3). The example domestic table (upper left quadrant) is built for each region from the base MRIO table (here for region r in trade zone K). Shadings in the domestic table correspond to respective elements of the example MRIO table (Figure 3). Zeros represent null matrices of matching dimension. Trade relations involving region r are extracted as arrays from the base MRIO table. Export arrays from region r to each trade zone ($\mathbf{ex}_{rK}^*$ and $\mathbf{ex}_{rL}^*$) include both intermediate exports (from $\mathbf{Z}_{rK}^*$ and $\mathbf{Z}_{rL}^*$) and exports to final consumers ($\mathbf{Y}_{rK}^*$ and $\mathbf{Y}_{rL}^*$). Imports to region r are accounted for separately depending on whether they are to be further processed (intermediate imports, $\mathbf{im}_{rK}^{*in}$ and $\mathbf{im}_{rL}^{*in}$) or used by final consumers (final imports, $\mathbf{im}_{rK}^{*fi}$ and $\mathbf{im}_{rL}^{*fi}$).

Figure 5. Example of an international trade block to describe sub-step 2 of the MS-GRAS algorithm.

Importing zone		L				Exports constraints
Type of commodities		Intermediate commodities		Final commodities		
Exporting Zone	Region	s_1	s_2	s_1	s_2	
K	r_1	$\mathbf{Z}_{r_1 s_1}^*$	$\mathbf{Z}_{r_1 s_2}^*$	$\mathbf{y}_{r_1 s_1}^*$	$\mathbf{y}_{r_1 s_2}^*$	$\mathbf{ex}_{r_1 L}$
	r_2	$\mathbf{Z}_{r_2 s_1}^*$	$\mathbf{Z}_{r_2 s_2}^*$	$\mathbf{y}_{r_2 s_1}^*$	$\mathbf{y}_{r_2 s_2}^*$	$\mathbf{ex}_{r_2 L}$
Imports constraints		$\mathbf{im}_{s_1 K}^{in}$	$\mathbf{im}_{s_2 K}^{in}$	$\mathbf{im}_{s_1 K}^{fi}$	$\mathbf{im}_{s_2 K}^{fi}$	

Note: During sub-step 2 of the MS-GRAS algorithm, each international trade matrix (see Figure 3) is balanced, using a basic RAS algorithm. The constraints on sectoral imports and exports are deduced from the domestic IO tables balanced in sub-step 1 (section 2.4.1, Figure 4). The resulting international blocks are therefore consistent with both the domestic IO tables balanced in sub-step 1 and with the original constraints on GDP and trade relations. For the balancing of international trade flows from zone K to zone K (intra-zone trade blocks), intra-regional blocks are not included in the international trade block. Diagonal blocks corresponding to the domestic matrices of the regions in K are replaced by null matrices (e.g. $\mathbf{Z}_{r_1 r_1}^*$ and $\mathbf{Z}_{r_2 r_2}^*$ would be null matrices in the trade block from zone K to zone K).

An example domestic table is presented in Figure 4, based on the table introduced in Figure 3.

The constraints that the row and column sums (margins) of the updated matrix should meet are deduced from the projection step (Section 2.3):

- The domestic inter industry table's margins should meet the gross production requirement $\mathbf{x}_r$.
- Export arrays to each trade zone should equal the volume of exports to the corresponding trade zone as prescribed in input.
- Import arrays plus imported final demand sum up to the volume of imports from the corresponding trade zone.
- Total value added and domestic final demand are linked to GDP and trade balance in accordance with Equations 11 and 12.

By means of the GRAS algorithm (Junius & Oosterhaven, 2003; Lenzen et al., 2007; Temurshoev et al., 2013), the domestic block is balanced with respect to these constraints. The basic RAS algorithm balances a matrix in order to meet pre-defined row-wise and column-wise constraints, adjusting iteratively the rows and the columns of the matrix until the maximal difference between the constraints and the margins of the updated matrix reaches a pre-defined threshold (Bacharach, 1970). The GRAS algorithm extends the basic RAS algorithm by permitting the handling of negative coefficients such as subsidies included in the value-added array. Similarly to the RAS algorithm, the GRAS algorithm minimizes the information loss between the base and the projected table under constraints on rows and columns totals, ensuring that the solution is as close as possible to the base table (Lenzen et al., 2007).

The first sub-step of the MS-GRAS procedure yields the regional inter industry blocks $\mathbf{Z}_{rr}$, the value-added array $\mathbf{v}_r$ and the final demand array of locally produced commodities $\mathbf{y}_{rr}$. The resulting exports and imports array are further used as intermediate constraints for the second sub-step of the procedure.

2.4.2. Sub-step 2: balancing of the international trade blocks

The second sub-step of the MS-GRAS algorithm successively adjusts the international trade blocks with respect to the exports and imports array obtained at regional scale during the first sub-step. The trade block from zone K to zone L is formed by aggregating the trade blocks from each region of K to each region of L (excluding intra-regional blocks for intra-zone trade blocks). Using regional imports and exports constraints determined in sub-step 1, each international trade block is optimized using the basic RAS algorithm.⁸ Trade flows between regions of the same trade zone (i.e. from zone K to zone K) are also adjusted during the second sub-step. However, intra-zone trade blocks do not include intra-regional blocks, since economic flows within a region are not considered as international trade flows.

By reconciling successively imports to each trade zone with exports from each other trade zone, the second sub-step of the balancing algorithm produces international trade blocks consistent with the domestic MRIO table of both the importing and exporting

⁸ The basic RAS algorithm is sufficient for the resolution of this operation because trade blocks do not contain any negative coefficient. The application of the GRAS algorithm would yield the exact same result but would require more computational resources than the simpler RAS algorithm.

zones. By combining the domestic blocks from the first sub-step with the international trade blocks adjusted during the second sub-step, a new MRIO table is obtained. This new table is balanced and consistent with the GDP and trade constraints initially prescribed. The projected table can further be used as a base table for another projection cycle.

3. Performance of the SPIN method

In this section, we exemplify the performance of the SPIN method by producing different sets of MRIO tables for the years 2010–2015 in accordance with different, partly hypothetical scenarios of how trade and GDP evolved during that time. The 2010–2015 period corresponds to the aftermath of the 2008 financial crisis and has been marked by the reinforcement of the importance of emerging countries on the international trade network (Gawande et al., 2015). In the first subsection, we use the SPIN method to produce reference tables for 2015 based on the observed evolution of the world economy, with GDP and trade constraints being defined either at national or regionally aggregated scale. In the second subsection, we use the same GDP constraints but assume different scenarios of evolution for international trade. We project the corresponding MRIO tables for 2015. In the first alternative scenario, we hypothesize that trade between all countries was increased/decreased by 25% compared to the observed baseline. For the second scenario, we use GDP and trade constraints at regional scale and hypothesize a stagnation of trade relations between five emerging countries and the rest of the world after 2009. Each projection is based on the 2009 EORA table (Lenzen et al., 2012, 2013), representing 183 countries with 26 sectors each (See Section S3.3 for more details). The tables are projected iteratively for each year from 2010 to 2015, with a convergence threshold set at 0.01% of relative error for the GRAS algorithm.

3.1. Reference scenario: projection of MRIO tables between 2010 and 2015 based on observed changes in trade relations and GDP

We here aim at evaluating the overall performance of the SPIN method, i.e. at demonstrating that the projected MRIO tables reproduce the overall evolution of the world economy during the projection period. Furthermore, the SPIN algorithm is applied with four different settings, corresponding to different aggregation levels of the required inputs (see Table 1). In all four settings, all input data are directly derived from the observed changes in the Eora table between 2010 and 2015. Setting A is the most stringent: GDP is constrained at national scale, and bilateral trade relations are prescribed between each pair of countries. The three other settings involve largely aggregated economic zones. In this section, the first economic zone corresponds to the five BRICS countries, namely Brazil, Russia, India, China and South Africa. The second economic zone aggregates all other countries in a *rest of the world* region. In setting B, GDP is prescribed at national scale and trade constraints are imposed for each country with regard to the two aggregated economic zones. For instance, German exports for a given year are prescribed as *exports to BRICS countries* and *exports to the rest of the world*. In opposition to setting A, the allocation of German exports between BRICS countries is endogenous in setting B. In setting C, the two economic zones are considered as unified aggregated regions (see Section S3.2). GDP is still constrained at the national level but trade constraints are only defined between the two

Table 1. Description of the different settings used for assessing the algorithm's performances, corresponding to different aggregation levels of the required inputs.

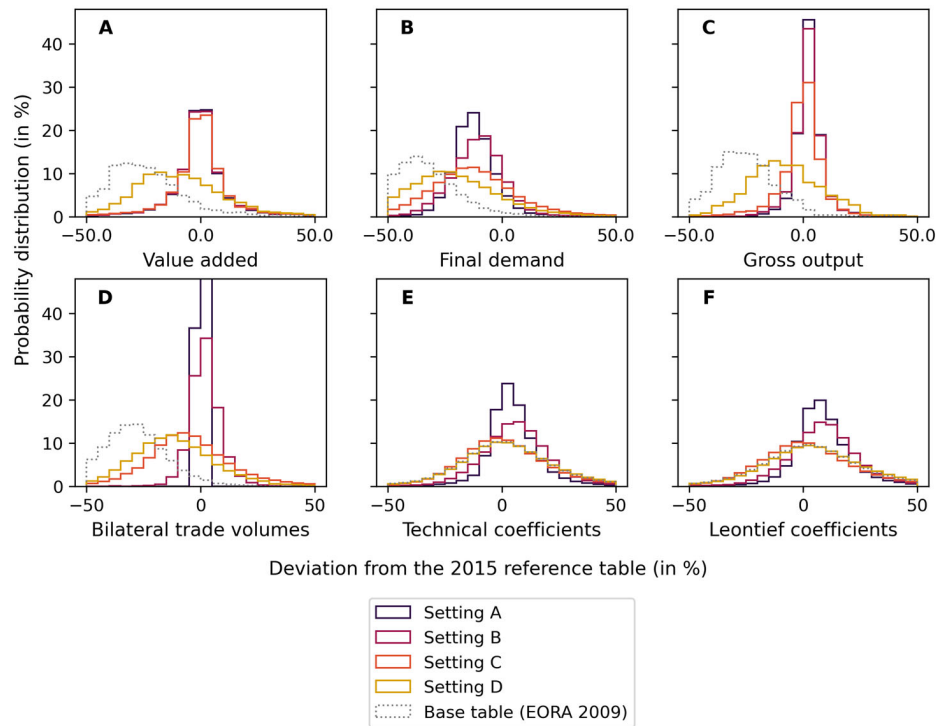
Setting	GDP constraints	Trade relations		No. of GDP + trade inputs for each projection year
		From	To	
A	National	Countries	Countries	$c + (c - 1)^2$
B	National	Countries	Economic zones	$c + 2 * c * z$
C	National	Economic zones	Economic zones	$c + (z - 1)^2$
D	Economic zones	Economic zones	Economic zones	$z + (z - 1)^2$

Note: Setting A constrains GDP and bilateral trade relations at the national scale. Setting B constrains GDP at the national scale and bilateral trade relations are prescribed between every country and each economic zone. In setting C, GDP is also constrained at the national scale, but trade relations are only imposed between economic zones. In setting D, both GDP and trade constraints are applied at the scale of economic zones. The fifth column denotes how many inputs are required for each setting with c representing the number of countries and z the number of aggregated economic zones. The reference scenario of Section 3.1 distinguishes between two economic zones: BRICS countries and the rest of the world.

large economic zones, i.e. from BRICS countries to the rest of the world and from the rest of the world to BRICS countries. Finally, setting D is the loosest constrained setting. Here, both GDP and trade constraints are defined at the regionally aggregated level, i.e. at the level of the two economic zones. The four settings are ordered by decreasing constraint stringency, hence by decreasing input requirements. For each year, setting A requires GDP data for every country, plus trade volumes for each and every pair of countries. Setting B requires less trade inputs, since exports and imports are only required at the country-economic zone levels. Setting C requires even less inputs because trade volumes have only to be described between the economic zones. Finally, setting D requires only four data points for each year, since GDP and trade are only defined at the scale of the two large economic zones.

Figure 6 compares the tables projected for 2015 using the different settings to actual EORA table for that year (referred to as EORA 2015 from hereon) based on different MRIO characteristics. Panels A-C show the volume of value added, final demand and gross output per sector and per country in the projected tables as compared to the EORA table. Panel D compares the volume of bilateral trade flows between every pair of country in the projected tables to the corresponding values in the EORA table. These four MRIO characteristics are directly related to inputs of the method (GDP and trade volumes) and largely reflect quantitative changes in the world economy. Together, they reflect how volume trends are captured in the SPIN projections (*quantitative* indicators). Panel E compares technical coefficients (or input coefficients), corresponding each to the relative share of an input in the production function of a given sector in a given country. Panel F depicts coefficients of the Leontief inverse matrix (see Section 2.2), representing each the direct and indirect dependency of a sector in a country to an input, in relative terms. Panels E-F both picture normalized coefficient that highlight interlinkages in the MRIO tables. Unlike characteristics observed in panels A-D, technical and Leontief coefficients are not sensitive to the volume growth of the world economy: they reflect how changes in the structure of the global economic network are captured by the SPIN method (*structural* indicators). Figure 6 also depicts the characteristics of the base table (referred to as EORA 2009 from hereon). Hence, it is possible to assess whether the projected tables are a more accurate representation of the 2015 trade network than the base table, i.e. whether the projections are *better than assuming persistence*.

Figure 6. Performance of the SPIN method when constrained by inputs at varying degrees of granularity.



Note: Relative deviation of the projected tables for 2015 from the EORA 2015 table, for different MRIO characteristics (panels A-F). Each line corresponds to a different set of input constraints (see Table 1), with A being the most constraining setting where all inputs are defined at the country-level and D the less stringent setting where GDP and trade are only constrained between BRICS region and the rest of the world. The dotted line represents the deviation of the EORA 2009 table, i.e. the base table for every projection, from the EORA 2015 table. A null deviation means that the (projected) value equals the respective value in the EORA 2015 table. A positive or negative deviation corresponds to a parameter overestimated or underestimated in the projections, respectively. Panels A and B figure absolute coefficients in value added and final demand, respectively. Panel C represents the deviation in terms of sectoral gross output, i.e. of the total production of each sector, whether it is to be further processed or consumed by final users. Panel D compares the volumes traded between each pair of countries. Panel E represents the technical coefficients, i.e. the coefficients of the normalized input matrix **A**. Panel F represents the distribution of the coefficients of the Leontief inverse **L**.

The accuracy of the tables projected with the SPIN method is highly dependent on the scale at which inputs are prescribed: more detailed constraints are associated with a more accurate reproduction of the 2015 table. When both trade and GDP constraints are applied at the regional scale, growth in macroeconomic inputs is only partially reflected in the allocation of value added, final demand, gross output and trade flows (setting D, panels A-D). This is partly attributable to heterogeneity in growth rates within economic zones, in particular since in our setting, the *rest of the world* zone gathers countries with very diverse economic characteristics (see Figure S1). Detailing GDP at the national scale (setting C) permits improving the accuracy of the projections slightly with regard to these quantitative

indicators (panels A-D). With GDP and trade inputs being defined at the national scale, the SPIN method produces an estimated table very similar to the reference table on all quantitative aspects (setting A, panels A-D, Figure S2). The definition of the trade constraints with regard only to large aggregated zones (setting B, as opposed to defining trade relations between every pair of countries – setting A) triggers a very limited loss of accuracy for the projected table. The regionalization of the trade constraints hence appears as a reasonable simplification to reduce the number of inputs substantially while conserving the quantitative accuracy of the method. Independent of the specific setting used, using our projected tables based on few inputs is superior to assuming persistence, i.e. using an older table. The characteristics of the projected tables are closer to the reference 2015 table than the base table. Overall, the SPIN method succeeds in reproducing the quantitative trends observed in the historical timeseries.

On structural aspects (Panels E-F), the application of the SPIN algorithm at the national scale (settings A-B) appears considerably more reflective of the changes actually observed in the time period than the application at the regional scale (settings C-D). The simplification of trade constraints (setting B) reduces slightly the structural accuracy of the projected tables compared to the most stringent setting (setting A). The definition of national GDP constraints within large economic regions (setting C) provides no significant improvement compared to the setting where GDP constraints are defined at the regional scale (setting D). However, even with constraints applied at the most detailed scale (setting A), the structural changes of the trade network are not fully reflected in the projected tables: the SPIN method globally conserves the structural properties of the base table.

3.2. Hypothetical scenarios: alternative evolution for the international trade network after the 2008 financial crisis

In this section, we apply the SPIN method to two hypothetical scenarios for the evolution of international trade between 2009 and 2015. These two scenarios differ not only with respect to the assumed evolution of international trade during that time but also regarding the level of aggregation of the inputs used for the projection (i.e. the setting as described in Table 1). The first scenario hypothesizes a homogeneous increase/decrease by 25% of the volume traded internationally in the course of the financial crisis. Tables are projected from 2010 to 2015 using setting B (compare Table 1). GDP is prescribed for each country as observed in the EORA timeseries from 2010 to 2015. Trade relations between each country and the rest of the world are increased by 25% compared to their observed values in that year (according to the respective EORA table), or decreased by 25%.⁹ The second scenario explores the differences induced by a hypothetical stagnation of trade between the BRICS countries and the rest of the world from 2009 to 2015. The corresponding set of tables from 2010 to 2015 is projected using the SPIN method with setting D from Table 1. That is, all inputs are prescribed at the scale of largely aggregated economic zones: the BRICS countries and the rest of the world. For each zone, we prescribe aggregated GDP at the level observed in the EORA timeseries from 2010 to 2015. As to trade, we assume that aggregated trade relations between the BRICS countries and the rest of the world stay at the level observed

⁹ Unlike for the reference scenario in Section 3.1, trade inputs for scenario #1 (and the respective reference scenario) do not distinguish exports and imports with regard to two economic zones (BRICS countries and rest of the world) but rather considers global exports and imports for each country.

in the EORA 2009 table for each year from 2010 to 2015. Both projection scenarios are based on the EORA 2009 table. The projected tables for both scenarios are compared to projected tables where trade relations correspond to observed changes in trade from 2010 to 2015 and produced using the same settings, respectively.

The aim of this section is twofold. First, we illustrate with two simple scenarios how the SPIN method can be used to generate consistent MRIO tables in line with alternative scenarios involving homogeneous (scenario #1) or heterogeneous (scenario #2) changes in international trade relations. Second, we analyze the projected tables and investigate how the SPIN method projects individual countries to be affected by changes in international trade relations depending on the scale at which inputs are prescribed.

3.2.1. Hypothetical scenario #1: change of $\pm 25\%$ in overall trade volume after the 2008 financial crisis

Figure 7 shows how national gross output in the projected 2015 tables for scenario #1 differs from that in the 2015 reference table where the projection is driven by the actually observed changes in trade. In every country, an increase in trade relations is associated with an increase in national gross output. Symmetrically, decreasing trade relations reduce gross output by the same value. While this overall pattern can be observed in all countries, the magnitude of the effect varies. For instance, large differences in gross output can be observed in many European countries whereas they are less pronounced in most Southern American countries.

The extent to which modifications in trade relations translate into differences in gross output is determined by each country's trade dependence. Figure 8 shows that the susceptibility of gross output of a country to a change in trade intensity is directly related to the share of intermediate imports in GDP (panel A), but less strongly to the share of final imports in GDP (panel B) and to the share of exports in GDP (Panel C). As trade balance is defined as the difference between exports and imports, negative trade balances are associated with larger differences in gross output than positive trade balances (Panel D). A similar pattern can be observed at sectoral scale. Here, an increase or decrease in trade relations compared to the reference table also leads to larger differences in gross output when that sector imports a large share of its inputs. However, this correlation is less robust at the sectoral scale, presumably because of differences in how sectors are interrelated (Figure S3).

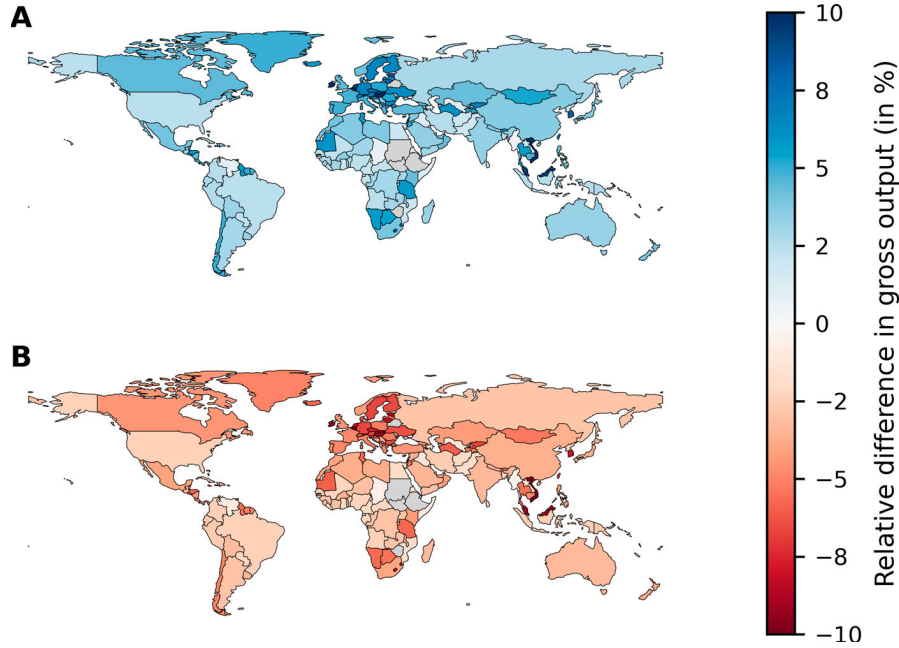
The fact that import dependence has a stronger influence on a country's susceptibility to changes in trade intensity can be explained by analyzing the contributions of exports and intermediate imports to gross output. In the MRIO framework, gross output equals gross input. We can decompose the gross output volume x_r in country r from the input side as

$$x_r = d_r + im_r^{in} + v_r; \quad (22)$$

where d_r denotes the intermediate commodities traded within the same country. The input constraints on national GDP in the hypothetical scenarios are the same as in the reference scenario. As a consequence, national value added v_r is the same in all three tables. Therefore, the difference in national gross output between the reference table and the two hypothetical tables, Δx_r can be written as

$$\Delta x_r = \Delta d_r + \Delta im_r^{in}. \quad (23)$$

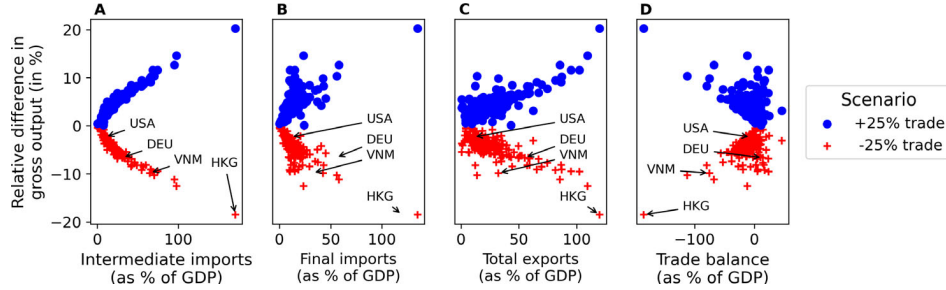
Figure 7. Difference in national gross output as induced by a hypothetical 25% change in trade volume compared to a scenario where trade evolves as observed.



Note: Shading of countries shows the percentage difference in national gross output for a scenario of a 25% increase (Panel A) or 25% decrease (Panel B) in exports and imports volume of each country from 2010 to 2015, compared to a reference table where trade during that period evolves as observed. The base MRIO table corresponds to 2009 data; projections are made for 2015 either following the actual evolution of trade (reference table) or a hypothetical evolution of $\pm 25\%$ compared to that reference. For each country and each scenario, trade relations to the rest of the world are constrained and GDP is imposed at the national scale, following the growth rates observed in the EORA baseline (Setting B, Table 1). Tables referring to 2015 are compared to each other. Gross output denotes the total output of all sectors in a country, encompassing both, commodities that are further processed (intermediate commodities) and commodities that are consumed (final commodities). The effect of an overall decrease in trade is symmetrical to that of an overall increase. An increase in trade (Panel A) increases gross output whereas it is reduced by a decrease (Panel B). The magnitude of this difference however varies significantly across countries.

This equation shows that observed differences in national gross output are driven by changes in the volume of intermediate commodities traded within a country (Δd_r) and by changes in the volume of imported intermediate commodities (Δim_r^{in}). Whereas the first term is adjusted endogenously by the algorithm, the latter is determined by the enforced $\pm 25\%$ change compared to the observed import volume, per scenario definition. Abstracting from d_r , a $\pm 25\%$ change in imports has hence a smaller effect on x_r in countries where im_r^{in} is small compared to x_r . This effect is likely to dominate over that of endogenous changes in d_r as can be seen when analyzing the production functions in the different tables: for most sectors, the modification of the production functions is mainly driven by a substitution between primary inputs and imported inputs, rather than by changes in the domestic matrix (Figure S4).

Figure 8. Difference in gross national output induced by a $\pm 25\%$ change in trade volume is strongest for import-dependent countries.



Note: Ordinates of the three panels indicate the difference in national gross output for each country compared to the reference table where trade between 2010 and 2015 is assumed to evolve as observed in the EORA baseline. Abscissa denotes intermediate imports (panel A), final imports (panel B), exports (panel C) and trade balance (panel D) as share of national GDP as observed in the baseline table for 2015. Dots and crosses refer to hypothetical scenarios of a 25% increase/decrease in trade during that period compared to the reference evolution, respectively. Annotations show the position of different countries by example of United States of America (USA), Germany (DEU), Vietnam (VNM) and Hong-Kong (HKG). Changes in national gross output are highly correlated with the importance of intermediate imports in GDP (Panel A).

It is also possible to decompose gross output from the output side:

$$x_r = d_r + ex_r + y_{rr}, \quad (24)$$

where y_{rr} is the volume of final commodities produced domestically and consumed domestically. Contrary to value added, final demand for commodities domestically produced in the hypothetical tables does not necessarily correspond to that in the reference table: domestic final demand is composed of the contribution of both GDP, trade balance and imports of final commodities (Equation 18). The first is identical in the three tables, but the second and the third vary proportionally to the assumed change in trade relations. Hence, from the output side, differences in gross output are a composition of changes in domestic inter industry relations (Δd_r), exports (Δex_r), imports of final commodities (Δim_r^f) and trade balance ($\Delta \delta_r$):

$$\Delta x_r = \Delta d_r + \Delta ex_r - \Delta im_r^f - \Delta \delta_r. \quad (25)$$

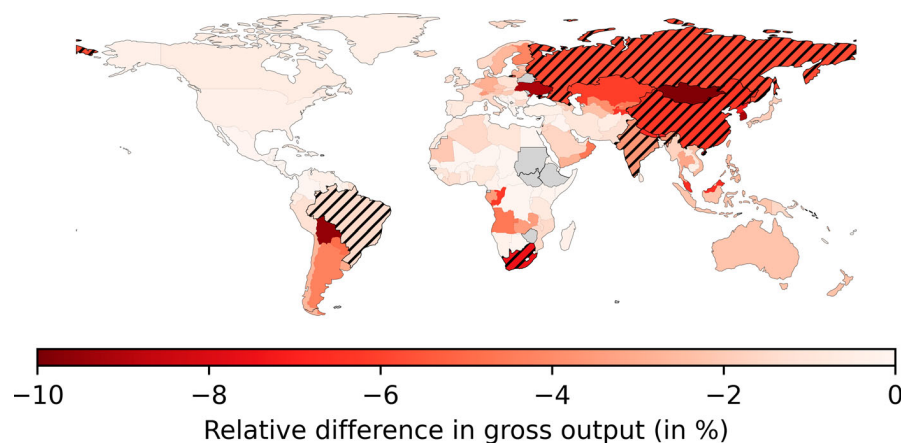
This equation highlights, from the output side, a competition between the effect caused by changes in exports (Δex_r), in imports of final commodities (Δim_r^f) and in trade balance ($\Delta \delta_r$).¹⁰ That competition effect explains why import dependence is the most direct driver of the differences in gross output caused by a modification of international trade relations when algorithm constraints are aggregated according to setting B.

3.2.2. Hypothetical scenario #2: no recovery of trade relations between the BRICS countries and rest of the world after 2008 financial crisis

Figure 9 compares gross output by country in 2015 for scenario #2 to a reference table, corresponding to the table projected in Section 3.1 where GDP and trade constraints

¹⁰ The difference in the domestic term (Δd_r) is the same here as for the supply side.

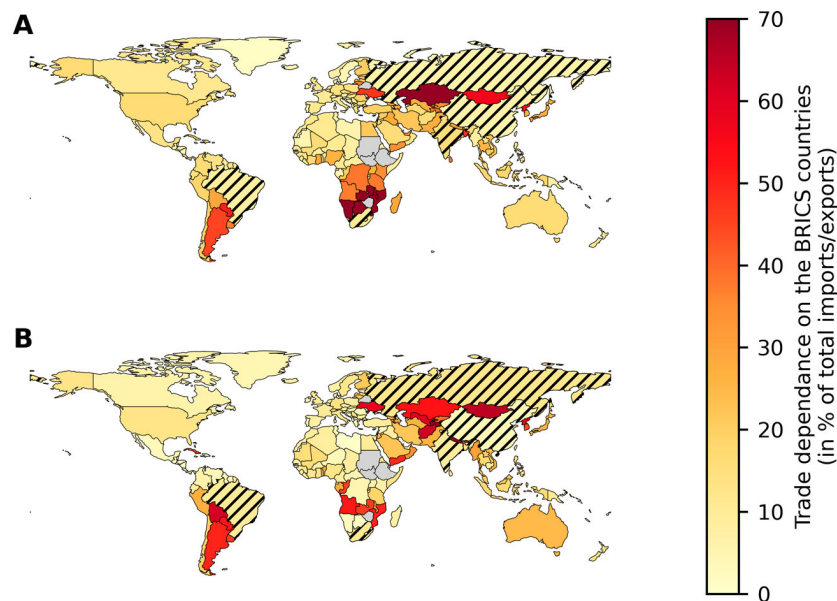
Figure 9. Difference in national gross output induced by a hypothetical stagnation of trade between the BRICS countries and the rest of the world after the financial crisis.



Note: Shading of countries shows the percentage difference in national gross output compared to the reference table, where aggregated GDP and trade volumes grow as observed in the EORA baseline. The BRICS countries are dashed. The base MRIO table corresponds to 2009 data; projections are made for 2015, using the observed evolution of GDP aggregated over all the BRICS countries and the rest of the world, respectively, and assuming that trade relations between the BRICS countries and the rest of the world stayed at their 2009 level (Setting D, Table 1). Gross output denotes the total output of all sectors in a country, encompassing both commodities that are further processed (intermediate commodities) and commodities that are consumed (final commodities).

were applied at the regional scale (setting D). The stagnation of trade relations between the BRICS countries and the rest of the world leads in every country to a reduction of national gross output. This is consistent with the effects observed in the first hypothetical scenario (Section 3.2.1): a limitation of the volume of international trade leads to an overall decrease in gross output all around the world. The diminution however varies across countries, highlighting different patterns of dependency on BRICS countries. The largest differences are observed for neighboring countries of the BRICS countries in South America, Central Asia and Southern Africa. Comparatively, Northern America, Western Europe and Northern Africa show a relatively low diminution of economic activity. The BRICS countries themselves figure among the most affected countries. Figure 10 shows how trade-dependent every country is on the BRICS countries in the 2009 base table, both for intermediate imports (Panel A) and exports (Panel B). Most countries for which gross output varies largely from the reference table display a high trade dependence on the BRICS countries (e.g. Kazakhstan and Mongolia, Ukraine, Bolivia, Angola). However, some countries largely depend on BRICS countries for their intermediate imports but are very lightly affected by the limitation of trade relations with BRICS countries (e.g. Namibia, Botswana, Bangladesh, Sri Lanka). These countries appear to have found new suppliers for their inputs, hence mitigating the loss related to the restriction of trade relations. On the contrary, all export-dependent countries are largely affected by the stagnation of trade relation with BRICS countries.

These observations differ to some extent from those made for scenario #1 (Section 3.2.1). There, a stronger dependence on intermediate inputs was directly related to a larger

Figure 10. Trade dependence on the BRICS countries.

Note: Shading of countries indicates how dependent each country is on intermediate imports (panel A) and exports (panel B) from/to the BRICS countries. Dependence is measured as percentage of intermediate imports and total exports traded with BRICS countries, respectively, according to EORA 2009 data. The BRICS countries are dashed. Countries in Central Asia, middle east and Southern Africa are largely dependent on the BRICS countries for both their intermediate imports and exports. Economies dependent on BRICS countries for their exports are relatively more affected than others by the limitations of trade relations between BRICS countries and the rest of the world.

output loss when trade was decreased. The qualitative differences between the outcome of both scenarios stem from the different settings used for projecting the tables, i.e. settings B and D, respectively. Gross output is projected in the first step of the SPIN method, using the estimated demand for domestically produced commodities (Section 2.3). This estimated demand volume is derived from the inputs of the method (Section 2.3.1, Equation 19). When trade constraints are defined at the national scale (as in setting B, scenario #1), demand is estimated at the national scale and accounts for imports, exports and local GDP (Section 2.3.1, Equations 17–19). Hence, in setting B, the volume of aggregated demand explicitly considers the reliance of the domestic economy on the volume of imports. When trade inputs are defined at the aggregated scale (as in setting D, scenario #2), however, demand is first determined at the aggregated scale and further allocated between countries following the demand repartition observed in the base table (section S3.2). Hence, in scenario #2, national gross output is estimated by combining inputs at the scale of economic zones (GDP, imports and exports) and the observed repartition of demand between countries of the same zone. Here, estimated demand for national economies accounts for imports at the level of economic zones, but not for national supply-side dependencies. Hence, some import-dependent countries are left almost unaffected by the restriction of trade relations with BRICS countries in scenario #2. Demand-side dependencies, by contrast, are directly considered since the observed structure of demand is accounted for when

allocating demand at the level of the economic zone between countries. Consequently, countries exporting large volumes to BRICS countries are more largely affected by the restriction of trade relations with BRICS countries.

4. Discussion and conclusion

In this paper, we present an algorithm to flexibly project Multi-regional input–output (MRIO) tables into the future, in line with exogenously defined constraints of how gross domestic product (GDP) and trade may evolve during that time. The Scenario-based projection of the international trade network (SPIN) method relies on the combination of a Leontief inversion and an extension of the RAS algorithm, both of which are well-established tools for the manipulation of IO tables. One major strength of our approach is that it offers a straight-forward and transparent mean to translate scenarios of future GDP and trade relations into consistent MRIO tables without requiring expert knowledge from the practitioner. It can hence be used to compare different scenarios and is directly applicable to existing GDP and trade projections. Additionally, the SPIN algorithm can be applied using regionally aggregated GDP and trade constraints, allowing the projection of global MRIO tables with limited inputs.

At the same time, the SPIN method is subject to several limitations. First, the SPIN method does not model the behavior of economic agents, but rather adjusts an MRIO table such that it meets prescribed GDP and trade developments. The projections may therefore appear oversimplified and unrealistic. For instance, in the first hypothetical scenario, a symmetrical increase or decrease in international trade relations results in perfectly symmetrical differences on gross output at both national and sectoral scale (Section 3.2).¹¹ Additionally, the SPIN method tends to replicate and amplify pre-existing trends (e.g. import or export dependence), within the boundaries of the prescribed GDP and trade constraints. The quality of the baseline table and consistence of the constraints are therefore critical to ensure the pertinence of the projections. Unlike more complex, integrated models, the SPIN method is unfit to forecast endogenous trends in the world economy.

Second, unlike most other projecting approaches, the SPIN method does not explicitly handle technological change. In our approach, alteration of the technical coefficients occurs in the second step of the procedure, via the application of the MS-GRAS-type algorithm (Section 2.3.2). The MS-GRAS algorithm minimizes the information loss between the projected and the base table, under constraints on row and column totals (Lenzen et al., 2007). Modifications of technical coefficients in the SPIN method are hence based on mathematical optimization procedures rather than on technological or economic arguments. As a consequence, projected technological change may be technically or economically implausible. Similarly, the SPIN method does not explicitly constrain the sectoral allocation of value added, e.g. labor availability or capital dynamics, nor the evolution of consumer preferences. Hence, the SPIN method would not be an appropriate tool to investigate the potential effects of technological change (De Koning et al., 2016; Lin & Nakamura, 2019; Wiebe et al., 2018). However, our results highlight that, over a period of a few

¹¹ Following the law of decreasing marginal productivity, we would rather expect a larger effect in magnitude from a decrease in international trade intensity than from an increase of the same volume.

years, the SPIN method is capable of convincingly reproducing the quantitative trends of the world economy, while being rather conservative with regard to structural changes (Section 3.1).

Third, aggregating diverse countries into aggregated economic zones can lead to distortions in the projected tables on quantitative, structural and qualitative aspects. Applying the SPIN method using aggregated inputs permits projecting tables with only a few inputs. However, we find that the SPIN method is relatively less accurate for reproducing historical evolutions when inputs are more aggregated (Section 3.1). This result confirms the usual observation that the more information used to project MRIO tables, the more accurate the projections (Valderas-Jaramillo et al., 2019). Additionally, the case studies explored in Section 3.2 highlight that the application of the SPIN method with aggregated inputs may obscure supply-side dependencies which would otherwise play an important role at the national scale. In other words, tables projected with different settings carry different assumptions. Hence, we recommend only applying the SPIN method to compare scenarios projected with inputs defined at the same scale.

Fourth, the SPIN method uses a simplified MRIO framework. This setting allows projecting tables with minimal inputs, i.e. only GDP and trade volumes, however, the projected tables do not necessarily contain all information typically included in an MRIO table. In particular, value added and final demand are aggregated, ignoring the distinction between capital, labor, taxes and subsidies on the value added side, and private or public consumption, investment and changes in stocks and inventories on the final demand side. Moreover, the SPIN method relies on a base table in basic prices, which does not detail the allocation of taxes and subsidies on products, nor trade and transportation margins. Additional assumptions (e.g. about the allocation of the revenue between capital and labor, investment rate, share of public spending ...) may be used to refine tables obtained with the SPIN method further thus enabling, for instance, analyses involving subcategories of final demand or value added.

Finally, compared to pre-existing projecting methods, the SPIN method favors simplicity and holistic consistency over accuracy and complexity. The main interest of the method is to project the structure of the international trade network based on few, available inputs which can be prescribed either at local or aggregated scale. As shown in Section 3.1, in the absence of MRIO tables for recent and future years, basing applications on these projected tables can be superior to using outdated MRIO data. The field of application of our approach is different from that of integrated projecting methods such as Computable General Equilibrium or technology-oriented models such as proposed by (Wiebe et al., 2018). Rather than producing autonomous projections based on predefined economic parameters or on technology deployment scenarios, the SPIN method aims at producing transparent estimations of the structure of the international trade network in line with simple GDP and trade scenarios. The hypothetical scenarios explored in Section 3.2 highlight that the SPIN method can be used to analyze trade-related interdependencies in existing MRIO tables. For instance, the SPIN method could be used to produce MRIO tables reflecting the five Shared Socioeconomic Pathways (O'Neill et al., 2017), for which GDP baselines are already available (Crespo Cuaresma, 2017; Dellink et al., 2017; Leimbach et al., 2017). Tables obtained with the SPIN method could further support scenario-based analyses of future vulnerability to climate change impact propagation (Kashiwagi et al., 2018; Otto et al., 2017) or resilience to economic shocks (Klimek et al., 2019). The SPIN method

can hence contribute to further integrating the MRIO framework into interdisciplinary research on the international trade network.

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Tracing externalities through the global trade network

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ABSTRACT: Understanding how countries contribute to the generation of externalities globally is important for designing sustainable policies aimed at reducing negative externalities such as carbon emissions. Commonly used approaches focus on either producers or consumers, thereby neglecting the role of intermediates. We here introduce the concept of throughflow to comprehensively quantify upstream externalities generated by the supply chains originating from, passing through or ending in a given country. We define the Throughflow Based Accounting (TBA) framework as the decomposition of the throughflow into local, imported, exported and traversing externalities. We illustrate the strength of the TBA by identifying the CO₂ emissions caused by supply chains involving the German economy. We show that Germany could use its position in global value chains to help reduce two times more CO₂ emissions than measured with usual production- or consumption-based accounting frameworks.



Beyond production and consumption: using throughflows to untangle the virtual trade of externalities

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ABSTRACT

Understanding how countries contribute to the generation of externalities globally is important for designing sustainable policies aimed at reducing negative externalities such as carbon emissions. Commonly used approaches focus on either producers or consumers, thereby neglecting the role of intermediates. We here introduce the concept of *throughflow* to comprehensively quantify upstream externalities generated by the supply chains originating from, passing through or ending in a given country. We define the Throughflow Based Accounting (TBA) framework as the decomposition of the throughflow into local, imported, exported and traversing externalities. We illustrate the strength of the TBA by identifying the CO₂ emissions caused by supply chains involving the German economy. We show that Germany could use its position in global value chains to help reduce two times more CO₂ emissions than measured with usual production- or consumption-based accounting frameworks.

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1. Introduction

Major challenges of our modern civilisation require a better control of externalities caused by human activities. Limiting global warming to well below 2°C compared to preindustrial levels as agreed upon in the Paris Agreement (Conference of the Parties, Adoption of the Paris Agreement, 2015) is only possible if greenhouse gas emissions reach net zero early in the second half of the twenty-first century (Riahi et al., 2022). Similarly, the achievement of the United Nations' Sustainable Development Goals (Transforming our world: The, 2030 Agenda for Sustainable Development, 2015) requires minimising negative externalities such as local air pollution and increasing positive externalities such as employment or education.

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Our current globalised economy is characterised by long, complex and often international production processes (Costinot et al., 2013; Hummels et al., 2001; Maluck & Donner, 2015; Xiao et al., 2020). Before being used at their final destination, commodities usually undergo numerous transformation steps, which involve different industries routinely located in different countries. This complexity blurs contributions to the joint production effort and therefore dilutes responsibilities for the generation of externalities (Davis et al., 2011; Kagawa et al., 2015; Peters et al., 2012; Wiedmann & Lenzen, 2018).

In addition to the economic actor directly generating externalities¹, actors involved in the supply chain associated with these externalities could also act to reduce or enhance their generation. For instance, the information that a product is causing environmental degradations may deter consumers from buying it (Rondoni & Grasso, 2021), stakeholders are increasingly considering sustainability criteria in decision making (Chatzitheodorou et al., 2019; Latapí Agudelo et al., 2019) and countries may modify their trade policies to pursue climate mitigation goals (Jakob, 2021; Jakob et al., 2022).

Multi-Regional Input–Output tables (MRIOT) are commonly used to identify externalities generated both directly and indirectly for supplying commodities to final consumers (Miller & Blair, 2009, pp. 446–452; Wiedmann et al., 2015; Wiedmann & Lenzen, 2018; Wood et al., 2018). *Consumption Based Accounting* (CBA) approaches quantify externalities that could be targeted by an economic actor through demand-side measures, e.g. via changes of consumption patterns (Wood et al., 2020). CBA is the basis of the concept of *consumption footprint*. By contrast, the *Production Based Accounting* (PBA) framework measures externalities directly generated by an economic actor (Peters, 2008), i.e. those an actor could target through production-side measures, e.g. technological change.

Beyond consumers and producers, intermediates could also target externalities generated along the supply chains they are involved in. Structural Path Analysis (SPA) allows decomposing supply chains by layers (Lenzen, 2003; Skelton et al., 2011) and may thus permit to identify critical intermediates in international supply chains. With the *Shared Producer and Consumer Responsibility* (SPCR) framework, Gallego and Lenzen (2005) proposed a mathematical formulation for allocating responsibilities along supply chains. This approach acknowledges the role of intermediates typically overlooked in PBA and CBA frameworks by using coefficients that weight the relative responsibilities of producers, consumers and intermediates. SCPR allocates responsibilities for externalities in a mutually exclusive way: acknowledging the role of intermediates within the SCPR framework effectively equates to reducing the responsibility of both producers and consumers. Therefore, SCPR does not provide a comprehensive assessment of the externalities an individual actor could potentially influence.

In a seminal paper, Liang et al. (2016) have proposed the *Betweenness Based Accounting* (BBA) measure, which combines SPA with the concept of betweenness centrality, capturing the ability of a node to transmit information in a network. In the context of MRIOTs, BBA captures externalities caused by the supply chains traversing a sector, i.e. how much a sector contributes to the generation of externalities by its position as an intermediate in these supply chains. The betweenness can also be computed for edges, i.e. for a given transaction in the global economic network (Hanaka et al., 2017). Using adjacency matrices and

¹ We here use the term ‘externalities’ in its broadest sense such that it can denote both, different externality types as well as varying amounts of the same externality.

clustering techniques, Kagawa et al. (2015) have also been able to measure the upstream CO₂ emissions related to specific trade relations. This set of methods is particularly well suited for identifying critical links or sectors in the global trade network and is readily used to explore sector-specific policies to curb the production of negative externalities, for instance by decreasing the input use from the most carbon-intense industries (Liang et al., 2016; Ward et al., 2017), or by reducing the dependence on major emissions clusters (Hanaka et al., 2017; Maeno et al., 2022; Tokito, 2018; Tokito et al., 2022).

Beyond sector-specific measures, policymakers can also implement economy-wide policies to reduce their contribution to the global generation of negative externalities, e.g. by uniformly pricing the creation of externalities. The most prominent example of such externality pricing is given by carbon markets, which have been implemented in different parts of the world (Stiglitz et al., 2017; World Bank, 2022). Carbon markets usually price CO₂ emissions from domestic producers only, thus relating to PBA. However, as domestic carbon markets may cause carbon leakage in trade-exposed sectors (Dechezleprêtre & Sato, 2017; Jakob, 2021; Misch, 2021; Naegle & Zaklan, 2019), policymakers are considering the implementation of Border Adjustment Mechanisms (BAM) to level the playing field between domestic and imported production by levying a price on imported commodities based on the emissions caused elsewhere (Jakob, 2021; Sakai & Barrett, 2016).

The methods previously introduced are not directly applicable to investigate how countries could address externalities production through BAMs. First, the methods referenced therefore are usually applied at the scale of sectors, while the investigation of BAMs calls for accounting frameworks at the national scale. In particular, a formulation of the BBA at the country level is still missing. Second, these methods often entail double counting, as externalities caused by supply chains looping several times through the same sector are counted multiple times (Liang et al., 2016; Tokito et al., 2022).² Such double counting impedes the investigation of externality pricing, as there is no ground to levy a price more than once on a given externality.

This double counting problem is identical to the one encountered in Global Value Chain (GVC) analysis. The Trade in Value Added (TiVA) framework provides a detailed decomposition of the value added embodied in the gross exports of a country and permits the identification of double counted elements (Borin & Mancini, 2019; Koopman et al., 2010, 2014). Though the TiVA framework is largely used for analyses in economic terms, it is rarely applied to externalities accounting problems. As highlighted by Los and Timmer (2018), the TiVA framework derives from the Hypothetical Extraction Method (HEM). The HEM is a standard technique of Input–Output analysis measuring a sector's or a country's interconnectedness to the global economy (Dietzenbacher et al., 1993; Miller & Blair, 2009, pp. 563–565). It is also used to develop analytical frameworks to investigate intermediate dependencies in the global economy (Dietzenbacher et al., 2019; Dietzenbacher & Lahr, 2013; Szyrmer, 1992; Szyrmer & Walker, 1983). In particular, the *Total Flow* (TF) framework has been originally developed by Szyrmer based on the HEM to analyse the interdependences between sectors not only with relation to changes in final demand, but also to changes in gross output (Szyrmer, 1992; Szyrmer & Walker, 1983). In the context of externalities accounting, the HEM can be directly interpreted as the volume of upstream

² In this paper, we use the term *double counting* when referring to externalities allocated to the same actor more than once (Liang et al., 2016; Tokito et al., 2022). In related literature, the same term is sometimes used to denote externalities allocated simultaneously to more than one actor (Gallego & Lenzen, 2005).

externalities caused by all the supply chains starting from, traversing and ending in a given sector (Hanaka et al., 2022; Tokito et al., 2022).

Tokito et al. (2022) have shown that the HEM is closely related to BBA, the only difference being the consideration of self-loops in supply chains: the HEM counts externalities only once, even when the associated supply chain loops several times through the same sector. HEM-based techniques are hence not prone to the double counting problem and are suitable to explore externality pricing policies. In a recent work, Hanaka et al. (2022) have proposed a decomposition of the HEM to account simultaneously for the production, consumption and transmission characteristics of a sector (*production*-, *consumption*- and *betweenness-oriented* scores), but these scores lack a clear link with the PBA and CBA frameworks and are only defined at the sector level.

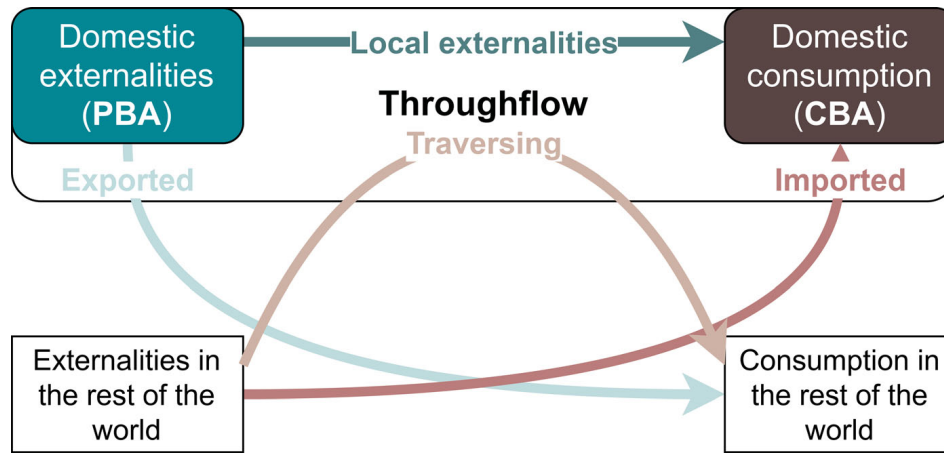
Our paper extends the existing literature by formulating the so-called Throughflow Based Accounting (TBA) framework. We propose the term *throughflow* to designate the total volume of externalities captured by the HEM, which is the volume of upstream externalities caused by all the supply chains starting from, traversing and ending in a given country. As the concept of *footprint* has made the use of the Leontief inverse popular beyond the Input–Output community, we believe that the concept of *throughflow* and the associated TBA framework can facilitate the communication and use of HEM-based methods and results. The TBA framework is further built on the decomposition of the throughflow into four meaningful elementary components: *local*, *imported*, *exported* and *traversing* externalities. Being defined at the national scale and built on intuitive concepts, the TBA framework bridges the gap between the work of Hanaka et al. (2022) and the canonical PBA and CBA frameworks (Figure 1). While the TBA is coherent with the PBA and CBA frameworks, it has a broader coverage than both of these by acknowledging simultaneously for the production, consumption and intermediate contribution of a country to externalities production worldwide.

The second section of this paper introduces the formal definition of the *throughflow* and derives the TBA decomposition from it. In the third section, we illustrate how the TBA can straightforwardly be applied to identify the externalities caused along the supply chains a country is involved in. As an example, we investigate the CO₂ throughflow of the German economy. We discuss the results of the study case and their policy implications in the fourth section, in relation with pre-existing accounting frameworks. Finally, the fifth section summarises the main findings of this paper and outlines avenues for further research.

2. Method description

In this section, we introduce the Throughflow Based Accounting (TBA) framework and anchor it within pre-existing frameworks. We first recap some basic relations of Input–Output Analysis (IO). Second, we introduce the concept of *throughflow* as an interpretation of the Hypothetical Extraction Method (HEM). Then, we formulate the TBA by decomposing the *throughflow* based on the position of a country in supply chains causing externalities. Finally, we compare the TBA to other accounting frameworks. As a global convention, we note matrices with capital letters and vectors with lowercases. Elements of matrices are indicated with subscripts. We here introduce the TBA at the scale of a country c , but the definitions can be extended to any group of countries or regions.

Figure 1. Overview of the Throughflow Based Accounting (TBA) decomposition. The throughflow quantifies the volume of upstream externalities caused by all the supply chains starting from, traversing or ending in a given country. The TBA is the decomposition of the throughflow into four elementary flows. Local and exported externalities are caused domestically to supply final users domestically and abroad, respectively. Together, they form the usual Production Based Accounting (PBA). Imported externalities are caused abroad along supply chains serving final users domestically. Local and imported externalities correspond to the Consumption Based Accounting (CBA) framework. Beyond the volumes of externalities embodied in the usual PBA and CBA frameworks, TBA also entails traversing externalities: these externalities are caused abroad to supply final consumption abroad, but the associated supply chains involve the local economy at least once in between.



2.1. Basic definitions

A Multi Regional Input–Output Table (MRIOT) describes the global production network (Lenzen et al., 2012; Miller & Blair, 2009). We note n the number of sectors and N the number countries covered. MRIOTs are characterised by the equation which puts the column vector of gross output $\mathbf{x}$ into relation with the matrix of input coefficients $\mathbf{A}$ and the matrix of final demand $\mathbf{Y}$:

$$\mathbf{x} = (\mathbf{I} - \mathbf{A})^{-1} \mathbf{Y} \mathbf{e} = \mathbf{L} \mathbf{Y} \mathbf{e}. \quad (1)$$

$\mathbf{A}$ is a matrix of dimensions $nN \times nN$. The input coefficient $a_{ir \rightarrow js}$ of $\mathbf{A}$ describes the quantity of output from sector i in country r that is directly used as input for the production of one unit of output by sector j in country s . This element corresponds to the $(r - 1)n + i$ -th row, $(s - 1)n + j$ -th column of the $\mathbf{A}$ matrix and is often noted a_{ir}^{js} in the literature. Unlike usual conventions, we here note both regions and sectors as subscripts in order to reserve superscripts for country specific variables. The matrix $\mathbf{L}$, defined as $(\mathbf{I} - \mathbf{A})^{-1}$ (with $\mathbf{I}$ the identity matrix) is known as the Leontief inverse and is also of dimensions $nN \times nN$. Coefficient $l_{ir \rightarrow js}$ of the Leontief inverse quantifies how much input from sector i in country r is needed both directly and indirectly to produce one unit of output for sector j in country s . $\mathbf{e}$ is a $N \times 1$ column vector of ones, i.e. the summation operator. The final demand matrix $\mathbf{Y}$ is of dimensions $nN \times N$. Element $y_{ir \rightarrow s}$ is the final demand for commodity i produced in country r stemming from country s . This element corresponds to the $(r - 1)n + i$ -th row, s -th column of the $\mathbf{Y}$ matrix. Hence, the s -th column of the final demand matrix represents the final demand for all commodities in country s .

We note $\mathbf{Y}^s$ the $nN \times N$ final demand matrix for country s , where all columns except for column s are set to 0. Using this notation, the final demand matrix $\mathbf{Y}$ can be written as the sum of the N national demand matrices:

$$\mathbf{Y} = \sum_{s=1}^N \mathbf{Y}^s. \quad (2)$$

In what follows, we denote $\mathbf{q}$ as the row vector of dimensions $1 \times nN$ quantifying the externalities directly caused by each sector per unit of output, in which element q_{ir} corresponds to the quantity of externalities per unit of output caused by sector i in country r . As for the final demand $\mathbf{Y}$, we can write the vector $\mathbf{q}$ as the sum of N national vectors of externalities coefficients:

$$\mathbf{q} = \sum_{r=1}^N \mathbf{q}^r, \quad (3)$$

where $\mathbf{q}^r$ is the vector of direct externalities coefficients for country r , in which all coefficients associated with countries $s \neq r$ are set to 0.

The volume of externalities caused in country r to supply the final demand in country s can be obtained by multiplying the vector of externalities coefficients of country r , $\mathbf{q}^r$ with the Leontief inverse $\mathbf{L}$ and the final demand in country s , $\mathbf{Y}^s$:

$$f_{rs} = \mathbf{q}^r \mathbf{L} \mathbf{Y}^s \mathbf{e}. \quad (4)$$

The sum of the externalities caused in country c to supply the final demand in any country corresponds to the Production Based Accounting (PBA) measure of the externalities attributable to country c , noted pba^c :

$$pba^c = \sum_{s=1}^N f_{cs} = \sum_{s=1}^N \mathbf{q}^c \mathbf{L} \mathbf{Y}^s \mathbf{e}. \quad (5)$$

According to equation (2), equation (5) becomes:

$$pba^c = \mathbf{q}^c \mathbf{L} \mathbf{Y} \mathbf{e}. \quad (6)$$

Reciprocally, the sum of the externalities caused in any country to supply the final demand in country c yields the Consumption Based Accounting (CBA) measure of that country, i.e. is the volume of externalities caused both directly and indirectly to supply the final demand of country c , noted cba^c :

$$cba^c = \sum_{r=1}^N f_{rc} = \sum_{r=1}^N \mathbf{q}^r \mathbf{L} \mathbf{Y}^c \mathbf{e}. \quad (7)$$

Using equation (3), the CBA measure of country c can finally be written as:

$$cba^c = \mathbf{q} \mathbf{L} \mathbf{Y}^c \mathbf{e}. \quad (8)$$

2.2. Measuring the throughflow

We define the *throughflow* as the result of the Hypothetical Extraction Method (HEM) applied to externalities accounting. The HEM compares a counterfactual of the global economy where a group of economic sectors or a country is assumed not to exist to the actual global economy, to identify the importance of the excluded economic sectors or countries (Dietzenbacher et al., 1993; Miller & Blair, 2009, pp. 563–565). In order to define the throughflow, we apply the HEM in such a way that all upstream externalities generated by supply chains either starting from, passing through or ending in a given country are considered, in line with the interpretation from Hanaka et al. (2022) and Tokito et al. (2022).

In order to formalise the measure of the throughflow, we need to introduce some additional notations. From the matrix of input coefficients $\mathbf{A}$, we derive the matrix of input coefficients *in absence of a given country* c , $\bar{\mathbf{A}}^c$. In comparison with the matrix $\mathbf{A}$, the coefficients corresponding to inter-industry relations within c , imports to c and exports from c are set to 0 (i.e. the $(c - 1)n$ -th to cn -th rows and columns are set to zeros):

$$\bar{\mathbf{A}}^c = (\bar{a}_{ir \rightarrow js}^c) = \begin{cases} 0 & \text{if } r = c \text{ or } s = c \\ a_{ir \rightarrow js} & \text{otherwise} \end{cases}. \quad (9)$$

Based on the matrix of input coefficients *in absence of country* c , we define the Hypothetically Extracted Leontief inverse $\bar{\mathbf{L}}^c$ as:

$$\bar{\mathbf{L}}^c = (\mathbf{I} - \bar{\mathbf{A}}^c)^{-1}. \quad (10)$$

The Hypothetically Extracted Leontief inverse describes the direct and indirect inputs needed to produce one unit of output in a hypothetical economy where country c were removed.

Then, we define $\bar{\mathbf{Y}}^c$ to be the global final demand of commodities outside of country c , built from the final demand matrix $\mathbf{Y}$ by setting the final demand of country c (c -th column) to zero:

$$\bar{\mathbf{Y}}^c = \mathbf{Y} - \mathbf{Y}^c = \sum_{s \neq c} \mathbf{Y}^s. \quad (11)$$

Likewise, we define $\bar{\mathbf{q}}^c$ to be the row vector of externalities produced outside of country c , by setting the externalities production from country c to zero:

$$\bar{\mathbf{q}}^c = \mathbf{q} - \mathbf{q}^c = \sum_{r \neq c} \mathbf{q}^r. \quad (12)$$

Following the interpretation of the HEM by Hanaka et al. (2022) and Tokito et al. (2022), we formally introduce the scalar **throughflow**³ tba^c as the volume of externalities identified with the HEM for country c :

$$tba^c = (\mathbf{qLY} - \bar{\mathbf{q}}^c \bar{\mathbf{L}}^c \bar{\mathbf{Y}}^c) \mathbf{e}. \quad (13)$$

³ We also propose a spatially explicit formulation of the throughflow in the Supplementary Materials (equation S.1). Element tba_{rs}^c of such *throughflow matrix* captures the externalities caused in country r to supply the final users in country s through country c . This alternative formulation is coherent with the forthcoming TBA decomposition (see equation S.4).

2.3. Decomposing the throughflow

Using these notations, we can identify four flows of externalities forming the throughflow: *local*, *imported*, *exported* and *traversing externalities*.⁴

The volume of externalities caused by local supply chains (*local externalities*) is captured by the scalar loc^c :

$$loc^c = \mathbf{q}^c \mathbf{L} \mathbf{Y}^c \mathbf{e} = f_{cc}. \quad (14)$$

These externalities are caused in country c for the production of commodities finally used in country c . Note that this flow of externalities can be further decomposed into two elements, depending on whether the supply chains causing these externalities traverse other countries (*re-imported externalities*) or not (*purely local externalities*, see Supplementary Materials equations S. 7–8).

The column vector of externalities caused by importing supply chains (*imported externalities*, $\mathbf{imp}^c$), of dimensions $N \times 1$, identifies the externalities generated abroad by supply chains ultimately serving final consumers in country c . Its elements are defined as follows for all countries r different from country c :

$$imp_r^c = \mathbf{q}^r \mathbf{L} \mathbf{Y}^c \mathbf{e} = f_{rc}. \quad (15)$$

Coefficient imp_r^c captures the volume of upstream externalities caused in country r to supply the final demand in country c .

The row vector of externalities caused by exporting supply chains (*exported externalities*, $\mathbf{exp}^c$), of dimensions $1 \times N$, represents the externalities caused in country c by supply chains reaching final consumers abroad:

$$exp_s^c = \mathbf{q}^c \mathbf{L} \mathbf{Y}^s \mathbf{e} = f_{cs}. \quad (16)$$

Coefficient exp_s^c captures the upstream externalities caused in country c to supply the final demand in country s .

Finally, the matrix of externalities caused by traversing supply chains (*traversing externalities*, $\mathbf{TRA}^c$), of dimensions $N \times N$ identifies the externalities caused abroad for supplying final demand abroad, but whose associated supply chain involves country c at least once:

$$tra_{rs}^c = \mathbf{q}^r (\mathbf{L} - \bar{\mathbf{L}}^c) \mathbf{Y}^s \mathbf{e}. \quad (17)$$

Here, coefficient tra_{rs}^c measures the externalities caused in country r to supply the final demand in country s through country c .

⁴ The terms used to define the components of the TBA decomposition are to be understood in a figurative way. The mention of *imported/exported/traversing externalities* do not refer to externalities being physically traded between countries, but rather to externalities generated to produce traded commodities. Such externalities associated with trade flows are sometimes referred to in the literature as *embodied externalities* (Skelton et al., 2011; Wood et al., 2018; Zhang, Guan, et al., 2020). As this formulation has been criticised for being ambiguous (Jakob & Marschinski, 2013; Liu, 2015; Jakob et al., 2021), we refrain from using it in this manuscript.

From these definitions, we define the **Throughflow Based Accounting** (TBA) as the following decomposition of the throughflow (see Figure 1 for illustration and the Supplementary Materials equations (S.9-17) for the demonstration):

$$tba^c = loc^c + |\mathbf{imp}^c| + |\mathbf{exp}^c| + |\mathbf{TRA}^c|, \quad (18)$$

where the symbol $||$ indicates the sum of all the coefficients of the corresponding matrices or vectors, i.e. the summation operator.

2.4. Relation with other accounting frameworks

Our concept of throughflow can be interpreted as an extension of the *Total Flow* framework (Szyrmer, 1992; Szyrmer & Walker, 1983) to externality accounting at the interregional level. In particular, our concept of *traversing externalities* (equation 17) relates to the *transit flow* coined by Szyrmer and Walker (1983). The TBA decomposition is also largely comparable to the decomposition of the HEM proposed by Hanaka et al. (2022), except that the latter is defined at the sector scale and distinguishes between intermediate and final trade (see Supplementary Materials).

The TBA decomposition (equation 18) explicitly contains the elements forming the PBA (5) and CBA (7) frameworks, through the element loc^c (14) and the vectors $\mathbf{exp}^c$ (16) and $\mathbf{imp}^c$ (15), respectively. By construction, both PBA and CBA frameworks can be formally expressed using the components of the TBA:

$$\begin{cases} pba^c = loc^c + |\mathbf{exp}^c|; \\ cba^c = loc^c + |\mathbf{imp}^c|. \end{cases} \quad (19)$$

Regarding BBA (Liang et al., 2016), TBA differs in two main aspects. First, there is to our knowledge no formulation of the betweenness at the scale of a country (or more broadly at the scale of a group of sectors). Second, the TBA being based on the HEM, it counts supply chains only once, even when such supply chain traverses the same country more than once (Tokito et al., 2022) (Figure S1).

There are similarities between the framework proposed here and the Global Value Chain (GVC) literature. In particular, the TiVA framework allows identifying the domestic and imported value-added content in the gross exports of a country (Borin & Mancini, 2019; Koopman et al., 2010, 2014), which are related to the *exported* and *traversing* elements of our decomposition, respectively. Beyond an obvious difference in scope (TiVA usually focuses on Value Added, while the TBA is defined for any externality), the TiVA and TBA decompositions differ in their respective perspective. While the TiVA decomposition is usually defined from gross exports (Koopman et al., 2010, 2014) or from bilateral trade flows (Borin & Mancini, 2019), the TBA is defined from the global final demand (equation (13)). Additionally, the TiVA decomposition allows distinguishing in exports and imports between the direct trade partner and the final consumer, while the TBA only allows the identification of the countries where externalities production and final consumption occur. Similarly, the TBA framework does not identify the double counted externalities associated with self-looping supply chains (Figure S1), nor differentiates between the trade of intermediate and final commodities.

Finally, the TBA framework is a non-additive framework: *traversing externalities* of a given country are necessarily *exported from* and *imported to* another country. In other

words, *traded* (i.e. *imported*, *exported* and *traversing*) externalities are counted as part of the throughflow of more than one country.⁵ Therefore, the throughflow of an ensemble of two regions is in most cases smaller than the sum of the throughflows of the two regions considered separately. Such non-additivity property is shared by most accounting frameworks referenced therebefore, with the exception of the PBA, CBA and SPCR frameworks (Gallego & Lenzen, 2005): these frameworks allocate externalities in a mutually exclusive way to producers, consumers and between all actors involved in the supply chains, respectively. Whereas non-additivity causes computational limitations (Szyrmer, 1992), additive frameworks require a normative choice as to which type of actor should hold responsibility for externalities. For instance, the SCPR approach requires setting *responsibility shares* (Gallego & Lenzen, 2005) to weigh the responsibilities between consumers, producers and intermediates, and the determination of these shares constrains the range of externalities that can be addressed by an actor. Instead, non-additive frameworks such as the TBA provide a comprehensive assessment of all externalities that are potentially within the reach of an actor and thus permit the evaluation of a broader range of policy options.

3. Study case: The CO₂ throughflow of Germany

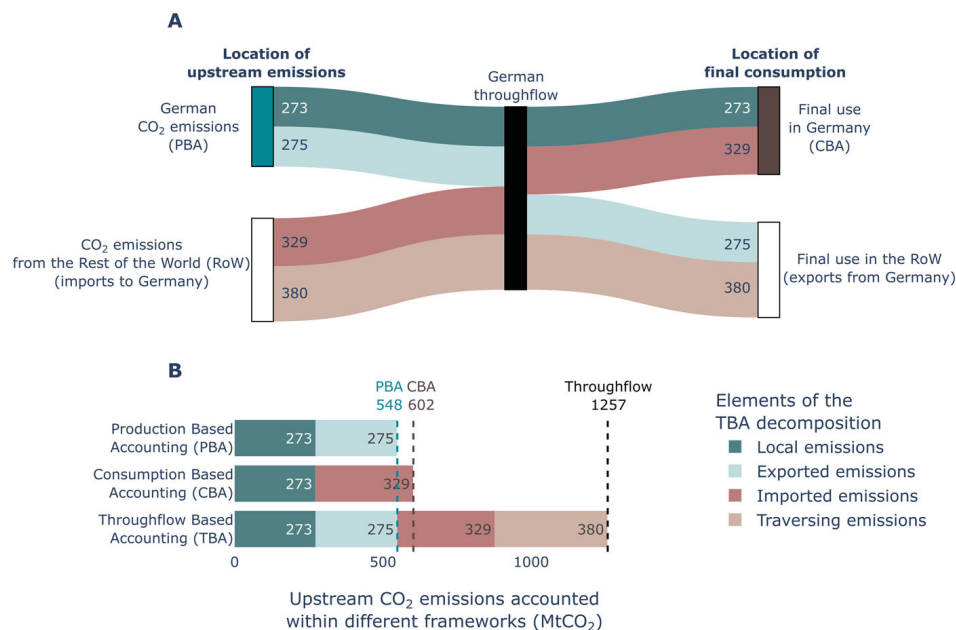
This section demonstrates the added value of the TBA framework by quantifying the upstream CO₂ emissions generated by the supply chains originating from, passing through or ending in Germany. We use EORA26 (Lenzen et al., 2012, 2013) for the year 2015 as MRIOT and CO₂ emissions from the Primap databases (Gütschow et al., 2020, 2021). The Primap databases contain CO₂ emissions data at different levels of sectoral and geographical detail. Using a tailored algorithm (see Supplementary Materials), we combine data from the Primap hist (Gütschow et al., 2021) and Primap crf (Gütschow et al., 2020) data sets with MRIOT data from EORA26 to allocate direct CO₂ emissions to the 26 sectors and final demand covered in the EORA26 MRIOT, from the 182 countries covered in the Primap hist database. We ignore in what follows the direct emissions from final users (e.g. CO₂ emissions from individual cars), since those emissions are not related to further processing steps.

Overall, we find that the TBA framework identifies substantially more CO₂ emissions than the usual accounting frameworks (Figure 2). We estimate the total throughflow of CO₂ of Germany to 1.26 Gt of CO₂, more than twice the quantities measured in both the CBA and PBA frameworks. Through its involvement in international supply chains, the German economy is linked with substantially more CO₂ than just those generated on its territory (PBA, Figure 2A) and those generated to supply its final consumption (CBA). Within our perimeter of CO₂ emissions (i.e. omitting direct emissions from final consumers), we estimate the quantity of CO₂ emissions directly emitted from within the German territory to be 548 Mt (PBA; Figure 2B). About half of these emissions, i.e. 275 Mt, are emitted to produce or process commodities that are consumed elsewhere in the world (*exported emissions*). For instance, this volume includes the CO₂ emitted by a German power plant to produce a car that is sold abroad. Reciprocally, 329 Mt of CO₂ are emitted

⁵ In a sense, these externalities can be described as *double counted* (Gallego & Lenzen, 2005). As already mentioned earlier in the manuscript (footnote 2), we reserve here the term *double counted* to externalities allocated twice to the same agent.

abroad to process commodities that are ultimately consumed in Germany (*imported emissions*). As an illustration, the CO₂ emitted to produce steel beams in China that are used to maintain the German railway is included in this flow of imported emissions. Because of the imbalance between the emissions generated to produce German's exports and imports, the volume of CO₂ emitted to supply the final demand in Germany (CBA) amounts to 602 Mt of CO₂, around 10% higher than the PBA measure.

Figure 2. TBA decomposition of the German CO₂ throughflow. A. Representation of the Throughflow Based Accounting (TBA) decomposition of the German CO₂ throughflow, in 2015. The width of the links is proportional to the volume of upstream CO₂ emissions captured by the corresponding element of the TBA decomposition. The numerical values are indicated on the links, in MtCO₂. The bars on the left indicate whether CO₂ emissions have occurred in Germany (upper left bar) or in the rest of the world (RoW, bottom left bar). The bars on the right show where the final commodities causing these CO₂ emissions are finally used, either in Germany (upper right bar) or in the RoW (bottom left bar). The black, central bar indicates the German throughflow, i.e. the volume of upstream CO₂ emissions generated by the supply chains Germany is involved in. B. Decomposition of the CO₂ emissions allocated to Germany in the PBA, CBA and TBA frameworks. The values refer to the volume of upstream CO₂ emissions measured by the different elements of the TBA decomposition, in Mt of CO₂. The dashed line indicates the total volume of CO₂ emissions allocated to Germany within each framework.

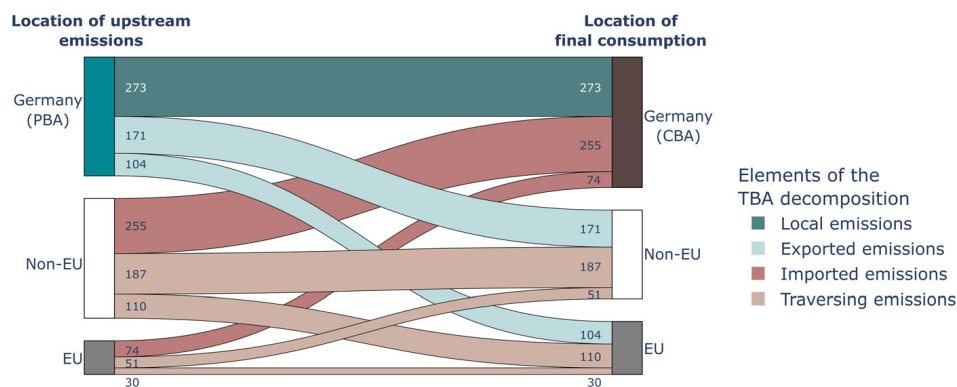


However, considering either PBA or CBA alone masks a substantial volume of CO₂ emissions associated with the German economy. Two elements explain this gap between the German PBA/CBA and TBA totals. First, PBA (CBA) accounts for the emissions generated to process German exports (imports) but omits emissions generated for its imports (exports). With regard to the examples introduced previously, the CO₂ emissions caused by the foreign steel production for the German railway do not count into the PBA account of CO₂ emissions for Germany; and the German emissions to produce cars for exports are not accounted for in a CBA-type assessment. TBA, however, includes emissions generated for both exports and imports. Second, both CBA and PBA do not account for emissions associated with supply chains going through the German economy (*traversing emissions*). An

illustration of such emissions is the CO₂ emitted abroad for producing aluminium, which is further used in Germany to produce cars finally sold abroad. We find that these emissions amount to 380 Mt of CO₂ in Germany, i.e. the same order of magnitude as German *exported* and *imported* emissions.

A closer look at the German throughflow shows that the German economy is linked to a large volume of CO₂ emissions occurring outside of the EU (Figure 3). More than three times more CO₂ is emitted in non-EU countries (255 Mt CO₂) than in EU countries (74 Mt CO₂) to supply the final demand in Germany. The contribution of non-EU CO₂ emissions to Germany's final demand is comparable to the volume of emissions caused in Germany itself (273 Mt CO₂). A similar relation holds for the emissions caused by supply chains traversing the German economy. For supplying the final demand in other EU countries, Germany is contributing to more CO₂ emissions in the rest of the world (110 Mt CO₂, e.g. emissions caused to prepare the Chinese aluminium used to produce German cars) than in Germany itself (104 Mt CO₂, e.g. emissions from coal burning for powering German car manufactures) or in other EU countries (30 Mt CO₂, e.g. emissions to manufacture spare parts of German cars in Poland). Finally, the supply of the final demand in non-EU countries via the German economy is causing almost twice as much CO₂ emissions (409 Mt CO₂) as those caused to supply the final demand in other EU countries (244 Mt CO₂). The formers are mainly caused in non-EU countries (187 Mt CO₂) and in Germany (171 Mt CO₂), but only marginally in other EU countries (51 Mt CO₂). Therefore, the trade of emission-intensive commodities from and to Germany appears to be more largely related to non-EU countries than to other EU member states.

Figure 3. Origin and destination of the supply chains causing the German throughflow of CO₂ emissions. As in Figure 2A, the left blocks show where CO₂ emissions associated with the German economy (i.e. Germany's throughflow) were originally emitted. The right blocks indicate where the commodities associated with these emissions were finally consumed. In comparison to Figure 2A, the Rest of the World (RoW) is here decomposed into countries members of the European Union (EU) and non-EU countries. The width of the flows is proportional to the volume of CO₂ emissions measured. The numbers indicate the volume of upstream CO₂ emissions captured by the correspond element of the TBA decomposition, in Mt CO₂. Colouring of links corresponds to the different components of the throughflow, as introduced in Figure 2. Table S1 in the Supplementary Materials presents the data in tabular form.



The TBA decomposition also gives insights on the position of a country's economy in global supply chains. Figure 4A shows, for each of Germany's trade partners, which share of their emissions supplies final users in Germany (*imported emissions*) relative to all of

their emissions caused by supply chains going through Germany (*imported and traversing emissions*). For instance, around 70% of CO₂ emissions induced in South-Eastern Asian countries by supply chains involving Germany are caused by the German final demand (*imported emissions*). As an example, such emissions include those required to produce textile in Laos, which is further sold in Germany. By opposition, most emissions related to the German economy in fossil fuel producing countries serve the production of final commodities consumed outside of Germany. Only 31% of the CO₂ emissions from Libya and Kazakhstan, 37% of the Russian emissions are used to supply the German final demand (*imported emissions*), for instance for powering domestic heating systems. The rest of it (69% in Libya and Kazakhstan, 63% in Russia) is further incorporated in German exports (*traversing emissions*). For instance, emissions caused by the extraction of oil and gas in Russia may serve powering a car factory in Germany, whose cars are further sold abroad.

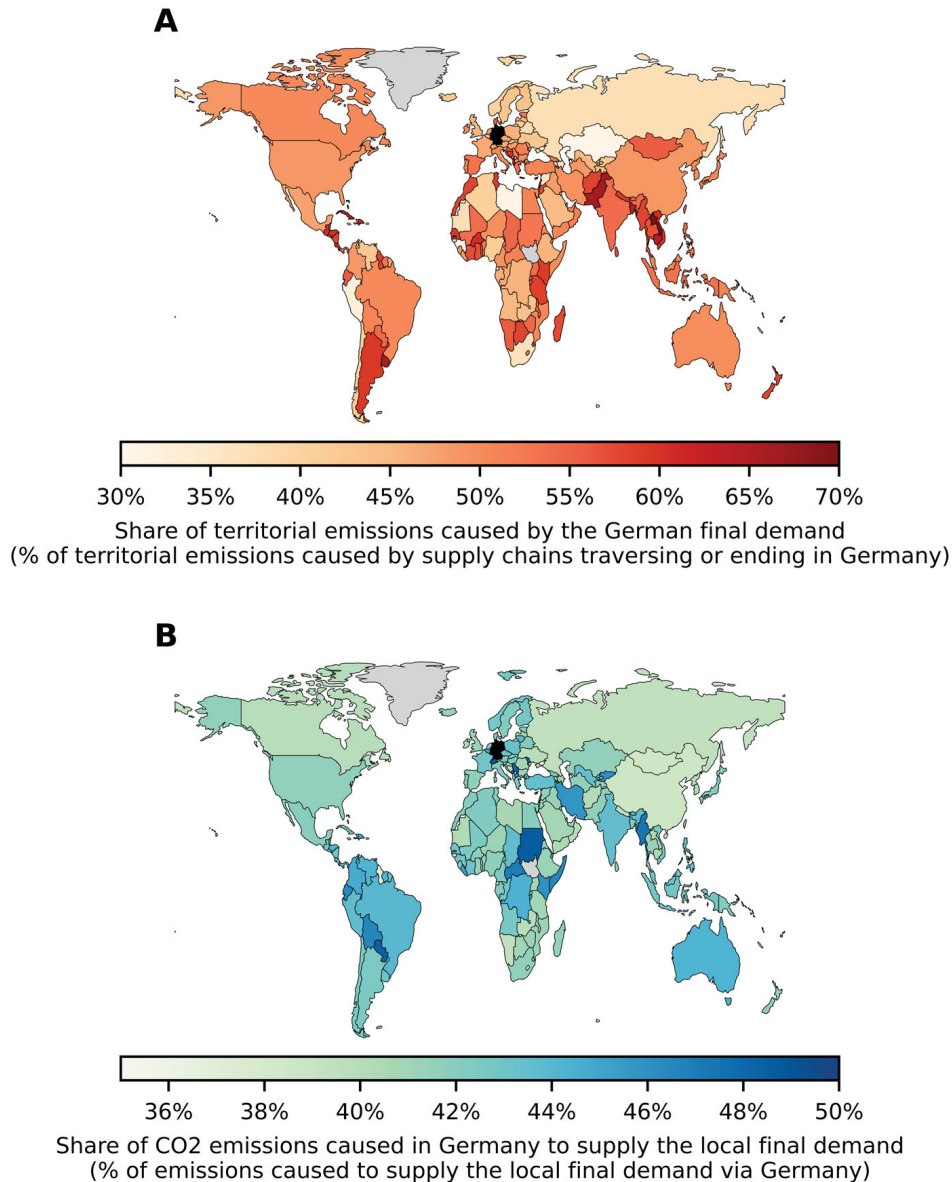
Reciprocally, Figure 4B indicates, for the supply chains going through Germany and supplying the final demand in each country (*exported and traversing emissions*), which share of the upstream emissions caused by these supply chains happened in Germany (*exported emissions*). While the position of the German economy with regard to the creation of emissions in other countries is very heterogeneous (Figure 4A), the origin of the emissions to supply the final demand in other countries via the German economy is rather similar from one country to another (Figure 4B). The CO₂ emissions caused by the German economy to supply the final demand of other countries are caused either in Germany (from 40% and 50% of all emissions generated) or in the rest of the world (from 50% to 60%). An example of emissions caused in Germany to supply another country's final demand (*exported emissions*) are the emissions from German gas plants to power car factories whose product is ultimately sold abroad. Conversely, the emissions related to the extraction of gas in Russia are associated with *traversing emissions*.

4. Discussion

In this section, we discuss the findings of the previous section and we explore the types of policy options that the different elements of the TBA may help to design. In the previous section we have applied the TBA framework to assess all upstream CO₂ emissions caused by the supply chains associated with the German economy. Specifically, we estimated the German CO₂ throughflow, i.e. the upstream emissions caused by supply chains originating from, passing through or ending in Germany, to be 1.26 Gt CO₂. Some but not all of these emissions could have been identified using alternative accounting techniques.

First, *local* and *exported* emissions could have been identified by means of the PBA framework. They are generated within the country and are thus the emissions a country has the most control on, as direct policy measures can be implemented domestically to limit them, e.g. by regulating the use of the most polluting processes, by supporting the adoption of cleaner technologies or by enforcing a carbon price on domestic production. Second, *imported emissions* could have been identified using the standard CBA framework (Davis et al., 2011; Kagawa et al., 2015; Peters, 2008). These emissions are more challenging to address, as they are produced abroad. Consumption-side policies may be implemented to curb the use of the most emissions-intense commodities, for instance using consumption taxes or by informing the final users about the emissions caused abroad. Such consumption-side policies may also contribute to reducing the emissions caused by

Figure 4. Position of the German economy in supply chains generating CO₂ emissions. A. Indication of the role of the German economy in the supply chains causing territorial emissions. Colouring of countries indicates the share of emissions generated in these countries to supply the German final demand (imported emissions), as a percentage of all emissions generated along the supply chains involving the German economy (imported and traversing emissions). B. Indication of the role of the German economy in supplying the final demand of other countries. The colour of a country shows the share of emissions caused in Germany to supply the final consumption in that country (exported emissions), as a percentage of all emissions caused to supply the final demand of that country via the German economy (exported and traversing emissions). Germany is shown in black. Countries for which no data are available are shown in grey.



local supply chains, as these are also dependent on domestic final consumers. While the TBA is conceptually coherent with both the PBA and CBA frameworks, the exact figures we obtain for PBA and CBA in our case study may differ from those found in other studies because of the use of different primary data sources and because of differences in

accounting perimeters. For instance, our figures do not include direct emissions from final users, nor emissions from international transportation.

Finally, supply chains *traversing* the German economy are causing emissions abroad and do not supply domestic final users. These emissions are thus not revealed by the PBA and CBA frameworks and left unaddressed by both production-side and consumption-side policy measures, even though they represent 30% (379 Mt CO₂) of the German through-flow according to our analysis. Such emissions could be targeted through supply chain specific measures, for instance by changing production processes to reduce the usage of the most emissions-intensive inputs or by sourcing these inputs from relatively low-carbon producers. Such supply chain specific policy options are usually explored using SPA, BBA or related frameworks (Hanaka et al., 2017; Liang et al., 2016; Maeno et al., 2022). As SPA and BBA techniques double count emissions caused by supply chains that loop into the German economy several times, these techniques may indicate higher volumes of CO₂ emissions than identified here. BBA or SPA frameworks may often be better suited for investigating supply chain specific policy actions than a HEM-based framework such as ours or such as the one proposed by Hanaka et al. (2022) because productivity improvements in one sector may have a multiplier effect if such sector is involved in several production steps of the same supply chain (Tokito et al., 2022).

Alternatively, *traversing emissions* could be targeted through the implementation of a comprehensive carbon pricing policy. While usual carbon pricing schemes only apply to domestic emissions, the implementation of Border Adjustment Mechanisms (BAMs) allows extending the carbon price to imported products as well (Böhringer et al., 2022; Sakai & Barrett, 2016). In such a case, the carbon price would cover both *local*, *exported*, *imported* and *traversing* emissions, hence corresponding to the whole throughflow. Conversely, the introduction of export rebates could be helpful to preserve the competitiveness of domestic companies and would relieve *exporting* and *traversing* supply chains from the carbon price (i.e. covering the emissions measured by CBA only). Because of the problem of double counting, BBA, SPA and related methods are not applicable to comprehensive carbon taxation analysis.

However, techniques usually applied to investigate the TiVA (Borin & Mancini, 2019; Koopman et al., 2010, 2014; Los & Timmer, 2018) could theoretically be used to derive the volume of CO₂ emissions traversing the German economy as done in the TBA, although we are not aware of any such study at the time of writing this paper. Meng et al. (2018) have used TiVA methods to investigate the share of foreign CO₂ emissions in Germany's gross production. Using MRIO data from 2009, they estimate that 35% of the emissions required to produce final goods and services in Germany are caused outside of Germany. This measure is not directly comparable to the throughflow due to a different framing: Meng et al. (2018) focus on emissions caused by the production of final commodities in Germany, while the throughflow includes the production of intermediate commodities as well. In the TBA, we measure the share of foreign emissions (i.e. *imported* and *traversing* emissions) to amount to 56% of the total production of products and services in Germany (i.e. the German *emission throughflow*). The inclusion of intermediate products may partly explain the difference between our result and the one from Meng et al. (2018) but the use of a different and older MRIOT is likely to contribute to this difference as well. Overall, both the TiVA methods and the TBA are applicable for investigating the implementation of BAMs, as both approaches exclude counting the same emissions multiple times. The TiVA

methods are in principle more flexible than the TBA, as they can be applied to specific trade relations. Conversely, the TBA provides a broader and more intuitive overview of the emissions a country could target through its supply chains' involvement.

Finally, we used the TBA decomposition of the German CO₂ throughflow to derive insights into the position of Germany in carbon-intensive Global Value Chains (GVCs). Our finding that Germany is a major emission hub both at the EU and at the global scale is coherent with more general studies on the position of the German economy in GVCs (Amador & Cabral, 2017; Godard & Gorg, 2011; Los et al., 2015; Xiao et al., 2020). However, in these studies, the German economy is shown to be trading in the same proportions with European than with non-European countries. Our results show instead a stronger representation of non-EU countries than EU countries in the CO₂ emissions caused by German exports and imports (see Figure 3). Beyond divergences in primary data sources, differences in emission intensities between EU and non-EU countries may be an explanation for the difference between our results and the pre-existing literature, as supply chains originating from non-EU countries are usually more carbon-intense than those originating from other EU countries.

The TBA framework paves the way for analysing a new category of policy measures. TBA does not allocate responsibilities for externalities exclusively to producers (as in PBA), to consumers (as in CBA), nor does it divide such responsibilities between all agents involved (as in SPCR, Gallego & Lenzen, 2005). Instead, the TBA framework comprehensively acknowledges the potential for each individual agent to mitigate externalities globally. In terms of policy making, countries could enforce pressure on other actors involved in the same supply chains, for instance by implementing BAMs or by restricting the trade of commodities involved in externalities production elsewhere. Our analysis shows that focusing on the throughflow offers a larger leverage than either the PBA and CBA perspectives, because it also addresses supply chains that are only traversing a region. Such throughflow-based perspective is relevant in the context of the carbon BAM envisioned in the European Union (European Commission, 2021a) and with respect to trade bans aiming at avoiding deforestation (European Commission, 2021b) or at safeguarding human rights abroad (European Commission, 2022). TBA provides a straightforward and comprehensive framework to gain insights into the potential spill-overs of such unilateral trade policies.

5. Conclusion

We here introduced the throughflow as the volume of upstream externalities generated by the supply chains a country is involved in; that is, the externalities generated along supply chains starting from, traversing or ending in a given country. We further defined the Throughflow Based Accounting (TBA) as the decomposition of the throughflow based on the origin and the destination of the supply chains causing these externalities. TBA has a broader perimeter than the commonly used externalities accounting frameworks: it accounts simultaneously for externalities directly produced in a country (as in Production Based Accounting), for externalities induced by the final consumption in a country (as in Consumption Based Accounting) and for externalities caused by the supply chains traversing that country (related to Betweenness Based Accounting, BBA). TBA hence captures all externalities that could be targeted by a country, either through supply-oriented,

demand-oriented or trade-oriented policy actions. In comparison to other accounting techniques based on the Hypothetical Extraction Method (Borin & Mancini, 2019; Hanaka et al., 2022; Koopman et al., 2010, 2014; Los & Timmer, 2018), the TBA decomposition is based on only four intuitive elements. While such simple framework comes with limitations, it renders the TBA straightforward and easily applicable beyond the Input–Output community.

The TBA gives a comprehensive overview of the upstream externalities a country could target through the supply chains it is involved in. Beyond international supply chains, there are other channels a country could explore to target externalities beyond its border, for instance via diplomatic efforts or via technology transfers (Ward et al., 2017). Similarly, the TBA only accounts for *upstream* externalities, i.e. externalities which have been produced at earlier stages of the supply chains. The TBA does not account for *downstream* externalities, i.e. externalities caused in further stages of the supply chains. For instance, limiting the trade of fossil fuel (Peters et al., 2012) or allocating primary inputs to less CO₂-intensive companies (Liang et al., 2017) have both a major potential for *downstream* mitigation of CO₂ emissions. Also, the TBA does not capture how many borders a supply chain is crossing (Zhang et al., 2017, 2020, 2020), which could be useful for assessing how directly other actors in international supply chains would be affected by local policy decisions.

Beyond estimating the volume of externalities a country could target through its supply chains, the estimation of the impact of actual policies requires dynamic approaches that go beyond the scope of this method. In particular, the reduction of the throughflow of a country may not necessarily coincide with a reduction of global negative externalities. For instance, Jakob and Marschinski (2013) show that reducing the imports of emissions-intensive commodities does not necessarily reduce global emissions, as the substitution of imports by domestic production may be more emissions-intensive. Similarly, shrinking the throughflow of one country does not necessarily reduce the global production of a negative externality. For instance, a diminishing throughflow in one country may simply be associated with a symmetrical increase of another country's throughflow as a result of the redirection of supply chains through this other country. A rudimentary integration of dynamic mechanisms in the TBA framework, as already envisioned for the PBA and CBA frameworks (Jakob et al., 2021), could acknowledge the flexibility of the global trade relations and provide more detailed insights into the power of intermediates to influence externalities production elsewhere.

As an intelligible flow-based approach, the TBA can readily be used to inform policy- and decision-makers on the potential for negative externalities mitigation by consumers, producers, and intermediates across the world. In the climate change mitigation debate, the fragmentation of the global trade regime has made the case for local policy measures to reduce emissions globally more attractive (Jakob et al., 2022): policy options to reduce carbon emissions abroad such as Carbon Border Mechanism Adjustments are now discussed in the EU (European Commission, 2021a). By straightforwardly identifying all the emissions caused by supply chains going through the EU economy, the TBA can be used to identify the countries which would be impacted by such measures.

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Data availability statement

All data and code used for this study are available on Zenodo (DOI: [10.5281/zenodo.7327470](https://doi.org/10.5281/zenodo.7327470)).

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The network effects of the EU CBAM

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ABSTRACT: The European Union (EU) will implement a Carbon Border Adjustment Mechanism (CBAM) to reach its climate mitigation targets while avoiding the relocation of its industries to countries with less stringent climate policies (carbon leakage). The exact implementation and possible future extensions of such an EU CBAM are still being debated. Here we apply a throughflow-based accounting method on detailed trade network data to assess the coverage of different implementation options. Using a stylized comprehensive EU CBAM as benchmark, we then quantify how an EU CBAM may affect the EU's trade partners by channeling the EU carbon price to other countries. We find that middle- and low-income countries for which the EU is an important export market would be disproportionately impacted even under conservative implementation options. We finally explore different international revenue recycling schemes to make the EU CBAM inclusive toward vulnerable countries and able to foster global climate cooperation.

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Assessing different European Carbon Border Adjustment Mechanism implementations and their impact on trade partners

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The European Union (EU) will implement a Carbon Border Adjustment Mechanism (CBAM) to reach its climate mitigation targets while avoiding the relocation of its industries to countries with less stringent climate policies (carbon leakage). The exact implementation and possible future extensions of such an EU CBAM are still being debated. Here we apply a throughflow-based accounting method on detailed trade network data to assess the coverage of different implementation options. Using a stylized comprehensive EU CBAM as benchmark, we then quantify how an EU CBAM may affect the EU's trade partners by channeling the EU carbon price to other countries. We find that middle- and low-income countries for which the EU is an important export market would be disproportionately impacted even under conservative implementation options. We finally explore different international revenue recycling schemes to make the EU CBAM inclusive toward vulnerable countries and able to foster global climate cooperation.

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The European Union (EU) aims to reduce net greenhouse gas emissions by at least 55% by 2030, relative to 1990¹. The reach of this ambitious goal relies largely on the reform and extension of the EU Emissions Trading System (ETS). Under an ETS, a limited volume of emission permits is auctioned or freely allocated to emitters and then traded on a dedicated market. The resulting emission price penalizes carbon-intensive production and incentivizes the adoption of low-carbon technologies². However, higher costs for industries subject to an ETS may lead to a relocation of carbon-intensive industries to countries with less stringent climate policies³. In order to minimize such “carbon leakage”, the EU ETS currently entails free allowances: a limited amount of emission permits allocated to sectors particularly exposed to carbon leakage (emission-intensive and trade-exposed sectors—EITE), to avoid competitiveness distortion for EU producers on both the domestic and export markets. However, free allowances are criticized for hindering the EU ETS by reducing the emission reduction ambition in EITE sectors and are incompatible with the EU target of net-zero emissions by 2050⁴.

As part of the “Fit for 55” policy package, the EU will gradually replace the free allowances by a Carbon Border Adjustment Mechanism (CBAM)¹. This CBAM will apply the price prevailing on emission allowances within the EU ETS to emissions released to produce commodities imported to the EU, unless a comparable emission price is already enforced in the exporting country. Export rebates are also currently discussed to refund allowance costs for products exported from the EU⁵. While a CBAM without export rebates would level the playing field within the EU domestic market only, export rebates would ensure that the competitiveness of EU production on the world market can be maintained.

Beyond producers and consumers within the EU, such an EU CBAM will affect other economic actors along international supply chains. Numerical analyses have shown that, even though the EU CBAM could in principle motivate emissions reduction abroad, key EU trade partners could as well retaliate with trade sanctions^{5,6}. Understanding how the EU emission price is channelled to other countries is therefore crucial to increase acceptance of the CBAM by EU trade partners and to avoid repercussions on the global climate cooperation. Previous studies have analyzed the effect of an EU CBAM on the EU’s major trade partners^{5,7,8}, but little is known about the exposure of middle- and low-income countries as they are usually modeled at a low level of detail. Yet, research at the sub-regional level has shown that the distributional effects of an EU CBAM might exhibit a broad variation depending on local conditions⁷.

We contribute to this literature by developing an analytical framework that allows numerically assessing the emission coverage of different EU CBAM implementations and their effects on the EU’s trade partners with a high spatial resolution. For that purpose, we use a throughflow-based accounting technique that allows us comprehensively tracking the CO₂ emissions caused by all the supply chains starting from, going through, and ending in the EU⁹ and apply it on highly-detailed economic network data from 2016^{10,11}. This approach enables estimating the pressure that an EU CBAM would impose on individual countries through direct and indirect trade dependencies, before any dynamic trade adjustments. Even though such trade adjustments might be changing the final effect of the CBAM, modelling them usually requires major assumptions on model parameters, a reduction of the regional resolution and a decrease in the tractability of the model. Here, by using simple assumptions, we complement such dynamic approaches by transparently estimating the drivers of these dynamic effects. Furthermore, we provide an assessment of the exposure of

middle- and low-income countries to the EU CBAM that is missing in the current literature.

The structure of the paper is as follows. First, we assess the coverage of several implementations of an EU CBAM based on different assumptions of products and scopes coverage. Second, we use a hypothetical Comprehensive CBAM (CCBAM) that covers all emissions generated by producing imports to the EU as a benchmark for evaluating the multilateral effects of the EU CBAM: we explore conceptually through which channels carbon pricing within the EU affects its trade partners and empirically identify the countries that would likely be the most affected by an EU CCBAM. Third, we propose compensating schemes for an international recycling of the revenues of such an EU CCBAM to make it inclusive toward the most vulnerable countries. In the final section, we discuss the limitations of our approach, the robustness of our findings and their implications for policymaking.

Our results show that the coverage of the current EU CBAM proposal is relatively modest compared to the total emissions caused by all EU imports, and that this incomplete coverage might limit the efficiency of the EU CBAM. Even with conservative implementation options, we find that some low- and middle-income countries dependent on the EU for their exports would be disproportionately affected by the EU CBAM, as a large share of their domestic emissions would be covered by the EU emission price. Finally, the implementation of an inclusive international recycling of the EU CBAM fiscal revenue might increase the acceptability of the EU CBAM globally by mitigating its impacts on the most vulnerable countries, but its implementation will require balancing the conflicting interests of the EU trade partners.

Results

Comprehensiveness of the EU CBAM. The CBAM that will be introduced in 2023 will initially only apply to the direct emissions caused by the production of iron and steel, aluminum, cement, fertilizers, electricity and hydrogen imported into the EU¹. Based on Multi-Regional Input-Output data for the year 2016^{10,11}, we estimate these emissions to be 83 Mt CO₂ (Fig. 1, “Scope 1 emissions”, “Conservative coverage”), in absence of trade adjustments (see discussion). As per the current CBAM proposal, a further extension of the CBAM to a broader range of products (horizontal coverage) is already envisioned (“the coverage of the CBAM should reflect the activities covered by the EU ETS”¹). Encompassing all the sectors currently covered by the EU ETS would increase the coverage of the EU CBAM to 179 Mt CO₂ (“Scope 1 emissions”, “Ambitious coverage”). As electricity production is a major source of emissions globally, the planned EU CBAM should also cover indirect emissions from electricity use (Scope 2 emissions)¹. Some downstream products derived from emission-intense commodities will likely be covered as well, as otherwise exporters to the EU could easily circumvent the EU CBAM by trading unregulated processed products instead of regulated raw materials. We estimate that including both scope 2 emissions and downstream products into the CBAM could enhance the volume of emissions covered by the EU CBAM to 328 Mt CO₂ or 490 Mt CO₂, depending on the horizontal coverage (“Scopes 1 and 2 and downstream product”, “Conservative coverage” and “Ambitious coverage”, respectively). Finally, an EU CBAM that would also cover the direct industrial emissions caused by EU imports in sectors not covered by the current EU ETS would amount to 504 Mt CO₂ when excluding downstream products (“Scope 1 emissions”, “Comprehensive coverage”) and to 932 Mt CO₂ when including these (“Scope 1 and 2 emissions and downstream products”).

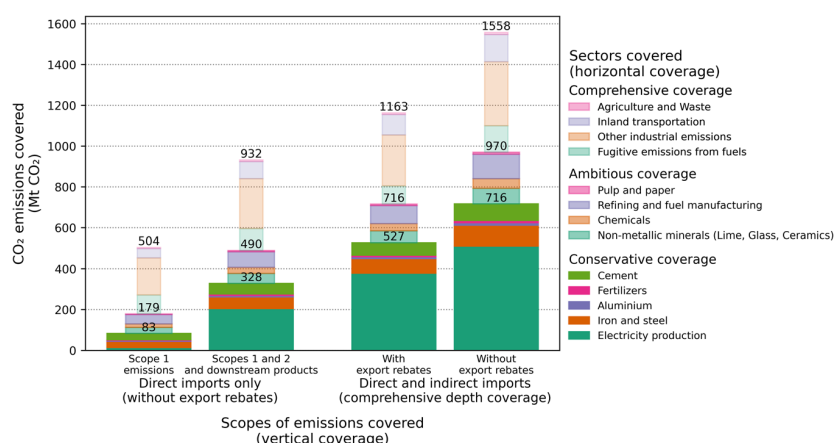


Fig. 1 CO₂ emissions covered by an EU CBAM under different implementation options. Bars show how much CO₂ emissions would be covered by an EU CBAM (assuming no trade adjustments), depending on the scope of emissions accounting (i.e., the number of layers in the supply chains included in emissions estimations - vertical coverage) and on the sectoral coverage (i.e., the sources of emissions covered by the EU CBAM — horizontal coverage). Four alternative vertical coverages are shown here. The option “Scope 1 emissions” only covers emissions directly caused by imports to the EU. Option “Scopes 1 and 2 and downstream products” also includes the emissions of the direct suppliers of exporters to the EU. These two implementation options are in line with the current EU CBAM proposal. By contrast, the “Direct and indirect imports” options account for all upstream emissions caused along the supply chains used to produce exports to the EU. In the setting “With export rebates”, emissions caused by EU imports for producing goods that are further exported from the EU are excluded from the EU CBAM coverage. Estimated CO₂ emissions are detailed based on the process causing them (see Methods and Data). These processes are grouped into three horizontal coverage aggregates. The “Conservative coverage” category (dark, wide blocks) entails emissions that are explicitly addressed in the EU CBAM proposal. These provide a lower bound estimate of the emissions that would be covered by the current EU CBAM proposal. Sectors included in the “Ambitious coverage” category (half-transparent, medium width blocks) are processes covered by the current EU ETS which may eventually be covered by the EU CBAM as well. The sum of the emissions covered in the conservative and ambitious categories form together the upper bound of a sectoral coverage in line with current EU CBAM policy proposal. Adding light and thin blocks forms a “Comprehensive coverage” category, which would cover all sectors and all sources of emissions and hence corresponds to an extension of the CBAM to all industrial emissions. All data refer to 2016. International transportation-, land use- and final use-related emissions are not included here. Detailed data points are provided in Supplementary Table 1. Supplementary Table 2 details the processes covered in the different horizontal coverages.

A Comprehensive CBAM (CCBAM) that would address all imports to the EU (“Comprehensive coverage” on the horizontal dimension) and all indirect emissions caused by these imports (“Direct and indirect imports - Without export rebates”) would cover 1 558 Mt of CO₂ through products imported to the EU. Even for the most conservative product coverage (“Conservative coverage”), a comprehensive scope of emissions already increases the volume of emissions priced nine fold (from 83 to 716 Gt CO₂ — “Direct and indirect imports - Without export rebates”). In particular, emissions from indirect electricity use increase sharply from 14 MtCO₂ to 511 Mt CO₂ (see Supplementary Table 1) when considering a deeper accounting scope: direct electricity imports to the EU represent only 3% of the total emissions from the electricity used to produce EU imports (“Direct and indirect imports - Without export rebates”).

Failing to comprehensively price the upstream emissions caused by EU imports could decrease the competitiveness of some EU industries in the long term, as producers along the supply chains located in third countries would not bear the price of upstream emissions. As the announced EU CBAM would only cover a fraction of all emissions caused by products imported to the EU, it would only partially level the playing field between EU producers and their international competitors. In contrast, an EU CCBAM would thoroughly reconcile the EU abatement targets with competitiveness concerns. Even though such a CCBAM is still hypothetical due to administrative, technical, legal, and political reasons⁵, it can serve as useful benchmark to evaluate the comprehensiveness of alternative CBAM implementations. In the remainder of the paper, we will focus on such an EU CCBAM and evaluate its impacts on the EU’s trade partners. We assess the

robustness of our findings with respect to more conservative implementation options in the discussion section.

Pricing locally, counting globally. An EU CCBAM covering all sectors and scopes in combination with a comprehensive carbon price on all EU domestic industrial emissions would cover a total of 3871 MtCO₂ (Fig. 2). About 60% of these emissions stem from domestic industrial production, while the remaining 40% would be priced via the EU CCBAM. Under such a CCBAM regime, exporters to the EU compete under an emission price (Fig. 2a, lower left corner): as the emissions they cause increase the price of their products, they have an incentive to reduce their emissions and those of their suppliers to gain competitiveness on the EU market. We call this incentive of the EU ETS is also channelled downstream along the supply chains, to non-EU consumers (Fig. 2a, lower right corner). However, such downstream pressure may have a negative effect on global carbon emissions, as it distorts the international competition in favor of producers not subjected to a carbon price (consumption leakage)¹². The combination of a domestic carbon price, a CCBAM and export rebates hence conveys the upstream pressure while minimizing the potentially adverse downstream pressure.

Beyond the upstream and downstream pressures created by an EU CCBAM and a domestic carbon price, these policy instruments would also create a fiscal resource for the EU (Fig. 2b). Assuming a carbon price at 100€/t CO₂, the combination of a domestic carbon price and an EU CCBAM would yield between €293 billion (with export rebates) and €387 billion (without export rebates) per year to the EU budget, which

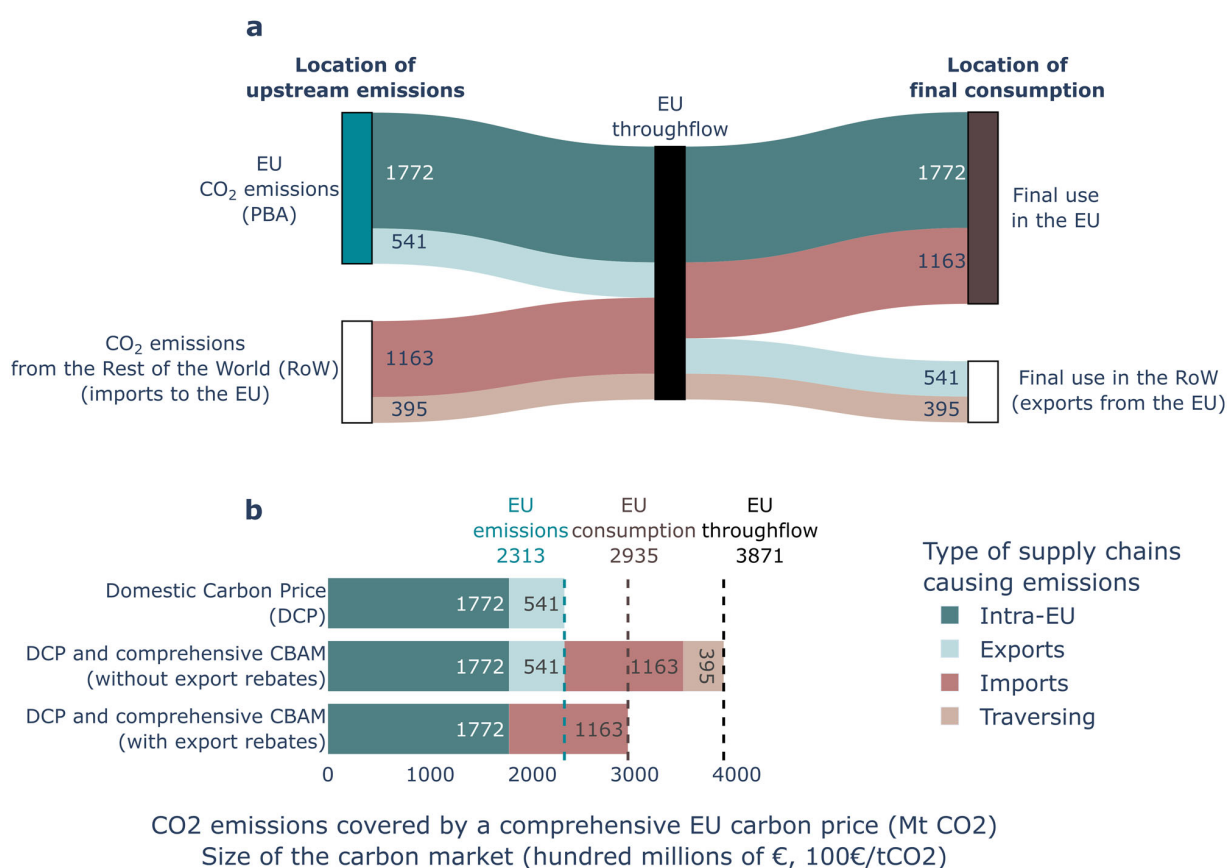


Fig. 2 Multilateral effects of comprehensive carbon pricing options in the EU. Panel **a** shows the upstream CO₂ emissions released along the supply chains involving the EU (central black bar). These emissions occur either in the EU (blue bar, upper left) or in the rest of the world (white bar, bottom left). The final product of these supply chains is used either in the EU (brown bar, upper right) or in the rest of the world (white bar, bottom right). The flows' thickness is proportional to the volume of upstream CO₂ emissions caused. Panel **b** describes the type of the supply chains covered by different comprehensive carbon pricing options and the size of the carbon market created, assuming an illustrative carbon price of 100€ per tCO₂. A Domestic Carbon Price (DCP) would cover all emissions generated within the EU, both for producing goods consumed in the EU (Intra-EU supply chains, dark green) and for producing goods consumed abroad (exports, light green). A comprehensive CBAM without export rebates would cover imported emissions as well (dark and light red), no matter whether these imports ultimately serve final users in the EU (Imports, dark red) or are used to produce goods further reexported outside of the EU (traversing supply chains, light red). Export rebates would exclude exported as well as traversing supply chains from the carbon pricing. We consider no free allocations here, as these are supposed to be phased out while the EU CBAM gets implemented. The comprehensive coverage analyzed here corresponds to a comprehensive sectoral coverage and a comprehensive depth coverage (see Fig. 1). We do not consider potential trade adjustments here.

corresponds to about 660€ per year and 870€ per year per EU citizen, respectively¹³. Even though our analysis likely overestimates the revenue of an EU CBAM (see the discussion section below), the existence of such fiscal revenue could create an incentive for non-EU countries to implement their own carbon pricing scheme — at least on their exports — to get the fiscal revenue otherwise captured by the EU.

This incentive would apply more intensively to countries releasing a large share of their emissions to supply the EU final consumers, as a substantial portion of their domestic CO₂ emissions would be covered by an EU CCBAM (relative upstream pressure, Fig. 3). According to our analysis, this is the case for many middle- and low-income countries, in particular in North and Sub-Saharan Africa. As the exports from these countries are largely directed to the EU and poorly diversified (Supplementary Fig. 1), these economies would have limited options to dampen the upstream pressure caused by an EU CCBAM. Furthermore, most of these countries have minor historical emission responsibilities while simultaneously being at the front line of climate change impacts^{14–16}. An EU CCBAM that would put high

pressure on such countries would oppose the fundamental principle of “shared but differentiated responsibilities” of the United Nations Framework Convention on Climate Change, which states that those countries should be supported in their transition to a low-carbon economy¹⁷.

Building a climate coalition. The implementation of a comprehensive and inclusive EU CCBAM could therefore include compensating measures to acknowledge the differentiated responsibilities of the EU's trade partners in the climate crisis. One avenue to alleviate the upstream pressure caused by a comprehensive EU CCBAM on the most vulnerable countries is to exempt them, either indirectly by limiting the coverage of the EU CCBAM to a selected set of industrial commodities which are not essential for these countries, or directly by exempting the imports from these countries from the EU CCBAM. However, restricting the EU CCBAM to a range of industries secondary to these countries would create a substantial entry cost to these sectors, which may hinder their development in low- and middle-

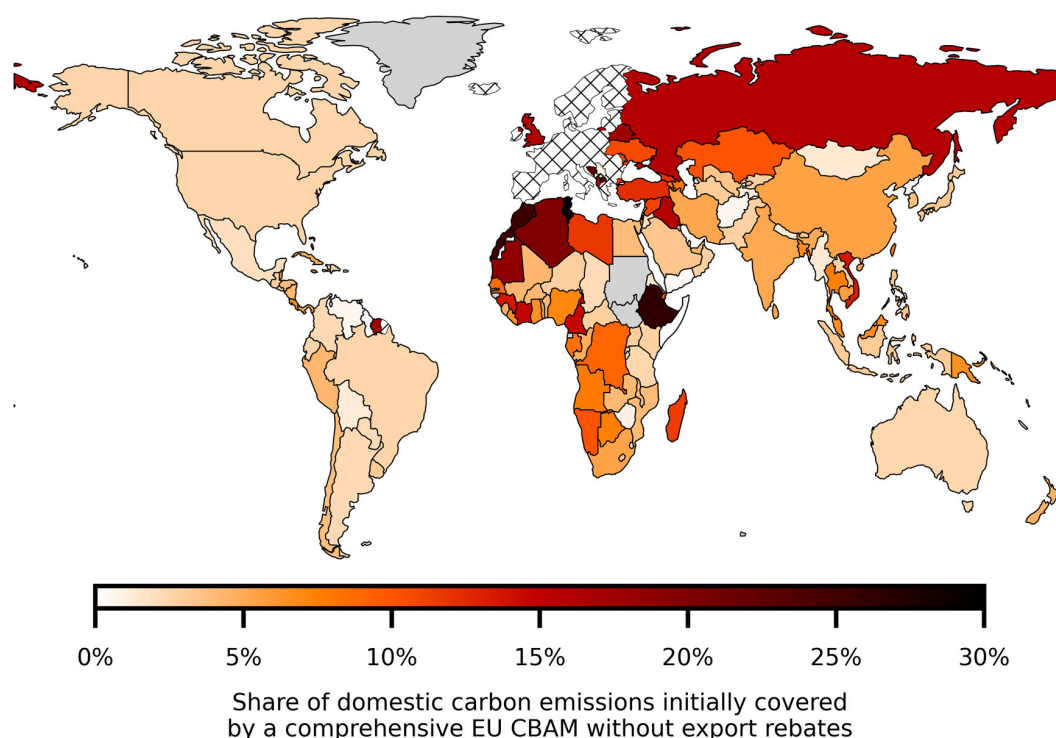


Fig. 3 Relative upstream pressure induced by a comprehensive EU CBAM without export rebates. The relative upstream pressure is defined as the share of CO₂ emissions caused to supply the final demand in the EU, as a percentage of domestic carbon emissions. Grey indicates lack of data, hatchings indicates member countries of the EU ETS. The relative upstream pressure does not consider possible trade adjustments.

income countries. In turn, exempting some countries from the EU CCBAM could give an incentive to these countries to develop emission-intensive industries, hence creating “pollution havens” and harmful lock-in effects¹⁸. An alternative, but less discussed avenue is an international recycling of the EU CCBAM revenues (Fig. 4). As for the double dividend yielded by a coherent recycling of the revenue of a domestic carbon price¹⁹, the inclusive recycling of the revenues of the EU CCBAM could likely benefit global climate cooperation, both by increasing the acceptability of the EU climate policy within non-EU countries and by helping the most vulnerable countries to access low-carbon technologies or to adapt to a changing climate.

Implementing an inclusive recycling scheme of an EU CCBAM revenue would require balancing the conflicting interests of the EU trade partners. In absence of revenue recycling, fossil fuel exporters such as Russia, Algeria or Saudi Arabia would be strongly affected by an EU CCBAM on a per capita basis (Fig. 4a). Refunding countries proportionally to the upstream pressure they experience would hence implicitly favor fossil fuel exporting countries (Fig. 4b), compared to the absence of a recycling scheme (Fig. 4a). Such option might ease the implementation of the EU CCBAM by saving the interest of major trade partners and limit the likelihood of trade retaliations⁶. However, it is at risk of neutralizing the effect of the carbon price, unless the recycled revenues are targeted toward the development of low-carbon alternatives.

Alternatively, the EU CCBAM revenue could be used to foster low-carbon development and to compensate for the damage caused by historical CO₂ emissions. Recycling schemes based on historical climate damages (Fig. 4c, here based on an empirically derived estimate of the influence of anthropogenic climate forcing on historical economic output²⁰), or on per-capita revenue (Fig. 4d) would strongly benefit countries in Africa, South-East

Asia, and South America. In particular, a recycling scheme aligned with historical or expected climate damages could support the “loss and damages” climate fund agreed upon at the 27th United Nations Conferences of the Parties in 2022²¹. In conclusion, a recycling scheme targeted at helping low- and middle-income countries to adapt to a warmer climate and to develop low-carbon technologies could be a compensation for these countries and render them more likely to accept the implementation of an EU CCBAM. However, such a recycling scheme would not decrease the risk of retaliation from major EU trade partners such as the US, China, and fuel-exporting countries, as these would remain net losers in most settings assessed here. Designing an inclusive revenue recycling scheme for the EU CBAM will hence require balancing these conflicting interests.

Discussion

Our analysis is based on a throughflow-based accounting framework that evaluates the effects of a comprehensive EU CBAM in terms of upstream and downstream pressures, based on the CO₂ emissions that would be covered by the implementation of an EU CCBAM. Our approach does not depict possible dynamic adjustments in production, trade, and consumption patterns, such as a transition to low-carbon energy production by trade partners or a shift to importing goods with a lower carbon intensity in the EU⁸. Considering possibilities to respond to a carbon price by, for instance, applying more efficient production technologies or using low-carbon energy sources would lower the adjustment burden and reduce the EU CCBAM revenue and coverage estimated here. The extent to which countries can adjust depends inter alia on their export portfolio, their technological capabilities, and their potential to produce renewable energy²².

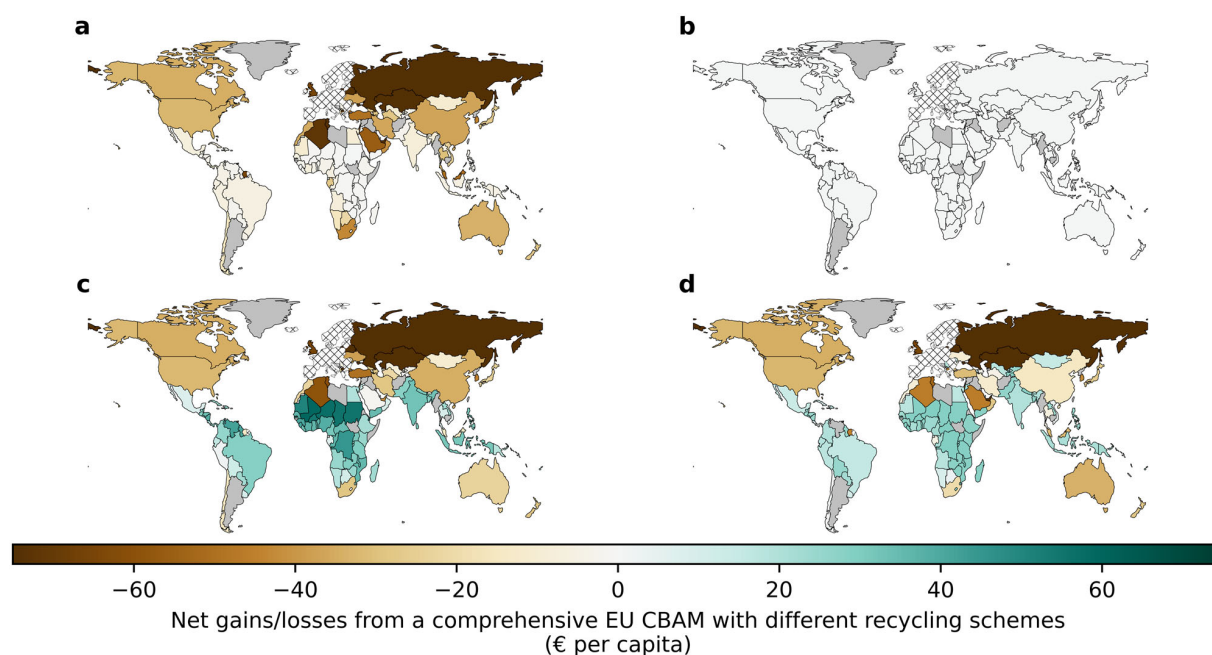


Fig. 4 Inclusiveness of a comprehensive EU CBAM without export rebates if the revenue is fully recycled towards non-EU countries based on different indicators. The proportion of the revenue each country receives is estimated based on the following indicators (see Materials and Data for details): **a** No recycling; **b** Emissions covered by the comprehensive EU CBAM; **c** Historical impacts of anthropogenic warming on economic output²⁰; **d** Difference in per capita Gross Domestic Product to the EU average. Losses are assumed to correspond to the upstream pressure, measured as the value of CO₂ emissions caused in a country to supply the final demand in the EU multiplied by a carbon price of 100€ per tCO₂. Grey indicates lack of data, hatching indicates member countries of the EU ETS. Supplementary Fig. 2 shows the revenue recycled to each individual country on a per capita basis.

For instance, whereas producers of energy-intensive products can draw on a range of available mitigation options, exporters of fossil fuels will face larger challenges to reduce the emission intensity of their exports. Hence, the former will find it easier to adjust to an EU CCBAM than the latter. The implications of these adjustments cannot be addressed by our method: quantifying such effects requires making a range of assumptions on parameters for which a strong empirical basis is largely missing. This would add substantial uncertainty to the analysis and make the interpretation of the results of our analysis challenging. Instead, a static approach similar to ours is frequently employed in analyses of the distributional effects of climate policy for the sake of tractability²³. Reconciling our framework with dynamic models allowing some level of adjustment while conserving a high enough regional resolution is a promising avenue for future research.

Our methods and data entail several sources of uncertainties that may affect our numerical results. First, economic network and emission data from middle- and low-income countries may be of limited quality and have a limited sectoral resolution^{10,11}. Second, our assessment of the CO₂ emissions caused by EU imports uses process-based emission data, while the EU CBAM is applied at the product level. Since few studies have focus on the impact of a CBAM on low- and middle-income countries, further research using alternative data sources and methods is required to validate our findings. Another source of uncertainty is the temporal dimension: our analysis uses data from 2016, while the EU CBAM will become operational in the forthcoming years. Technological change such as the implementation of low-carbon processes and energy sources should arguably reduce the volume of emissions covered by the EU CBAM. As high-income countries are globally setting more ambitious abatement targets than middle- and low-income countries, it is likely that the wealthiest

trade partners of the EU will decarbonize their economies faster than low- and middle-income countries. Our finding that the latter are more strongly exposed to the EU CBAM hence seems robust to this aspect. Hydrogen production is also not included in our model as it was marginal in 2016, even though it may become a larger source of emissions in the future as the trade of hydrogen is set to increase in the next decades²⁴. Using prospective models and data might provide guidance on the future distributional effects of the EU CBAM but would also imply major uncertainties regarding technological change and economic development scenarios.

As shown in Fig. 1, the comprehensive EU CCBAM that we analyze is more ambitious than the EU CBAM currently envisioned: based on our analysis, an EU CCBAM would cover between 3 and 20 times more emissions than the current policy proposal and fully level the playing field between the EU producers and their international competitors with regard to carbon pricing. However, the implementation of such a CCBAM faces challenges that we cannot address here. For instance, the proper channeling of the EU carbon price would require an accurate, regularly updated, and transparent estimation of the CO₂ emissions caused for the production of each individual product imported to the EU, which goes beyond the capability of current evaluation techniques²⁵. Even if such product-level assessment was available, the administrative costs of monitoring such an EU CCBAM and the induced trade frictions could exceed the financial benefits of extending the EU CBAM to a comprehensive product and scopes coverage⁵. While an EU CCBAM is largely hypothetical, it remains theoretically attractive as it provides a simple benchmark to compare possible implementations to. At the same time, it allows avoiding assumptions on the exact design of the EU CBAM, which is still under debate, thus making our analysis more transparent. Still, we acknowledge that both the

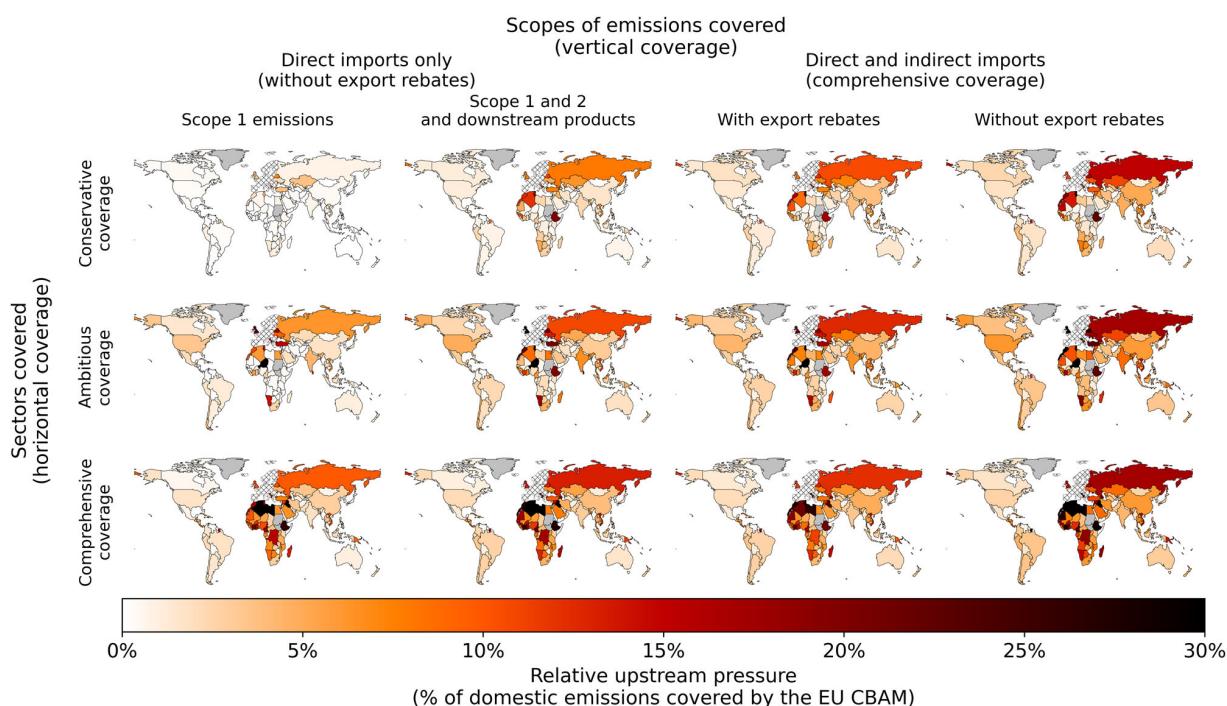


Fig. 5 Distribution of the relative upstream pressure under different EU CBAM implementations. Coloring shows the share of domestic emissions of each country covered by the EU CBAM implemented. Rows indicate the types of emissions covered by the EU CBAM (see Fig. 1). Columns correspond to the scope of emissions being covered by the EU CBAM (see Fig. 1). The numerator of the relative upstream pressure corresponds to the volume of emissions caused in the corresponding country and priced by the EU CBAM (absolute upstream pressure). The denominator is the domestic volume of emissions in the sectors covered by the EU CBAM. The upper-left panel corresponds to the most conservative estimation of the coverage of the EU CBAM (only direct emissions from a few sectors). The bottom-right panel corresponds to a comprehensive EU CBAM without export rebates, as shown in Fig. 2.

volume of CO₂ emissions covered by a realistic EU CBAM and the subsequent fiscal revenue raised would be lower than estimated here. With regard to the robustness of our findings, Fig. 5 shows the relative upstream pressure caused by the different EU CBAM implementations analyzed in Fig. 1. We find that, even with more conservative EU CBAM implementations, low- and middle-income countries dependent on the EU for their exports would still be disproportionately exposed to the relative upstream pressure caused by the EU CBAM, even though with a lower intensity. Our qualitative results thus remain largely valid for implementation options in line with the current policy proposal.

We here suggest the inclusion of an international revenue recycling scheme to the EU CBAM, to enhance the international acceptability of this policy and to foster global climate cooperation. Our analysis highlights which general principles could be used to design such inclusive policies, thereby abstracting from practicability concerns. First, our recycling indicators are based on several plausible normative perspectives on who should be entitled to receive this revenue. Our analysis hence provides a preliminary assessment of the dimensions along which an inclusive use of revenues could be designed and highlights potential trade-offs between these illustrative recycling options. For the design of an actual recycling scheme, these indicators should be carefully balanced and negotiated in order to build large enough international support to avoid major trade retaliation. Such indicators should be transparently evaluated and use up-to-date and robust data. The use of region-specific damage estimates as done here could provide a guidance in that direction, even though these estimates are subject to large uncertainties²⁶.

Second, building a truly inclusive recycling scheme raises governance issues, both within the EU and at the global level. At the EU level, consumers would bear most of the cost of the EU

CCBAM as consumption prices would increase because of the extension of carbon pricing. Fostering the acceptability of the EU CBAM internally arguably requires some internal revenue recycling mechanism as well, as already planned in the current EU CBAM¹. Balancing such internal redistribution mechanism with an international recycling scheme requires further work and collective deliberation. The use of dynamic approaches that account for both production and consumption elasticities could likely provide guidance in that direction^{7,27}. At the international level, an inclusive recycling scheme would also require some level of shared governance between the EU and its trade partners, particularly if this recycling is targeted toward adaptation and mitigation projects. Global discussion forums such as the Conferences of the Parties may in principle support these multilateral negotiations, but the unanimity principle involved there is likely not compatible with the ambition of the EU CBAM. Smaller forums such as the G7, the G20, or the OECD could also host such discussions, but would exclude low- and middle-income countries. Alternatively, the EU could involve third countries into the governance of the recycling of the EU CBAM revenue based on the voluntarily adhesion to an international Green New Deal, providing the adoption of minimal climate targets, for instance²⁸. At the cost of an increase of financial support toward low- and middle-income countries, the EU could then use a CBAM to reconcile the protection of its local industry against carbon leakage with a global reinforcement of climate mitigation policies. However, this solution will require overcoming the conflicting interests of its trade partners.

Methods

Data. Our model is based on the EORA 26 Multi-Regional Input Output Table (MRIOT) for 2016, which describes trade flows at the industry level between

26 sectors and 189 regions worldwide^{10,11}. EORA is the dataset with the most detailed spatial coverage available at the time of the study. Data on CO₂ emissions stem from the Primap-hist²⁹ and Primap-crf³⁰ datasets. Primap-hist contains emission data for all countries signatory of the United Nations Framework Convention on Climate Change (UNFCCC)¹⁷, but with limited details on the emitting sectors. Primap-crf provides a detailed disaggregation of CO₂ emission by process level following the Intergovernmental Panel on Climate Change (IPCC) classification, but is limited to Annex I countries of the UNFCCC. We use a tailored procedure to combine these two datasets and to map the resulting emission data to the EORA trade data⁹: First, detailed data from Primap-crf are extrapolated to all UNFCCC countries using aggregated data from Primap-hist and production data from EORA. Second, resulting emission estimates are allocated to EORA sectors. Note that PRIMAP emission data do not include emissions from international transportation nor from Land-Use, Land-Use Change, and Forestry (LULUCF). We also exclude direct emissions from final users from our analysis, as these would not be covered by a CBAM.

Modelling of the different CBAM implementation options. The different horizontal coverages (number of products covered by the CBAM) correspond to different grouping of process-based emission data based on their IPCC emission category (see Supplementary Table 2). The vertical coverages (scope of emissions accounted) are estimated using the MRIOT. Let imp^{ic} denote the value of imports of products from sector i in country c to the EU in basic prices and q_k^{ic} the volume of CO₂ emissions per unit of output in sector i in country c for IPCC category k . “Scope 1 emissions” from category k from country c , $E_{\text{scope1}}^{k,c}$ are estimated by multiplying the import array by the corresponding intensity emission array:

$$E_{\text{scope1}}^{k,c} = \sum_i q_k^{ic} \times \text{imp}^{ic}. \quad (1)$$

“Scope 2 and downstream emissions” are estimated by computing the emissions caused by the direct inputs required to produce imports to the EU. Let a_{ic}^{js} denote the technical coefficient, quantifying the value of input from sector i in country c required to produce one unit of output in sector j in country s , extracted from the MRIOT³¹. The emissions caused by inputs to EU imports for IPCC emissions category k ($E_{\text{scope2}}^{k,c}$) in country c are then:

$$E_{\text{scope2 and downstream}}^{k,c} = \sum_i \sum_{j,s \in \text{EU}} q_k^{ic} \times a_{ic}^{js} \times \text{imp}^{js}. \quad (2)$$

“Scope 1 and 2 and downstream emissions” values are then obtained by summing “Scope 1 emissions” and “Scope 2 and downstream emissions”.

Finally, the comprehensive coverages (i.e., “Direct and indirect imports”) are estimated using the Throughflow Based Accounting (TBA) method⁹. The TBA is an Input-Output Analysis technique to quantify the volume of upstream CO₂ emissions caused by supply chains starting from, going through, or ending in the EU. The core idea is to artificially exclude the EU from the global economy and to compare the actual world CO₂ emissions to the emissions in the hypothetical scenario where all supply chains involving EU countries are extracted. This difference is further decomposed into four elementary flows (intra-EU, imports, exports, and traversing) depending on where emissions occur physically and on where final users are located (see Fig. 2a). Emissions caused by traversing flows are excluded from the computation when exploring an EU CCBAM with export rebates, as these emissions are caused outside of the EU for making products ultimately exported from the EU. In absence of export rebates, both imported and traversing emissions are counted. A detailed description of the TBA method can be found in Beaufils et al.⁹.

Analysis of different revenue recycling schemes. Our recycling estimates (Fig. 3, Supplementary Fig. 2) use population and Gross Domestic Product (GDP) data from the World Bank for 2016^{13,32}. Historical costs of climate change at the country-level are here approximated by the impact of anthropogenic warming on annual economic growth as empirically estimated for the period 1991–2010²⁰. The estimates for the EU CCBAM-induced losses correspond to the value of CO₂ emissions caused in a country to supply the final demand in the EU (upstream pressure), assuming a carbon price of 100€ per tCO₂. The revenue estimates under the different recycling schemes are detailed below.

In panel a, no recycling is applied and the losses simply correspond to the volume of CO₂ emissions covered by an EU CCBAM without export rebates, assuming an illustrative carbon price of 100€ per tCO₂.

In panel b, the revenue is recycled proportionally to the emissions covered by the CBAM. We note p^c the population of country c , E^c the volume of emissions from country c covered by the EU CBAM. With τ the carbon price, the per capita fiscal revenue of country c in recycling scenario b , (r_b^c) is computed as:

$$r_b^c = \frac{1}{p^c} \times E^c \times \tau. \quad (3)$$

Panel c assumes no revenue for the countries which benefited from climate change (i.e., with negative historical damages²⁰). Climate damage estimates²⁰ are expressed as relative GDP losses (i.e., percent of GDP lost due to climate change), noted f^c . We weight these climate damages by a country’s population (p^c) to account for the number of people exposed. Revenue r_c^c is then allocated

proportionally to the share of each country in the global damages:

$$r_c^c = \frac{\max(0, f^c)}{\sum_{s \in \text{EU}} \max(0, f^s) \times p^s} \times \left(\sum_{s \in \text{EU}} \tau \times E^s \right). \quad (4)$$

Finally, revenue recycling in panel d accounts for the income per capita of a country c , noted w^c . Countries that have larger GDP per capita than the EU average receive no revenue in this scheme. Again, revenue differences are weighted by population. Per capita revenue recycled to country c in panel d, r_d^c , is finally computed as:

$$r_d^c = \frac{\left[1 - \min\left(\frac{w^c}{w^{\text{EU}}}, 1\right) \right]}{\sum_{s \in \text{EU}} \left[1 - \min\left(\frac{w^s}{w^{\text{EU}}}, 1\right) \right]} \times p^s \times \left(\sum_{s \in \text{EU}} \tau \times E^s \right). \quad (5)$$

Data availability

All data used and generated for this study are available on Zenodo³³ (<https://zenodo.org/record/7741702>), at the exceptions of proprietary MRIO data^{10,11}, accessible under academic license at <https://worldmrio.com/eora26/>.

Code availability

Python and iPython scripts used for processing data and generating the figures of this study are available in the Zenodo repository³³, with detailed instructions on how to replicate the results and figures (<https://zenodo.org/record/7741702>).

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Author contributions

T.B., M.J., H.W., and L.W. designed the study, interpreted the results, and revised the paper. T.B. collected and processed data, prepared figures, and wrote the manuscript with contributions from M.J., H.W., and L.W.

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Response options to the EU CBAM in Africa

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The EU Carbon Border Adjustment Mechanism as an incentive for carbon pricing in African countries

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ABSTRACT: The European Union (EU) is gradually phasing in the Carbon Border Adjustment Mechanism (CBAM). The CBAM will eventually apply the carbon price prevailing in the EU on emissions that were released to produce imports of certain carbon-intensive industries. This chapter uses Mutli-Regional Input-Output data to discuss to what extent five selected African countries, namely Cameroon, Ethiopia, Mozambique, Nigeria and Tunisia, might be affected by the EU CBAM. It then analyses how the CBAM could pose an incentive for carbon pricing in these five countries. This would reduce the amount that exporters need to pay to the EU and instead channel the revenues to their domestic budgets. We also demonstrate how different degrees of exposure to the CBAM may matter for the choice of emission coverage for a domestic carbon pricing scheme.

The EU Carbon Border Adjustment Mechanism as an Incentive for Carbon Pricing in African countries

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Abstract

The European Union (EU) is gradually phasing in the Carbon Border Adjustment Mechanism (CBAM). The CBAM will eventually apply the carbon price prevailing in the EU on emissions that were released to produce imports of certain carbon-intensive industries. This chapter uses Mutli-Regional Input-Output data to discuss to what extent five selected African countries, namely Cameroon, Ethiopia, Mozambique, Nigeria and Tunisia, might be affected by the EU CBAM. It then analyses how the CBAM could pose an incentive for carbon pricing in these five countries. This would reduce the amount that exporters need to pay to the EU and instead channel the revenues to their domestic budgets. We also demonstrate how different degrees of exposure to the CBAM may matter for the choice of emission coverage for a domestic carbon pricing scheme.

Keywords: Carbon Pricing, Carbon Border Adjustment, Competitiveness, Africa

1. Introduction

Carbon pricing allows reducing carbon emissions efficiently (Franks et al. 2018), such that the implementation of carbon pricing is supported by international institutions (like World Bank's partnership for market readiness) and might help attract funds for climate action (ACMI 2022). However, carbon markets come with challenging distributional implications (Steckel et al. 2021; Howie et al. 2020) and potential disadvantages for international competitiveness (Ward, Steckel, and Jakob 2019). Because of these constraints, South Africa is the only African country with a carbon price in 2024 but others are at least considering the introduction of carbon prices (World Bank 2024)¹.

Whatever the carbon pricing option African countries adopt, the potential macroeconomic implications underlie its viability. So, it is pertinent to analyse how a domestic carbon pricing initiative could yield (dis)advantages for some African countries in the international and regional context. The nature of competitive (dis)advantages could inform and/or influence future design of domestic carbon pricing or indirect imposition of carbon pricing. The foregoing highlights some macroeconomic motivations to put a price on carbon arising from the international environment in which national policies are formulated.

Trade is a key driver of economic activities, growth (Guepie et al. 2023) and carbon emissions – especially, in developing countries (Egbetokun et al. 2020). Africa's current trade patterns and free trade aspirations (through the AfCFTA) have implications for emissions reduction and climate change mitigation. Moreover, due to the lack of carbon pricing initiatives in many countries within the continent, Africa is attractive to emissions leakage from other parts of the world. Domestic carbon pricing could be a channel for the achievement of income distribution goals, domestic resource mobilization, trade and industrialization policies, as well as, nationally determined contributions of emission abatement (NDCs). From a global context, it becomes necessary to show the interconnectedness of Africa's trade, implementation of AfCFTA and the emerging carbon emissions reduction initiatives. Invariably, more knowledge is needed in this regard for impactful policy-making towards decarbonizing goods in AfCFTA and global trade.

¹ We invite the reader to refer to other chapters of this handbook for a more comprehensive overview of carbon pricing initiatives in Africa.

One of the most important developments regarding this is the Carbon Border Adjustment Mechanism (CBAM) recently introduced by the European Union (EU). This Mechanism imposes the carbon price prevailing in the EU Emission Trading System on emissions that were released to produce imports of certain carbon-intensive industries (Jakob 2021). Though aimed at mitigating carbon leakage, it will affect the competitiveness of exports from Africa to the EU and could make them competitively worse off (Luke 2023). The EU CBAM entered - in a transitional form - into force in October 2023. In its ramp-up phase of three years, it only requires reporting the emissions released to produce imported iron and steel, aluminium, cement, fertilizers, electricity and hydrogen (possible extensions to other sectors, such as organic chemicals and plastics, will be considered at a later stage). From 2026 on, importers will need to surrender dedicated CBAM certificates, which closely mirror the price in the EU Emission Trading System (ETS). Until 2035 the requirements to surrender CBAM certificates will increase in parallel to the phasing out of free allocation of EU ETS permits for EU producers, which currently constitutes the main instrument to address carbon leakage. In its current form, CBAM mainly covers emissions that directly occur in the production process (Scope 1). Emissions from electricity inputs (Scope 2) and intermediate products (Scope 3) are only included in a few very specific cases, such as emissions released to generate electricity for hydrogen production or for clinker that serves as an intermediary input for cement. Revenues collected by the sale of CBAM certificates will be used as an 'own resource' for the EU budget and can be used e.g. to fund the net-zero transformation or to pay back common debt incurred during the Corona Pandemic to promote economic recovery. The CBAM applies to all trade partners, regardless of their economic situation or level of development. The only exception occurs for countries that have a carbon price in place (other policies, such as performance standards or support schemes for clean energy, are not taken into account). In this case, the domestic carbon price is deducted from the obligation to surrender CBAM certificates to prevent emissions from being priced twice.

For EU trade partners this means that their exports of goods covered by the EU's CBAM will compete under a carbon price on the EU market. Exporters with relatively high emission intensity will become less competitive, which will likely lead to reduced output and consequently losses in jobs and value added. The extent to which a country's economy will be affected by the CBAM or an export tariff depends, among others, on the overall dependence on exports to the EU, the share of carbon-intensive sectors in exports, the carbon-intensity of production and the size of the economy

A possible response to the EU CBAM could consist of implementing an export tariff for emissions embodied in exports from CBAM sectors to the EU. Such an export tariff would negatively affect the competitiveness of affected industries. Still, an export tariff on sectors covered by the CBAM might cause little political resistance by affected industries since exporting industries would bear the costs of the EU's CBAM anyway. Whereas the revenues of the CBAM go to the EU budget, the revenues of such an export tariff would go to the public budgets of exporting countries. If such revenues are used to compensate the most affected industries, such an approach could even increase support for carbon pricing and act as a stepping stone to extend carbon pricing to either exports to non-EU countries or even to other sectors and production for domestic consumption.

Some previous studies have addressed effects of border carbon adjustment policies on trade partners. Boehringer et al. (2012) compare scenarios generated with integrated assessment models to assess the effects of border carbon adjustments implemented by certain countries or regions. Their study, which does not consider the specific design of the EU CBAM but instead analyses a broad coverage, highlights that border carbon adjustments increase the effectiveness of climate change mitigation measures but shifts substantial costs to low- and middle-income countries. Beaufils et al. (2023) employ a multi-regional input-output model to shed some light on the emissions embodied in exports from different EU trade partners covered by the current CBAM design as well as potential future extensions. Magacho et al. (2023) employ a similar modelling approach. Their analysis, which provides estimates of effects of the EU's CBAM in its current design, highlights that for all countries analysed, the overall magnitude of CBAM on other countries would be quite small (amounting to less than 0.1% losses in employment and GDP for almost all countries), but might still be relevant for certain energy-intensive sectors. Finally, Jakob (2023) discusses the political economy of the CBAM, highlighting that this instrument can lower political resistance against climate policy inside the EU. He also shows that the CBAM has the potential to incentivize more ambitious climate action in third countries, but might also cause conflict, for instance in the form of retaliatory trade barriers.

This chapter adds to the literature by providing an overview of the exposure of African countries to the EU CBAM, using a portfolio of trade vulnerability indicators. A special focus is on five selected African countries - namely Cameroun, Ethiopia, Mozambique, Nigeria and Tunisia - discussing how the adoption of a domestic carbon price could ease the adverse effect of the

CBAM on these countries. Additionally, the chapter investigates how the CBAM or a carbon price on exports to the EU might impact the international competitiveness of selected African countries. A particular focus of our analysis lies on the revenues that could be generated from an export tariff. The findings of this study will be a guide for policymakers aiming to sequentially phase in domestic carbon pricing, starting with exports of carbon-intensive goods to the EU. This chapter also serves as a reference point for further research at the interaction of climate policy, trade policy and sustainable development in Africa (Gershon, Azubuike, and Asekomeh 2022). It is novel because the issue of imposing export tariffs on carbon-intensive goods to avoid being the EU's CBAM has not been addressed in the academic literature.

This chapter starts with a brief overview of the analytical approach employed and the data used to operationalize it (Section 2). We then analyse trade data and detailed information on sectoral emission intensity to assess exposure to the CBA (Section 3). We then discuss to which extent the CBAM provides an incentive for implementing a domestic carbon price for EU trade partners. Even though a domestic carbon price would also raise the prices of the covered products, its revenues would accrue to the producing country (in contrast to the CBAM revenues, which accrue to the EU). For this reason, we examine different designs in which a carbon price is applied to (i) exports from CBAM sectors to the EU, (ii) all exports from CBAM sectors, (iii) all emissions from CBAM sectors, regardless of whether output is exported or consumed domestically and (iv) economy-wide emissions (Section 4). Finally, we discuss the policy implications of our findings (Section 5).

2. Analytical Approach and Data

This chapter considers to what extent African countries are exposed to the EU CBAM and evaluates different policy options to respond to the EU CBAM by implementing their carbon pricing schemes. This involves the use of data to determine the carbon footprint of exports from Africa to other parts of the world and consider the carbon trading potentials of each nation. The analysis is based on Multi-Regional Input-Output (MRIO) analysis, following the approach used in (Beaufils, Ward, et al. 2023). MRIO tables indicate how output from one economic sector is used in other sectors or for final consumption. They thus describe how industries and trade partners are interlinked at the global level. In combination with information of greenhouse gases

that are released during production, MRIO analysis can be used to track emissions through international supply chains and attribute them to final consumers (Beaufils, Berthet, et al. 2023). This allows a better understanding of the climate implications of international trade (Borin and Mancini 2019). MRIO analysis is also used to evaluate the first-order exposure of trade partners to the EU CBAM (Perdana and Vielle 2022; Zhong and Pei 2022; Beaufils, Ward, et al. 2023).

Here, we base our analysis on MRIO data from GTAP 11 for the year 2017 (Aguiar et al. 2022). We derive process-level emission intensities from the PRIMAP data sets (Gütschow, Johannes, Jeffery, M. Louise, and Günther, Annika 2021; Gütschow, Johannes, Günther, Annika, and Pflüger, Mika 2021), following the method described in Beaufils et al. (2023). A more detailed discussion of the methods used is provided in the supplementary materials and the code and data is available online².

² The code and data used for this chapter are available online, at the exception of the raw trade data from the licensed GTAP data: <https://doi.org/10.5281/zenodo.11394385>

3. Exposure to the CBAM

The countries analysed were chosen to ensure each African region is represented based on trade with the EU, high fossil-fuel base (carbon emissions intensity) and macroeconomic context.

South Africa took the lead in Africa by setting a legal and hybrid system for pricing carbon emissions (KAD 2020). Though it offers very generous allowances and the price of carbon emissions appears to be very low (ACMI 2022), it will reduce the burden of the CBAM by the level of the carbon price applied. More so because South Africa aims for rising carbon tax - reaching at least \$30 by 2030 (World Bank 2023). Therefore, South Africa was excluded from the scope of analysis in this Chapter. Meanwhile, Mozambique is a major exporter to the EU, has high carbon intensity but does not have a mechanism for pricing carbon emissions. For Mozambique, CBAM covers emissions related to the electricity used to produce exports, including Aluminium to the EU. Mozambique's Aluminium industry, which employs almost 3,000 persons and produces about 570,000 tonnes annually.

Meanwhile, Mozambique is captured as an interesting case in point for other reasons. Mozambique does not yet have a domestic mechanism for carbon pricing but it is the first country to be paid from the Forest Carbon Partnership Facility of the World Bank in 2021 (World Bank, 2024). Furthermore, Guepie et al. (2023) estimated that Mozambique's wages could fall 0.12% as a result of CBAM. Ethiopia is included as an outlier (somewhat, as a control variable) and to represent East Africa. It is a large, fast-growing economy that has some quite ambitious targets for renewable energy (Telaye Mengistu et al. 2019).

In Central Africa, the largest middle-income country is Cameroon. The economy is diverse and has a dynamic private sector, contributing to the economic stability and development of the region. Cameroon is committed to reducing greenhouse gas emissions by 35% (relative to its 2010 level) by 2035 (IMF 2024), but does not yet have a legal system for pricing carbon emissions (Ngwome, 2023). In respect to sectors covered by the CBAM, 49% of Cameroon's exports in 2022 was to Europe (Aguiar et al. 2022) and 34% of its electricity is from petroleum (OEC 2024). Western Africa exhibits a strong heterogeneity - Niger, Burkina Faso, Equatorial Guinea and Mali rank among the countries most exposed to CBAM, while Gabon and Ivory Coast have a low exposure (Luke, 2023). However, the trade and emissions data of some of the vulnerable countries appear inconsistent with the size of their economies. So, we considered

the factor of fossil-fuel base and located Nigeria. Though the most populous country with the largest economy in Africa, Nigeria is projected to be the most important emitter in the region (Ugwoke et al. 2020).

In North Africa, Morocco and Tunisia trade mainly with the European Union. Morocco's exports are mainly fertilizers and the country has a Green Partnership with the EU on energy (DG, 2022). However, Tunisia is more export dependent on the EU than Morocco. Tunisia's largest trade partner is the EU and in 2022 70% of its exports went to the EU (Aguilar et al. 2022). Moreover, the EU and Tunisia signed a Memorandum of Understanding on strategic and global partnership towards developing instruments for export of renewable energy from Tunisia to the EU due to the CBAM (EC 2023).

Country	Regions of Africa	Dependence on EU Trade	High Fossil-Fuel Base	Size of the Economy
Ethiopia	East	Medium	Low	Large
Nigeria	West	Medium	High	Large
Tunisia	North	Large	Medium	Small
Mozambique	South	Medium	Medium	Small
Cameroon	Central	Large	High	Medium

Table 1: Qualitative overview of the selection of countries.

Individual countries' exposure to the EU's CBAM crucially depends on the importance of exports from CBAM sectors to the EU and their carbon intensity. For this reason, we present four relevant indicators of countries' trade portfolios (Figure 1). First, we assess the overall export orientation of the economy by looking at the share of exports in GDP (upper left). Second, we discuss the importance of the EU as a trade partner by analyzing the share of total exports of the countries under study that goes to the EU (lower left). Third, we evaluate the importance of CBAM sectors in the domestic economy by looking at the share of sectors included in the CBAM in domestic GDP (upper right). Finally, we combine the latter two aspects - the importance of CBAM sectors and the importance of the EU as a trade partner - by presenting information on the share of the emissions in the CBAM sectors that will be covered by the EU CBAM (lower right).

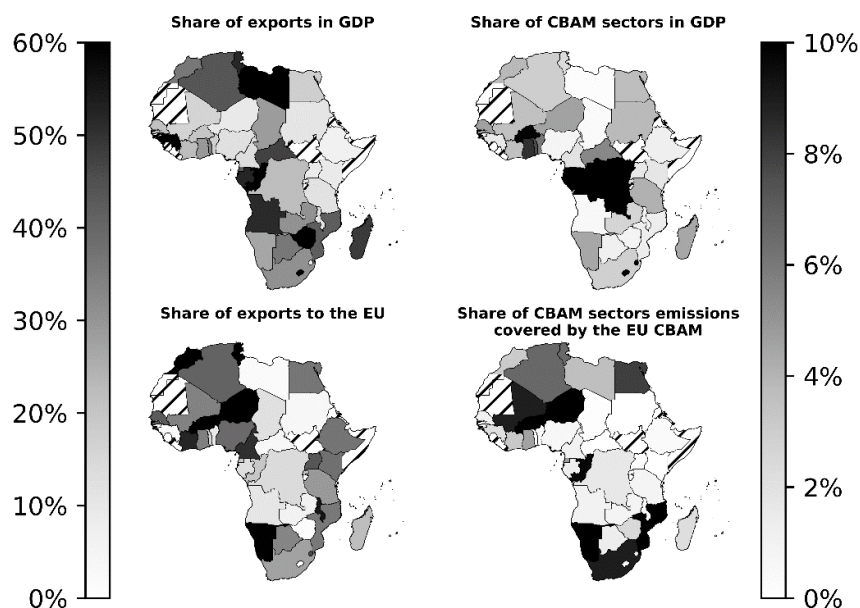


Figure 1 - Exposure of African countries to the EU CBAM based on four different indicators. Economic indicators are derived from the GTAP 11 database for the year 2017 (Aguiar et al. 2022). Emissions covered by the EU CBAM are derived from process-level emission data from the PRIMAP-hist and PRIMAP-crf databases, mapped at the sector level to GTAP 11 (see (Beaufils, Berthet, et al. 2023) for a description of the mapping method). Hatches indicate countries not covered in the analysis. The scales on the left and on the right of the figure refer to the maps on the respective sides.

African countries exhibit a strong heterogeneity in their exposure to the EU CBAM, and the perceived intensity differs depending on the indicator used. For many countries, exports account for more than 60% of their GDP (figure 1, upper left panel). Most of these countries' economies are highly dependent on natural resources (e.g. oil and gas in Congo and Libya, minerals in Guinea and Zimbabwe), which are not covered by the EU CBAM. These countries typically exhibit a relatively low trade exposure to the EU: among the 6 countries for which exporting constitutes more than 70% of GDP, the EU typically accounts for 3% or less of total exports (lower left panel), where 20% of exports are in direction of the EU. By contrast, the countries in Western and Northern Africa are the most dependent on exports to the EU. More than half of the exports of Tunisia, Niger, Morocco, Cameroon and Ivory Coast are directed to the EU. However, the current EU CBAM specifically covers the emissions caused by the manufacturing of aluminium, iron and steel, fertilisers, cement, electricity and hydrogen exported to the EU. The share of these sectors in GDP is relatively small in most African countries (upper right panel), limiting the exposure of the overall economy to the EU CBAM. Still, future extensions of the EU CBAM to other sectors would progressively increase such exposure.

In its current state, large share of the emissions from CBAM sectors in many African countries are covered by the EU CBAM (lower right panel). The large exposure of Niger and Mali to the CBAM indicated by our analysis (31% of emissions from CBAM sectors) is biased upwards due to nuclear ore processing, which is out of the scope of the current EU CBAM. Beyond this example, countries in Southern Africa stand out as the most exposed geographical zones, with about 10% of emissions of the CBAM sectors in South Africa, Mozambique and Namibia being covered by the EU CBAM.

Among the five countries we selected, Tunisia and Mozambique are the most export-oriented economies, with ratios of exports to GDP as high as 52% and 42%, respectively. Conversely, exports only represent about 10% of the GDP of Nigeria, Cameroon and Ethiopia. The EU is the destination of more than half the external trade of Tunisia (67% of export shares) and Cameroon (51%). It represents about one third of exports of Nigeria, Ethiopia and Mozambique. CBAM sectors represent less than 5% of the exports to the EU for four of the five countries of our panel. The exception is Mozambique, for which 20% of the export value to the EU would be covered by the CBAM. These indicators suggest that among the five countries considered, Mozambique and Tunisia will likely be the most exposed to the current EU CBAM implementation. Despite a relatively low production volume in the CBAM sectors, Tunisia is highly dependent on the EU for its external trade and might be vulnerable to future extensions of the EU CBAM to other products. In Mozambique, the overall dependence on the EU is much lower, but the relative importance of domestic aluminium production will cause a relatively high exposure to the EU CBAM.

Throughout our analysis, we assume a carbon price of US\$ 100/tCO₂. This price level is roughly the highest one reached in the EU ETS so far and model projections for the EU ETS suggest that this price will likely be reached (and exceeded) in the near future according to emission scenarios consistent with the EU Green Deal (Pahle et al. 2023). With this carbon price, firms from Tunisia and Mozambique would need to spend 25 mn US\$ and 38 mn US\$, respectively, to acquire CBAM certificates for the emissions embodied in their exports to the EU. In comparison, for Nigeria, Cameroon and Ethiopia, we estimate costs of 5.1 mn US\$, 1 mn US\$ and 1.2 mn US\$, respectively.

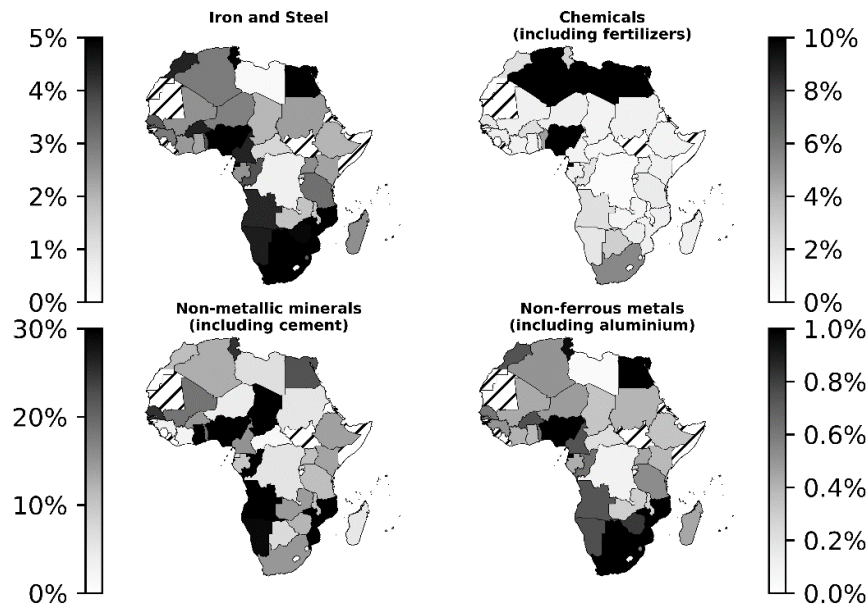


Figure 2 - Price increase in the exports of different sectors to the EU. Emissions covered by the EU CBAM are derived from process-level emission data from the PRIMAP-hist and PRIMAP-crf databases, mapped at the sector level to GTAP 11 (see Beaufils et al. 2023 for a description of the mapping method) and multiplied by a carbon price of 100 US\$ per tonne of tCO₂, in line with recent evolutions of the EU ETS emission price. The price increase is estimated by assuming that the emission price markup is fully transmitted by the exporter. Hatches indicate countries not covered in the analysis. The scales on the left and on the right of the figure refer to the maps on the respective sides.

The effects of the EU CBAM on exporters depend on their respective carbon intensity: exporters with a relatively low emission intensity will gain a competitive advantage on the EU market over producers with more emission-intensive production processes. Figure 2 shows the potential price increase in different markets as a result of a carbon price at 100 US\$ per tonne of CO₂. Overall, the non-metallic minerals show the highest potential price increase, mainly because of the high emission intensity of cement production (lower-left panel). However, these commodities are mostly used domestically, therefore reducing the potential effect of the EU CBAM on these sectors. Still, the large increase of the price of construction materials might be a major concern for imposing a domestic carbon price aligned with European standards within African countries. The possible price changes shown here are based on sectoral averages, which might overlook differences in product types. In particular, the price changes for chemicals (upper right panel) likely reflect differences in chemical types rather than differences in specific products' emission intensities. In particular, Nigeria, Algeria and Egypt are producers of fertilisers, which are emission-intensive chemicals covered by the EU CBAM. Among the selected countries, Nigeria stands out as a country with a higher-than-average emission intensity for all sectors. With a

carbon price of US\$ 100 per tonne of CO₂, the prices of iron and steel, chemicals, non-ferrous metals and non-metallic materials sectors might increase by 13%, 6%, 1% and 90%, respectively. In comparison, Ethiopia and Cameroon have relatively low emission intensities in all sectors, with expected price increase of about 15% in the non-metallic minerals sectors and below 5% for the other sectors.

4. How the CBAM provides incentives for a domestic carbon price

The EU CBAM will only apply to products not covered by a comparable carbon price in exporting countries. In that context, exporters to the EU could implement a carbon price domestically - at least on their exports - to collect the fiscal revenue of the tax domestically.

The attractiveness of a sectoral carbon price largely depends on the relative emission intensity of that sector compared to their competitors' carbon intensity and to the share of exports (Figure 3). As the carbon price shifts competitiveness in favour of the cleanest producers, implementing ambitious carbon pricing policies will likely come at higher costs for countries with higher emission intensities. In the context of the EU CBAM, the structure of the exports also plays an important role, as exports to the EU compete under a carbon price.

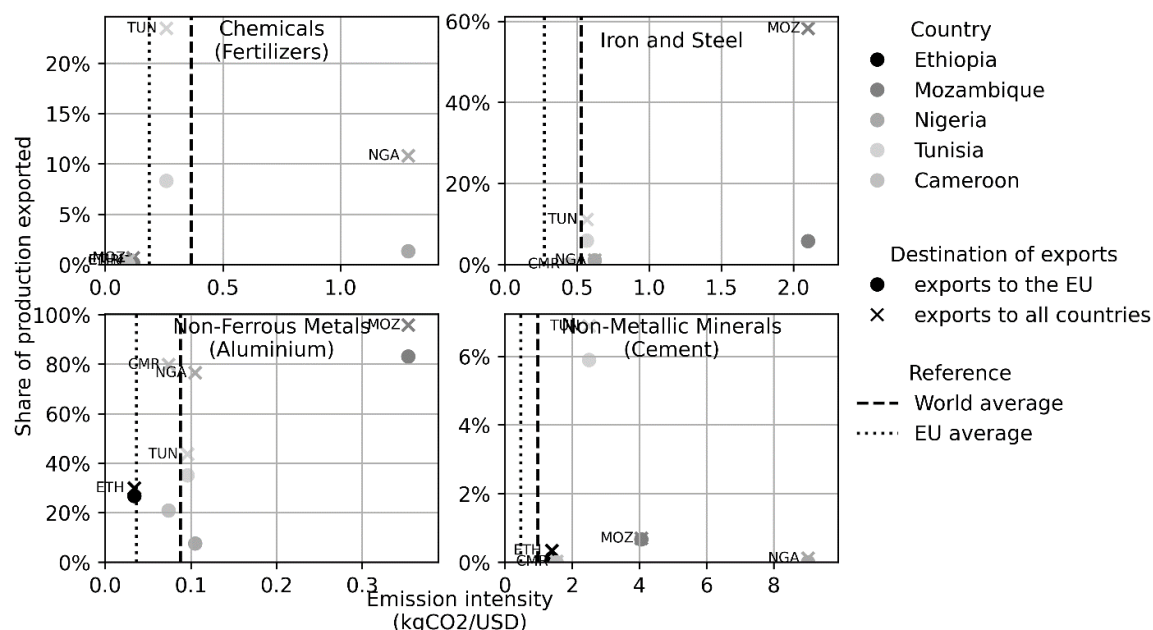


Figure 3 - Emission intensity and export shares of different sectors in a selection of African countries. For each sector, the emission intensity of energy-intensive sectors is compared to the world average emission intensity of the sector (dashed line) and the average emission intensity in the European Union (dotted lines). Markers indicate the share of exports to the EU (dots) or to all countries (crosses) compared to the total sectoral output. The sectoral emission intensities are derived from GTAP 11 and PRIMAP data as detailed in the caption of Figure 1.

For the countries analysed, non-metallic minerals (lower right) and chemicals (upper left) are mainly used domestically, such that the EU CBAM does not provide a particular motivation for implementing a domestic carbon pricing mechanism. Conversely, a large share of iron and steel (upper right) and non-ferrous metallic products (lower left) are exported. For these sectors, implementing a domestic carbon price would have a relatively limited impact on domestic prices, as most of the price increases would be borne by the trade partner. In Cameroon and Ethiopia, the emission intensity of non-ferrous metals is low compared to the world average. The industries of these countries would hence gain a competitive advantage if they were to compete under a carbon price, thus giving a relative incentive to implement an ambitious carbon pricing policy there. Conversely, Mozambique has a much larger-than-average emission intensity in aluminium production, such that the implementation of a carbon price would be costlier, as domestic producers would be disadvantaged when competing under a carbon price.

Still, most of the Mozambese production of aluminium is exported and more than 80% to the EU. If aluminium producers in Mozambique cannot redirect their exports to other countries, most of their production will be covered by the EU CBAM, whose revenue will accrue the EU budget.

Instead, Mozambique could implement its own carbon price and use the revenue to invest in cleaner aluminium production processes. This analysis only partially apply to aluminium producers in Nigeria and Cameroon. In these countries, about 80% of non-ferrous metals are exported, but the EU market is a relatively smaller export market for both countries (about 8% of total production in Nigeria, 20% in Cameroon). Here, the application of a domestic price would hurt exports to non-EU countries. Ideally, these countries could implement a carbon price on its exports to the EU only, but such a targeted export tax would likely violate the rules of the World Trade Organization. The same holds for Mozambique iron and steel sector (upper right panel). Finally, the chemical and non-metallic minerals sectors are traded relatively less. In these sectors, applying a carbon price would have larger impacts on domestic consumers, which are out of the scope of this chapter.

In what follows, we analyse four different approaches on how countries could employ a carbon price to generate public revenues (which could be used to alleviate adverse effects from the CBAM). These revenues could be used, for instance, for public investments in clean energy sources to reduce firms' costs of adopting clean production techniques in covered sectors. This could be of particular importance to avoid 'carbon lock-in' (Seto et al. 2016) for industries that are in the process of being built up and which do not yet depend on a complex web of infrastructures and political dynamics rooted in fossil fuel combustion. Governments could also help reconcile socio-economic development with environmental considerations by investing in education to prepare the population to grasp the opportunities arising from low-carbon production. To alleviate social hardships resulting from declining employment or wages in energy-intensive sectors of the economy, some of the revenues from a carbon price will likely also be required to scale up social systems.

To get a solid understanding of the revenues that might become available, we explore four different approaches to carbon pricing. The first option we consider is a carbon price that is exclusively applied to exports from CBAM sectors that go to the EU. This option thus features the identical coverage and revenues as the CBAM. The crucial difference, however, is that the revenues would accrue to the exporting country and not, as is the case for the CBAM, to the EU. This kind of discriminatory treatment in which exports to the EU are subject to different rules than exports to other trade partners might not comply with international trade law. We thus consider a second option in which countries apply a carbon price on all exports from sectors covered by the CBAM. This might also be a promising starting point to extend emission pricing

to energy-intensive goods produced for the domestic market. For this reason, we analyse a price on all emissions from sectors that are included in the CBAM, regardless of whether the produced goods are exported or consumed domestically, as the third option. This option would already cover a substantial share of total emissions in the countries considered, ranging from 7% in Nigeria to 19% in Ethiopia. The fourth and final option is an economy-wide carbon price. This option exhibits the broadest coverage and consequently the highest potential to create public revenues and achieve emission reductions (in addition to co-benefits, such as improved local air quality). This option would, however, also entail the highest mitigation costs.

	Ethiopia	Mozambique	Nigeria	Tunisia	Cameroon
Exports from CBAM sectors to EU	0.23 US\$ (0.012 MtCO ₂)	3.7 US\$ (0.381 MtCO ₂)	0.07 US\$ (0.051 MtCO ₂)	238 US\$ (0.25MtCO ₂)	0.6 US\$ (0.01 MtCO ₂)
All exports from CBAM sectors	0.27 US\$ (0.019 MtCO ₂)	4.3 US\$ (0.488 MtCO ₂)	0.7 US\$ (0.426 MtCO ₂)	7.5 US\$ (0.39 MtCO ₂)	2.2 US\$ (0.04 MtCO ₂)
All production in from CBAM sectors	4.7 US\$ (3.2 MtCO ₂)	6 US\$ (1.24 MtCO ₂)	2.4 US\$ (8.7 MtCO ₂)	38 US\$ (3.8 MtCO ₂)	6.9 US\$ (0.99 MtCO ₂)
Economy-wide (all emissions)	16 US\$ (17 MtCO ₂)	33 US\$ (9.5 MtCO ₂)	70 US\$ (133 MtCO ₂)	261 US\$ (29 MtCO ₂)	42 US\$ (10 MtCO ₂)

Table 2: Per capita fiscal revenue from a carbon price at 100US\$ per tonne of CO₂ on different parts of the economy, in US\$. Figures in parentheses give the volume of emissions covered, in MtCO₂ emissions. Population figures are from the World Bank ("Population, Total" 2022)

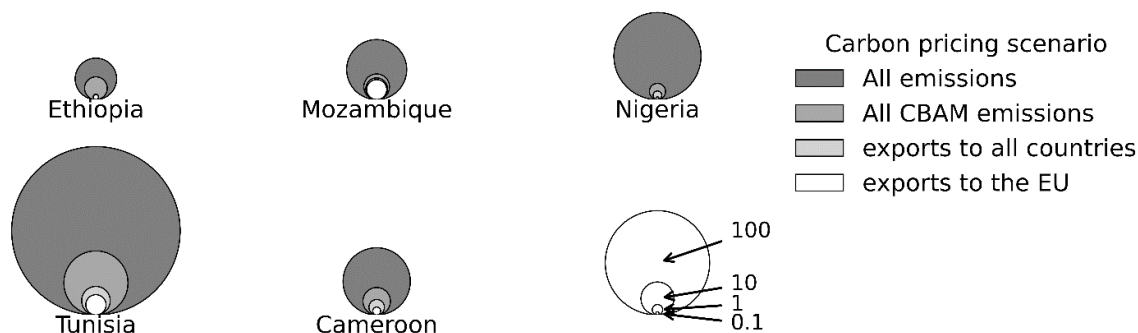


Figure 4 - Comparison of the per capita revenue of different carbon pricing schemes in a selection of African countries. The shade of the bubbles indicate the scenario considered and the area of the circle is proportional to the fiscal revenue per capita. The lower right circles indicate the reference size of the circles, in US\$ per capita. Values correspond to table 2.

In Ethiopia, Nigeria and Cameroon, a carbon price on exports would yield little fiscal revenue, even if applied to all trade partners, with no more than US\$2 per capita per year in Cameroon. Even when applied to the full output of the CBAM sectors, a carbon price appears very limited, all the more since our estimates do not account for the administrative costs of implementing and monitoring a carbon pricing system. Conversely, the relative importance of the CBAM sectors in Mozambique and Tunisia makes it a more attractive option from the fiscal revenue perspective. In particular, in Mozambique, the option of a tax on the full production from the CBAM sectors yields very similar revenues to a tax on exports only.

Hence, the CBAM might offer a quite straightforward motivation for Mozambique to introduce some sort of domestic carbon pricing mechanism, at least on exports of energy-intensive goods. This approach would still result in higher prices for these products. Yet, the associated revenues would accrue to Mozambique's government budget instead of the EU. For the other countries, this incentive is substantially smaller. Nevertheless, the CBAM might still strengthen policy makers' resolve to adopt carbon pricing, especially if they anticipate that either (i) other countries will follow up with similar schemes or (ii) that the EU will expand the CBAM to additional economic sectors or (iii) if energy-intensive sectors will in the future play more important roles for the structure of their economies.

5. Discussion

In this chapter, we have used global MRIO data to evaluate the exposure of African countries to the EU CBAM. Our analysis highlights strongly contrasting exposure patterns in the African countries and different incentive structures regarding the implementation of a domestic carbon price.

First, our analysis suggests that Mozambique seems to be the only African country acutely vulnerable to the EU CBAM. Using a diversity of vulnerability indicators, we find that most countries score highly in at least one of our exposure metrics, but there is relatively little overlap between the vulnerability indices. The countries largely dependent on the EU for their exports have comparably small exports covered by the EU CBAM (Cameroon, Tunisia) and the countries with more emission-intensive production processes (like Nigeria) are relatively less exposed to international trade. The relatively small overlap between exposure metrics might however be challenged by future extensions of the EU CBAM. Countries largely dependent on the EU for their external trade might become strongly affected by the EU CBAM if it covers more sectors.

Second, we find that countries have very different incentives to implement a domestic carbon price as a response to the EU CBAM. Ethiopia, Nigeria and Cameroon have a relatively low exposure to the EU CBAM and relatively few CBAM sectors in their economy, such that the current EU CBAM does not provide a specific motivation for implementing a carbon price there. Still, relatively low carbon intensities in some countries (such as Ethiopia, with large hydropower resources and plans to scale up solar energy) might support the development of energy-intensive industries. With a carbon price low-carbon domestic production would have a competitive advantage over more emission-intensive producers from other countries. At the opposite end of the spectrum, the CBAM sectors in Mozambique and Tunisia are strongly export-oriented. In Mozambique, the importance of the EU as a trade partner provides a strong motivation for implementing a carbon price on exports, as most of the exports of the CBAM sectors will be covered by the EU carbon price anyway.

For the other countries analysed, the current EU CBAM does not seem to provide a strong case for implementing a carbon price. Either the country has few carbon intensive industry (Ethiopia), or the EU is not a major export destination for these products (Cameroon), or most of it is used

domestically (Tunisia). Still, extensions of the EU CBAM to other sectors are envisioned in the medium to long term. The EU is a major trade partner for many African countries (Figure 1, lower left panel). In all of these countries, the possibility of these extensions should be anticipated.

6. Conclusion and policy implications

The EU Carbon Border Adjustment Mechanisms increases the attractiveness of carbon pricing policies in African countries. While the current EU CBAM implementation will likely have limited impacts on most countries, future extensions to additional sectors could affect the competitiveness of African economies. By assessing the implications of an economy-wide carbon price, this chapter provides a starting point for African policy makers and industries to assess response measures to an expanded EU CBAM. A domestic carbon pricing would ensure that the fiscal revenue remain with the implementing countries and can be employed to accelerate the transition to a low-carbon economy.

This chapter highlights that countries face strongly heterogeneous exposure patterns and might therefore favor diverse policy responses. The CBAM and its potential implications are an argument in favour of carbon pricing and, especially in countries where there is already substantial political support for this policy option. Our analysis shows that the exposure to the EU CBAM and the challenges of carbon pricing are largely sector- and country-specific. Introducing a carbon price needs to account for a broad range of social objectives, such as potential impacts on poverty and inequality (Aggarwal et al. 2021) and how the associated revenues can be used to improve human well-being by e.g. increasing access to education, healthcare, water, sanitation or energy (Dorband et al. 2022). In addition, as special interest groups have an influence on policy formulation, decision makers need to find ways to create political winners whose support can act as a counterbalance to the political resistance of actors who would likely lose out from a carbon price (Steckel and Jakob 2021). These dimensions all relate to the political economy of carbon pricing, which are largely covered in other chapters of this handbook.

Trade liberalization in the context of AfCTA could also raise concerns that carbon pricing provides an incentive for emission-intensive industries to relocate to other African countries that do not have a carbon price. Whether this can be expected to matter in practice depends on the

emission intensity and the carbon prices applied. In particular, coordinated carbon prices by AfCTA members would greatly alleviate such concerns. Further research will be required to assess potential trade-offs between trade liberalization and national carbon prices and to devise the potential of coordinated response measures.

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The coalition-building potential of the EU CBAM

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The potential of carbon border adjustments
to foster climate cooperation

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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. While primarily designed as a domestic policy instrument to avoid carbon leakage, the EU CBAM also entails a multilateral dimension. Since it makes foreign producers compete under a carbon price, it may motivate some trade partners to implement their own carbon pricing mechanisms. Down the road, the EU CBAM might trigger the creation of a coalition of countries with ambitious carbon pricing policies, protected by a common 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. Specifically, we use a fully interlinked New Quantitative Trade model to evaluate the pay-offs of a dynamic club negotiation model, which allows us to explore the formation and stability of climate coalitions under different CBAM implementation options. Compared to previous research, our approach allows for a more granular definition of

climate policies, entails a larger regional resolution and requires relatively little input data and numerical power, enabling the simulation of a larger range of CBAM implementations. Our results show that the EU CBAM is relatively successful at limiting carbon leakage and reducing the cost of the climate policy in the EU. In its current version, the EU CBAM would trigger the formation of a modest coalition. Future extensions of the EU CBAM could motivate the adoption of carbon pricing in all countries except for China, India and Russia.

THE POTENTIAL OF CARBON BORDER ADJUSTMENTS TO FOSTER CLIMATE COOPERATION

WORKING PAPER

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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.

Keywords Carbon Border Adjustment · Climate policy · International trade · Climate cooperation · Climate clubs

JEL Codes C68; F18; Q56

Highlights

- We extend a Quantitative Trade Model with a climate policy module and combine it with an agent-based model
- We study the potential of the EU Carbon Border Adjustment Mechanism (CBAM) to trigger climate coalitions
- In its currently planned form, the EU CBAM reduces carbon leakage and shifts mitigation costs to trade partners
- It motivates climate policies in Korea, Japan and Taiwan
- Extensions of the EU CBAM could induce a broader coalition but Russia, China and India stay out of the coalition in all scenarios

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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-intensive production to countries with less stringent climate policies (Grubb et al., 2022). It is set to substitute the free allowances currently granted to emission-intensive, 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; Böhringer 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:

$$\begin{aligned}\bar{x}_{ir} &= \sum_{j,s} z_{ir}^{js} + \sum_s y_{ir}^s \\ &= \sum_{j,s} z_{js}^{ir} + v_{ir}.\end{aligned}\tag{1}$$

124 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
 125 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
 126 country s . Note that we use this formalisation for both domestic (i.e. $r = s$) and trade policies (i.e. $r \neq s$).

127 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
 128 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 :

$$\begin{aligned} x_i^s &= \sum_r \tau_{ir}^s \zeta_{ir}^s (z_{ir}^s + y_{ir}^s) \\ &= \sum_r \tau_{ir}^s \zeta_{ir}^s \bar{x}_{ir}^s. \end{aligned} \quad (2)$$

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

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

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

$$\gamma^{js} = \frac{v_{js}}{x_{js}}. \quad (4)$$

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

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

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

$$\alpha_i^s = \frac{y_i^s}{y^s}. \quad (6)$$

134 2.1.2 Basic trade model

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

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

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

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).

³We 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.

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

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

$$\hat{p}_i^s = \left(\sum_r \pi_{ir}^s (\hat{\tau}_{ir}^s \hat{\zeta}_{ir}^s \hat{c}_{ir})^{-\theta_i} \right)^{-\frac{1}{\theta_i}}. \quad (II)$$

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

$$\hat{\pi}_{ir}^s = \left(\frac{\hat{\tau}_{ir}^s \hat{\zeta}_{ir}^s \hat{c}_{ir}}{\hat{p}_i^s} \right)^{-\theta_i}. \quad (III)$$

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

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

154 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
155 consumption.

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

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

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

$$\kappa_\eta^{s'} = \sum_{j,r} (\hat{\zeta}_{js}^r \zeta_{js}^r - 1) \frac{\hat{\pi}_{js}^r \pi_{js}^r}{\hat{\tau}_{js}^r \tau_{js}^r \hat{\zeta}_{js}^r \zeta_{js}^r} x_j^{r'}. \quad (8)$$

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

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

162 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
163 economy:

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

164 The model is solved by introducing an exogenous variation in tariffs and subsidies (noted $\hat{\tau}_{ir}^s$ when applied to inputs
165 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:

$$e_i^s = \frac{\bar{e}_i}{p_i^s}. \quad (9)$$

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, $\hat{p}_i^s$:

$$e_i'^s = \frac{e_i^s}{\hat{p}_i^s} \quad (10)$$

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 , $\epsilon_{ir}'^s$, is linked to the price of product i in importing country s , $\hat{p}_i^s$:

$$\epsilon_{ir}'^s = \frac{\epsilon_{ir}}{\hat{p}_i^s}. \quad (11)$$

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:

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

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

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

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:

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

$$\begin{cases} (\widehat{\tau}_f)_{is}^r &= \left(1 + \lambda_r' \frac{e_i^r}{\widehat{p}_i^r}\right); \\ (\widehat{\tau}_{ia})_{is}^r &= \left(1 + \lambda_r' \frac{e_{is}^r}{\widehat{p}_i^r}\right); \\ (\widehat{\zeta}_p)_{ir}^s &= \left(1 + \lambda_r' \frac{e_{ir}^s}{\widehat{c}_{ir}^s}\right). \end{cases} \quad (\text{VII})$$

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

200 The cost effect of the climate policy on the production of i in country r is proportional to the value of carbon tax paid
 201 on indirect emissions, $\lambda_r' \frac{e_{ir}^s}{\widehat{c}_{ir}^s}$. Under this assumption, the rebates that compensate the indirect cost of the climate policy
 202 on exports to country s , $(\widehat{\zeta}_{er})_{ir}^s$, are:

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

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

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

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

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

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

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

227 2.2 Agent-Based Model

228 In the second part of the analysis, we simulate the potential effects of the EU CBAM on climate cooperation. This
 229 simulation is based on an agent-based model, which mimics negotiation rounds to form a potential climate coalition.
 230 The model is similar to the approach used in Farrokhi and Lashkaripour (2023) and Böhringer et al. (2016), but our
 231 proposition supports additional decision criteria. The first part of this section (2.2.1) introduces the model in plain
 232 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 $r_1, \dots, r_n$. At the beginning of each iteration i , countries share their current status: in the coalition or neutral. We note $\Omega_i^+ = \{r_1, \dots, r_{n^+}\}$ the subset of countries willing to join the coalition and $\Omega_i^- = \{r_1, \dots, r_{n^-}\}$ the subset of neutral countries⁵. Together, the ensemble of the two subsets Ω_i^+ and Ω_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 (Ω_i^{r-})⁶. country r decides by comparing the hypothetical outcomes by choosing either of these conditional states:

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

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*:

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

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

$$\exists i < j, \Omega_i = \Omega_j. \quad (16)$$

- 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 (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.

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

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*.

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, $\tilde{Q}_f^s$ ⁷. 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 :

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

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

$$\bar{x}_{js} = \sum_r \frac{\pi_{js}^r}{\tau_{js}^r \zeta_{js}^r} x_j^{r'}. \quad (18)$$

Following equation 10, the baseline nominal emission intensity is:

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

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 , $\bar{x}_{pr}$:

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

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 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.

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 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 Kingdom (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 endogenized 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.

In quantitative terms, the EU ETS reduces by 239 Mt the CO₂ 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.

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.

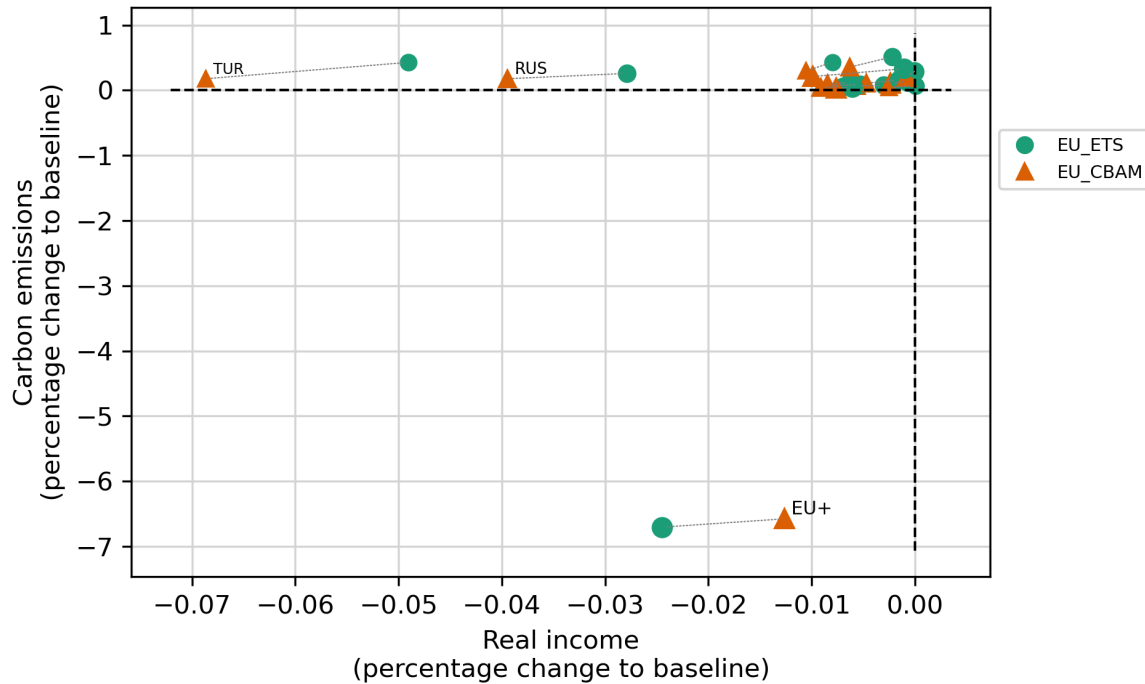


Figure 1: **Assessment of the impact of the EU ETS and EU CBAM on emission and income levels.** The blue dots figure the income (x-axis) and emission effects (y-axis) of applying a carbon price of 100 USD per tCO₂ on the EU industrial emissions (EU ETS scenario). The red triangles correspond to a policy 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 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 be 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.

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

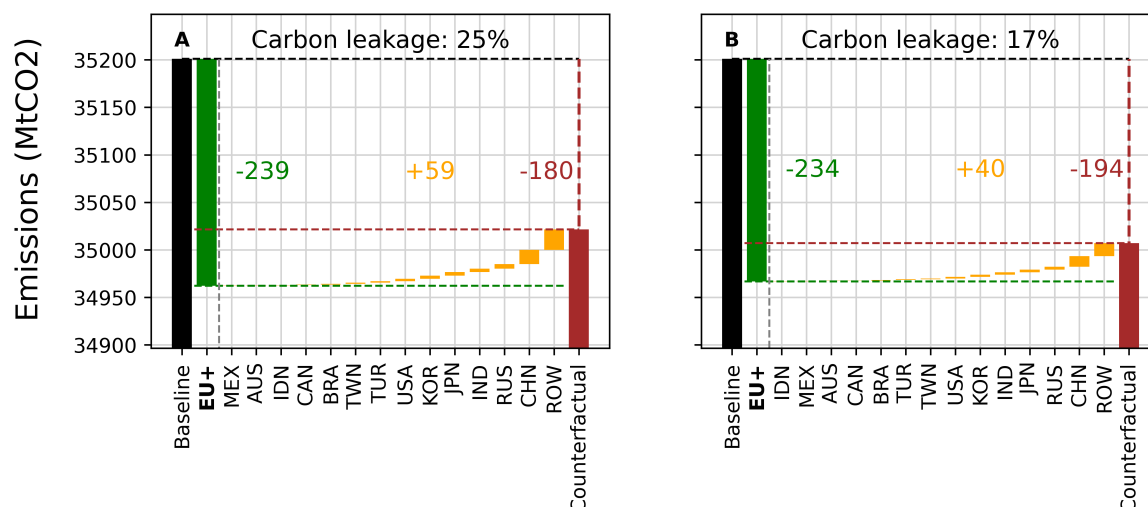


Figure 2: **Comparative contributions to climate change mitigation under an EU ETS (panel A) and an EU CBAM (panel B).** The black, left bar shows the global volume of CO₂ emissions in the baseline scenario. The red bar on the right shows the global emissions in the counterfactual scenario, i.e. with 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.

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 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.

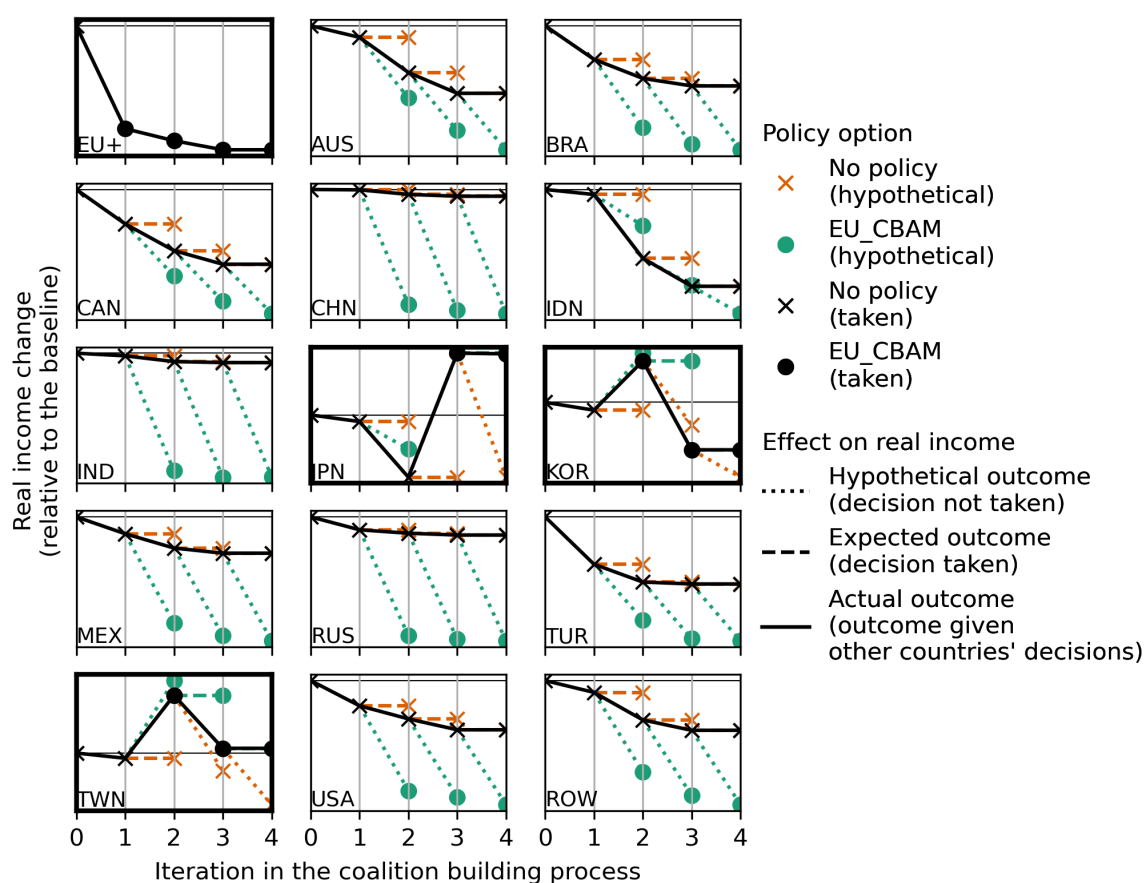


Figure 3: **Description of the construction process of a climate coalition.** Panels show the steps in the decision-making of each country and the "rest of the world (RoW)". (x-axis). The y-axis represents the relative income effect in each conditional state. In each step of the model, countries choose 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.

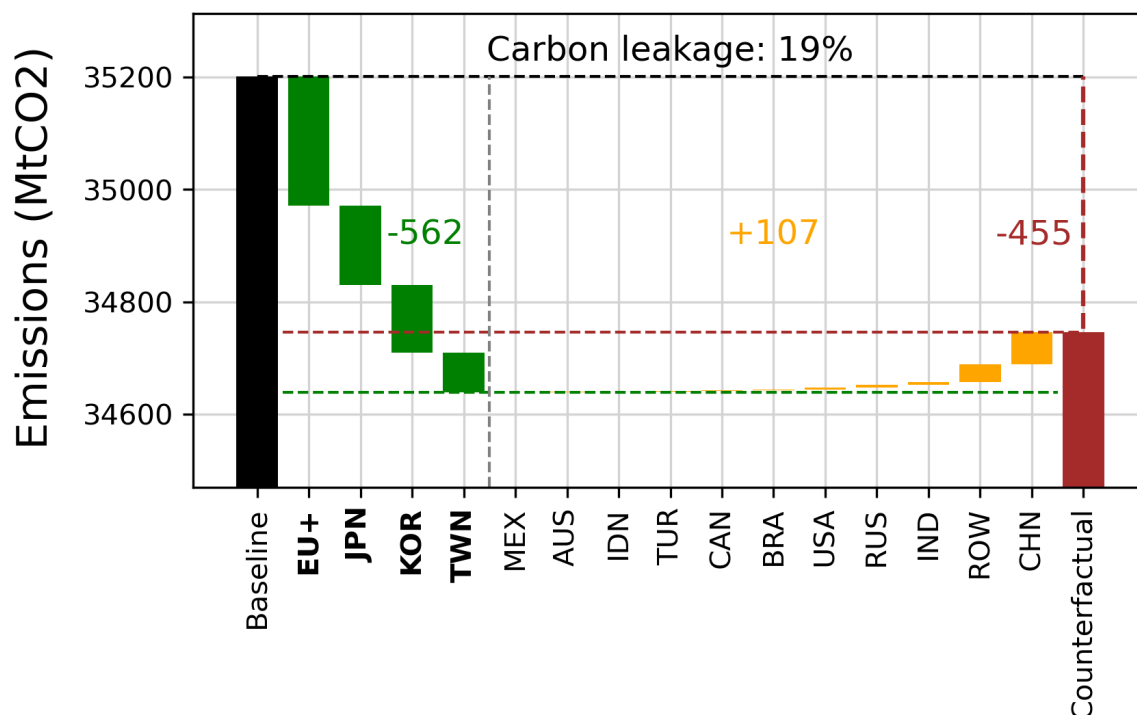


Figure 4: **Comparative contributions to climate change mitigation under an EU CBAM with endogenous policy responses.** The red bar on the right shows the global emissions in the counterfactual scenario, i.e., with the applied climate policy. The green and yellow bars show how much countries contribute 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.

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

412 *deep* CBAM. Fourth, we evaluate the introduction of *Export Rebates* (ER) in the EU CBAM design. ER are export
413 subsidies compensating the emission price paid in the EU.

414 4.3.1 Unilateral policy

CBAM implementation	Emission reduction in the EU (MtCO ₂)	Global emission reduction (MtCO ₂)	Carbon leakage (%)
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.

415 Abstracting from possible policy response of the EU trade partners, all the implementation options of the EU CBAM
416 yield between 230 and 240 Mt of CO₂ emissions reduction in the EU (table 1), except for Export Rebates, which
417 only abate 225 MtCO₂ in the EU. When accounting for carbon leakage and emission changes in the rest of the world,
418 the range of emission reduction widens between different implementation options. While an EU ETS without an
419 anti-leakage instrument only abates 180 MtCO₂ globally (25% leakage), a comprehensive CBAM reduces the leakage
420 rate to 9%, reaching an overall mitigation level of 216 MtCO₂. A comprehensive CBAM combines a horizontal (*wide*
421 CBAM) and a vertical (*deep* CBAM) extension. Taken in isolation, these implementation options yield similar effects,
422 both in terms of global emission mitigation (211 MtCO₂ and 208₂ emission reduction, respectively) and carbon leakage
423 (11 and 12%, respectively).

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

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

435 4.3.2 Coalition building potential

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

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

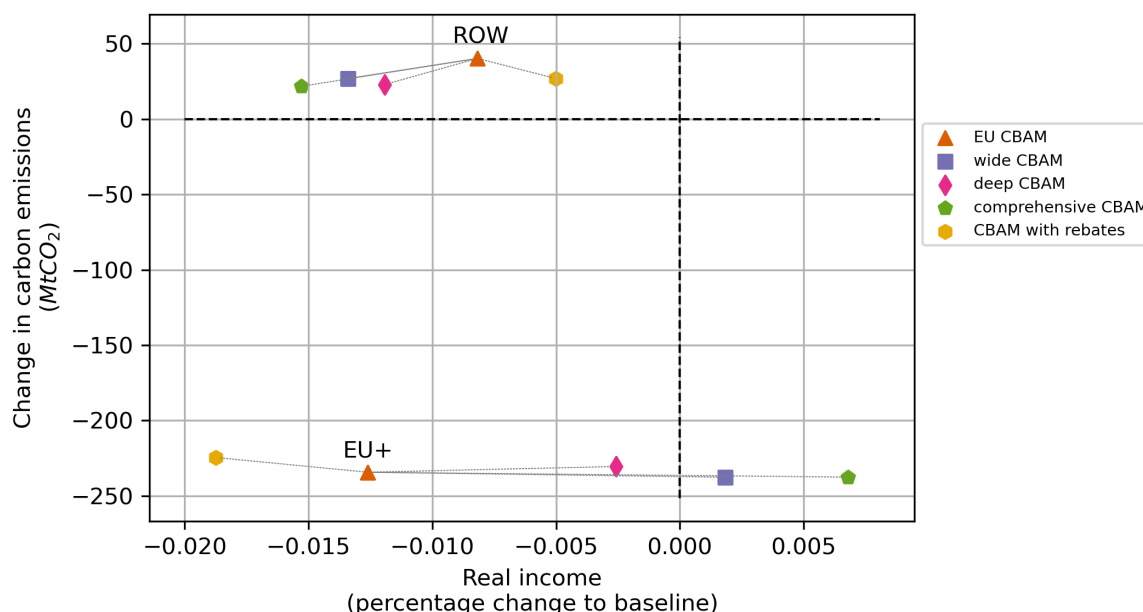


Figure 5: **Assessment of the effect of different EU CBAM implementation options on emissions and real incomes in the EU and in the rest of the world.** The orange triangles indicate the emission reduction (y-axis) and the real income change (x-axis) associated with implementing the EU CBAM, in the EU 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.

CBAM implementation	Countries in the coalition	Overall emission reduction (MtCO ₂)
EU CBAM	EU, TWN, KOR, JPN	455
wide CBAM	EU, AUS, BRA, CAN, IDN, JPN, KOR, MEX, TWN, ROW	1 463
deep CBAM	EU, CAN, IDN, JPN, KOR, TWN	526
comprehensive CBAM	EU, AUS, BRA, CAN, IDN, JPN, KOR, MEX, TUR, TWN, USA, ROW	1 681
CBAM with ER	EU, TWN (JPN, KOR)*	337

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.

451 In comparison, Farrokhi and Lashkaripour (2023) find that the EU alone would not be able to trigger the formation of a
 452 climate coalition under an optimal setting, but that the commitment of both the United States and the EU would be
 453 sufficient to reach commitment from all the countries. Our approach differs from Farrokhi and Lashkaripour (2023) by
 454 departing from their optimality condition. They let countries freely chose both the optimal level of carbon pricing and
 455 of import tariffs. Instead, we reduce the countries' policy choices to the binary decision of whether to join the coalition.
 456 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 reduces the abatement level of all participants (crowding out effect). Relative to both papers, we find that the 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 (Aguilar 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; Aguilar 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 even in the absence of the EU. In that regard, the role of the EU for motivating the formation of 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.

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

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

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Discussion

Mitigating climate change in an interconnected world poses a coordination dilemma. Not only should countries negotiate joint emission reduction commitments, but the economic competition through international trade undermines the efficiency of unilateral climate policies. My thesis interprets the Carbon Border Adjustment Mechanism (CBAM) the European Union (EU) is implementing as a way to address these challenges jointly. I first propose methodological improvements for projecting Multi-Regional Input-Output Tables (MRIOTs) and their application to the diffusion of emission responsibilities through the global trade network. I then explore the implications of the EU CBAM on trade partners and find uneven impacts, particularly on developing countries. I finally show that the EU CBAM can motivate other countries to implement more ambitious climate policies, thereby instrumentalising trade interdependencies for climate co-operation. This final section puts these findings in perspective and paves the way for future research. I **first** review the main assumptions and limitations of using MRIOTs and discuss alternative data sources. **Second**, I discuss underlying modelling choices. **Third**, I connect my thesis with broader scientific and societal debates.

I Mapping the global trade network

All five articles of this dissertation use MRIOTs to model the global trade network, thereby sharing underlying assumptions and limitations. I review the general uncertainties associated with MRIOTs in the **first paragraph**.

Second, I discuss the criteria for choosing the MRIOTs I used in this dissertation. **Finally**, I discuss alternative approaches to model global trade.

1.1 On the accuracy of MRIOTs

The construction of MRIOTs requires collecting, harmonising and aggregating conflicting data from multiple national and international statistics (Guo, Webb, and Yamano 2009), largely extrapolating the economic structure of countries with low data availability (Lenzen, Moran, et al. 2013), the industry-by-industry international trade flows (Andrew and Peters 2013; Schulte, Jakobs, and Pauliuk 2021) and ultimately balancing the MRIOT (Lenzen, Gallego, and Wood 2009). Some MRIOT providers release uncertainty estimates for their MRIOTs (Lenzen, Moran, et al. 2013), but these estimates mainly capture the deviations caused by the balancing procedures (Lenzen, Gallego, and Wood 2009). Environmental extensions are also major sources of uncertainties (Moran and Wood 2014; Tukker, Pollitt, and Henkemans 2020) and the tracing of supply chains across the global trade network entails additional assumptions (Lenzen, Wood, and Wiedmann 2010; Schulte, Jakobs, and Pauliuk 2024; Wiedmann 2009). In the absence of a perfect benchmark, assessing the relative accuracy of MRIOTs is challenging. Comparative studies show a relative agreement of the most used MRIOTs on aggregated trends but potentially large differences at the country-level (Owen et al. 2014; Moran and Wood 2014; Giljum et al. 2019; Tukker, Pollitt, and Henkemans 2020). The diversity of MRIOTs available in the literature (Lenzen, Moran, et al. 2013; Lenzen, Geschke, Abd Rahman, et al. 2017; Dietzenbacher et al. 2013; Aguiar et al. 2022; Wiebe and Yamano 2016; European Commission. Statistical Office of the European Union. 2019) follow different technical and design choices and entail alternative sectoral, regional and temporal resolutions.

Sectors in MRIOTs aggregate products with vastly different production functions, supply chains and associated environmental externalities (Lenzen 2011; Steen-Olsen et al. 2014). While the EU CBAM applies to specific prod-

ucts, articles 3, 4 and 5 are based on MRIOTs with a much coarser definition. In my dissertation, I use process-level emission data (Gütschow, Jeffery, and Günther 2021; Gütschow, Günther, Annika, et al. 2021) to model the EU CBAM beyond the sectoral scale. Alternatively, the growing availability of MRIOTs with an enhanced sectoral definition is a promising avenue for future research (Lenzen, Geschke, Abd Rahman, et al. 2017; Lenzen, Geschke, West, et al. 2021). In principle, MRIOTs can be expanded to an arbitrary number of sectors. However, MRIOTs being network representations, their complexity grows quadratically. For an MRIOT with m sectors and n countries, including an additional sector to each country requires adding n nodes and up to $(nm)^2$ edges to the network. This complexity is challenging to handle from both the data availability and numerical perspectives, such that increasing the MRIOT size might increase the prevalence of data outliers and reduce the agreement with official statistics (Moran and Wood 2014; Owen et al. 2014). This observation also applies to the regional disaggregation of the MRIOTs. While increasing the regional coverage has a major effect on the precision of the analysis (Su and Ang 2010), such extended geographical coverage largely relies on extrapolations, thereby limiting the accuracy of the table. The temporal dimension embodies the same trade-off. MRIOT time series are usually developed for a base year and back- and forecast to different years based on proxy data (Lenzen, Moran, et al. 2013; Dietzenbacher et al. 2013; Wood et al. 2015; Andrew and Peters 2013). As discussed in article 1, projecting MRIOTs with incomplete data negatively affects the accuracy of the resulting table (Valderas-Jaramillo et al. 2019).

Extending MRIOTs is always an underdefined problem: the number of data points to be included vastly exceeds the number of input constraints, such that larger databases necessarily entail a larger uncertainty on specific coefficients. Choosing an MRIOT therefore requires an arbitrage between extensivity and precision.

1.2 Data choices

This dissertation utilises three different MRIOTs: EORA26 (Lenzen, Moran, et al. 2013) in the articles 1, 2 and 3; GTAP11 (Aguiar et al. 2022) in article 4 and WIOD16 (Timmer et al. 2015) in article 5. This paragraph justifies these choices in light of the data limitations discussed earlier and the respective research questions.

Considering the difficulty of assessing the quality of MRIOTs, I have chosen to work exclusively with MRIOTs that have been largely used in the literature at the time of the studies, thereby excluding MRIOTs with larger resolution which have not yet been systematically compared to more established tables, such as Gloria (Lenzen, Geschke, Abd Rahman, et al. 2017) or R-MRIO (Cabernard and Pfister 2020). Article 1 presents a projection method I test against an MRIOT time series, for which the availability of a sufficiently long time series was a requirement. In articles 2, 3, 4 and 5, I use of the Multi-Scale Mapping (MSM) method (Beaufils 2023) to extend the MRIOTs with emission data. The MSM method requires mapping emission categories with the MRIOT's sectors and better allocates emissions when the MRIOT sectoral resolution is comparable to the emission data source (Gütschow, Jeffery, and Günther 2021). Articles 3 and 4 study the distributional effect of the EU CBAM on developing countries, thereby requiring a sufficiently large regional resolution. I have chosen to work with two MRIOTs that offer alternative compromises regarding spatial and regional resolution, data availability, transparency and accuracy. Article 5 uses an MRIOT with a lower regional and sectoral resolution, limiting the complexity of the numerical modelling and increasing the traceability of the results. This choice was also influenced by the limited availability of estimated trade elasticities in the literature (Fontagné, Fouré, and Keck 2017).

On the temporal dimension, the analysis in the articles 2, 3, 4 and 5 use several years old MRIOTs. In the meantime, the global economy underwent a global pandemic and different episodes of sanctions, which have modified

the trade network and are not captured in the MRIOTs (Barbero, Lucio, and Rodríguez-Crespo 2021; Steinbach 2023; Espitia et al. 2022). Some MRIOT providers release updated and projected tables (Tukker, Pollitt, and Henkemans 2020; Lenzen, Moran, et al. 2013; Lenzen, Geschke, Abd Rahman, et al. 2017), and the method described in [article 1](#) could have been used to overcome this limitation. However, the analysis of the EU CBAM in the articles [3](#), [4](#) and [5](#) requires reliable data at the sector level, which the SPIN method could not deliver. Again, acknowledging the trade-off between temporal resolution and data accuracy, I favoured the second criterion and relied on well-established historical MRIOTs.

The combination and the ranking of such criteria involve value judgments which are naturally disputable. The robustness of my findings to different MRIOTs has not been addressed in this dissertation and remains an avenue for future research. The Multi-Scale Mapping (Beaufils 2023) and MRIO toolbox (Beaufils 2024) software packages I developed during my thesis will simplify the replication of the articles with different MRIOTs by limiting the changes required for implementing the research methods.

1.3 Alternative data sources

Beyond the realm of MRIOTs, more granular data apply to exploring the interactions between international trade and climate change mitigation. First, Life-Cycle Analysis (LCA) assesses the externalities associated with producing, using and disposing of specific products, using bottom-up explorations of supply chains (Islam, Ponnambalam, and Lam 2016). Because this process is data- and time-intensive, LCAs can only focus on the first supply chain layers, thus lacking comprehensiveness compared to MRIOTs (Ward et al. 2018). Additionally, LCA data are context-specific, so their application to global studies is delicate (Hellweg and Milà i Canals 2014). The analyses of articles [2](#) and [3](#) are therefore beyond the scope of LCA. Instead, LCA can complement the findings of [article 4](#) with sector-

and country-specific insights on the exposure of supply chains to the EU CBAM (Schlipf, Striegl, and Gaugler 2024).

Second, bilateral trade data (Gaulier and Zignago 2010; Nations 2020) are widely used for analysing the response of the international trade network to exogenous shocks (Barbero, Lucio, and Rodríguez-Crespo 2021; Steinbach 2023; Espitia et al. 2022) and trade policies (Bratt 2017; Baier and Bergstrand 2007). On the one hand, using bilateral trade data to assess trade policies' effect is handy, as they are directly collected from institutional sources and thereby more disaggregated and reliable than MRIOTs. On the other hand, bilateral trade data crucially ignore sectoral interlinkages and thus the network structure of international trade. As highlighted in this dissertation, the network properties of international trade play a crucial role in tracking emissions along supply chains (articles 2, 3, 4) and integrating the indirect effect of trade policies (article 5). Bilateral trade data are therefore better suited for ex-post analysis of trade policies than for the kind of prospective analysis presented in this thesis (Caliendo and Parro 2022). Still, such data can improve the robustness of my findings by ensuring the validity of critical data points in the MRIOTs and enabling empirical testing of the mechanisms modelled in my dissertation.

Finally, an emerging body of literature builds an alternative network perspective on bilateral trade data, at the interface between physics and economics (Hidalgo and Hausmann 2009; Hidalgo 2021; Teza, Caraglio, and Stella 2021). So-called “complexity economics” explores the interaction between the complexification of economic systems, measured by machine learning techniques, linear algebra and network sciences; and diverse dimensions of human and economic development. As for bilateral trade data, complexity economics does not capture sectoral interlinkages and is mainly used empirically. To my knowledge, assessments of the overlaps between complexity economics and MRIOTs are still missing and are a promising avenue for future research.

2 All models are wrong, but some are useful²

This section discusses important modelling choices underlying the dissertation. Article 2 introduces the Throughflow Based Accounting (TBA) framework to assess the emissions associated with specific supply chains. The method is directly applied in articles 3 and 5 and a related approach is used in article 4. The **first subsection** motivates the scope of emissions considered in these articles. The **second subsection** normatively discusses the methods used for modelling the evolution of the trade network in the articles 1 and 5. The **third subsection** compares the approaches used to evaluate the impacts of the EU CBAM in articles 3, 4 and 5

2.1 Emissions accounting

The analysis in articles 2, 3, 4 5 exclusively account for the carbon dioxide emissions from domestic fuel combustion and industrial processes. The next paragraphs address the reasons for excluding the emissions from international transportation, Land-use, Land-use Change and Forestry (LULUCF) and non-CO₂ emissions, respectively.

The exclusion of the emissions from international transportation might appear surprising since these emissions are directly attributable to trade. Two arguments motivate this omission. First, reporting emissions from international transportation to countries raises specific difficulties: should the emission from a cargo ship be allocated to the ship-owner, the operator, the owner of the transported commodities, the country of the home port, the one of origin, the destination, or the fuel supplier? In the absence of a global consensus on these questions, emissions from international transportation are reported apart from national emissions (Cadarso et al. 2010; UNFCCC 2005) and excluded from the emission datasets used in this dissertation (Gütschow, Günther, Annika, et al. 2021; Gütschow, Jeffery,

²(Box and Draper 1987)

and Günther 2021). Second, MRIOTs only report the margins of the transportation sectors, which do not allow a straightforward estimation of the emissions associated with bilateral transactions (Mahajan et al. 2018). Instead, accounting for international trade emissions requires a modelling effort outside the scope of this work (Wang, Liu, Lv, et al. 2021; Wang, Liu, Guan, et al. 2022).

The exclusion of LULUCF emissions derives from different arguments. First, LULUCF emission data are usually less robust and more volatile than combustion and process emissions data (McGlynn et al. 2022). Second, whereas the CO₂ emissions from combustion and industrial processes result from active industrial transformations, LULUCF emissions largely derive from sources not associated with industrial activities. For instance, changes in the forest cover are a major driver for these emissions (IPCC 2022). The link between forest cover and international trade is the core of a distinct literature that requires specific modelling of agricultural production (Pendrill et al. 2022). Still, provided the models are adjusted to account for the specificities of LULUCF emissions, the methods introduced in articles 2 and 5 could be used to investigate the links between trade and deforestation. In particular, the EU has introduced an anti-deforestation policy instrument that shares similarities with the EU CBAM (EU 2023a). Investigating the coalition-building potential of this policy instrument is a promising avenue for future research.

The exclusion of *non* – CO₂ emissions is due to similar data and modelling limitations. For example, methane (CH₄) is the second contributor to anthropogenic climate change (IPCC 2021). Methane emissions derive from a variety of processes that include livestock, fugitive emissions from oil and gas production and waste treatment (UNEP 2022). As for LULUCF emissions, associating these emissions with economic activity requires additional modelling beyond the scope of this dissertation. Again, adjusting the methods used throughout this dissertation would allow extending the analyses to other greenhouse gases.

2.2 The future of the global trade network

In the four years I invested into my dissertation, the global economy underwent a pandemic (Barbero, Lucio, and Rodríguez-Crespo 2021; Espitia et al. 2022), the blockage of the Suez canal (Wan et al. 2023) and the imposition of major sanctions by the EU on its main energy supplier, Russia (Gars, Spiro, and Wachtmeister 2022). In the meantime, extreme weather events are regularly disrupting international supply chains (Middelanis, Willner, Otto, Kuhla, et al. 2021) and their impact will increase with climate change (Middelanis, Willner, Otto, and Levermann 2022; Kuhla, Willner, Otto, Geiger, et al. 2021; Kuhla, Willner, Otto, and Levermann 2023). These events interact with an underlying trend of polarisation in international trade relations, which materialises already in a relative slowing down of global trade (Antràs 2020) and increases the risk of trade wars (Gars, Spiro, and Wachtmeister 2022; Itakura 2020). The *first* and *fifth* articles of my thesis provide alternative options for navigating such a deeply uncertain future (Kwakkel, Walker, and Marchau 2010). While it is clear that neither of these approaches can tell us the future, the next paragraphs discuss the modelling philosophy underpinning both prospective approaches.

In *article 1*, I propose the SPIN method to project MRIOTs under exogenous evolution scenarios for the global economy. This approach was inspired by the Shared Socioeconomic Pathway (SSP) concept. The SSPs are a set of qualitative scenarios describing possible states of the future economy and are used to map mitigation and adaptation pathways in the space of possible futures (O'Neill et al. 2017; IPCC 2022). However, the applicability of the SPIN method for illustrating hypothetical states of the global economy is limited, because the minimal input requirements for applying the SPIN method conflict with the information density of MRIOTs. The SPIN method minimises the difference with a historical MRIOT under aggregated constraints. This procedure lacks explicit mechanisms justifying the evolution of individual coefficients, limiting the traceability of the outcomes. While the SPIN method might yield plausible results for

illustrating marginal evolutions of the network, such plausibility decreases as the scenarios diverge from the initial conditions.

Instead, [article 5](#) builds on clear hypotheses regarding the mechanisms driving the evolution of international trade. The model is comparatively more tractable, allowing the identification of causal mechanisms driving the results. This approach requires disputable assumptions, such as the simultaneous clearing of perfectly competitive markets ([Arthur 2009](#); [Arthur 2021](#)) and simplified input substitution mechanisms ([Nightingale 2004](#)). Still, [article 5](#) makes these assumptions explicit and transparent, such that future work could test the robustness of the findings to alternative model specifications.

2.3 The impact of climate policies

Articles [3](#), [4](#) and [5](#) assess the effects of the EU CBAM on trade partners, based on different metrics and approaches. [Article 3](#) directly applies the TBA method introduced in [article 2](#) to assess the exposure of countries to the EU CBAM, defined in terms of the share of domestic emissions in the scope of the EU CBAM. This definition is simple and transparent but provides a narrow definition of vulnerability. The EU CBAM will indeed more strongly impact the countries with a high share of emissions covered, but such a metric overlooks whether these impacts will be negative or positive. The EU CBAM will make exporters in the EU market compete under a carbon price, such that exporters with lower emission intensity will gain a competitive advantage over more polluting competitors and benefit from the EU CBAM. Instead, [article 4](#) uses a combination of exposure indicators, such as the dependence on international trade and relative emission intensities. This approach favours a more nuanced analysis of the exposure of individual countries, highlighting qualitative differences between countries' exposure that were overlooked in the previous article. However, such analysis requires country-specific considerations, thereby reducing the scope of the study.

Both articles 3 and 4 build on the crucial assumption that the trade interlinkages described in the MRIOTs are unaffected by the introduction of the EU CBAM. Instead, article 5 explicitly models the evolutions of the trade network in response to the EU CBAM, in a General Equilibrium (GE) framework (Arrow and Debreu 1954; McKenzie 1959). This approach endogenises economic mechanisms that mediate the impacts of the EU CBAM on trade partners, resulting in a more comprehensive analysis. However, the validity of a model depends on the validity of its underlying assumptions. Such underlying assumptions are comparatively more explicit, and therefore easier to discuss, in articles 3 and 4, than in article 5 (Parker and Winsberg 2017). Still, article 5 captures the interaction between different mechanisms driving the impact of the EU CBAM, which is out of the reach of the models used in articles 3 and 4.

My dissertation highlights the benefits of using diverse modelling approaches (Jebeile and Crucifix 2021). Far from competing with each other, the three methods I used to assess the impacts of the EU CBAM answer distinct research questions and shed complementary light on the impacts of the EU CBAM on trade partners (Knuuttila 2011).

3 Solving the climate coordination dilemma

My dissertation highlights that the EU CBAM extends the EU climate policy through the global trade network and motivates climate policies in other countries. From that perspective, the EU CBAM instrumentalises trade interdependencies for diffusing climate action, thereby resolving the climate coordination dilemma. Practically, my proposition raises questions that reach beyond the data and method discussions. This final section puts my thesis in perspective with the broader academic and public discourse and outlines future research priorities.

3.1 Making climate policies acceptable

In 2018, massive popular protests forced the French government to retract a tax increase on fossil fuels. The so-called “yellow vests” movement exposed the general unpopularity of carbon pricing (Douenne and Fabre 2022). The perceived regressivity of carbon taxation is a major source of opposition (Maestre-Andrés, Drews, and Bergh 2019), as poorer households are expected to be relatively more affected by carbon pricing (Wang, Hubacek, et al. 2016; Dorband et al. 2019; Feindt et al. 2021). Targeted transfers of the carbon tax fiscal revenue can partially soothe this opposition (Dechezleprêtre et al. 2022), even though sociological findings point to deeper geographical and cultural factors for opposing climate policies (Drews and Bergh 2016; Latour 2017; Oatley 2023). The introduction of the EU CBAM adds an international layer to the question of the distributional impacts of climate policies. Articles 3 and 4 stress the exposure of some developing countries to the EU CBAM, which have a negligible responsibility in historical emissions and limited capacities to respond to the EU CBAM. Implementing domestic carbon pricing might help these countries cope with the EU CBAM pressure, but such implementation raises practical and distributional questions beyond the scope of my dissertation. In particular, articles 3, 4 and 5 provide impact assessments at the national level only and overlook subnational distributional effects. In that regard, combining MRIOTs with household-level data is a promising research avenue (Steckel et al. 2021).

Relatedly, my dissertation exclusively investigates carbon pricing and overlooks alternative climate policies. This focus connects with a well-identified path dependency bias in the literature, driven by the relative simplicity of modelling carbon pricing and its theoretically higher efficiency (Pottier 2016). Nonetheless, alternative policy instruments can motivate emission reduction in other countries, while being potentially more attractive politically (Schwerhoff et al. 2018; Kemp and Volpi 2008; Linsenmeier, Mohommad, and Schwerhoff 2023). In particular, subsidising

the development and adoption of clean technologies can give a competitive edge to domestic industries and yield long-term economic benefits (Driesen, Mehling, and Popp 2024; Fischer and Newell 2008). However, the mechanisms at play require different modelling approaches than those applied in my dissertation.

3.2 Competing interpretations of the EU CBAM

The mechanism by which the EU CBAM incentivises climate policies abroad resonates with concepts from different disciplines, calling for contrasting interpretations.

The mechanism modelled in [article 5](#) can be qualified as a tipping point, a local change in the trade network inducing system-wide effects. In climate physics, tipping points are associated with critical thresholds of the Earth System and often entail adverse consequences for human societies and the biosphere (Lenton et al. 2008; Ritchie et al. 2021). In the broader literature, tipping points characterise a diversity of system shifts that can have either positive or negative effects (Milkoreit et al. 2018). The main finding of this dissertation hints towards a positive role of socio-economic tipping points for accelerating climate mitigation, as proposed in [Otto et al. \(2020\)](#).

Alternatively, international studies use the concept of weaponised interdependencies to explore how countries use power asymmetries in the global economic network to leverage strategic advantages (Drezner 2011; Farrell and Newman 2019; Beaumier and Cartwright 2024). In principle, the EU CBAM derives from different motivations, but the distributional effects highlighted in [articles 3 and 4](#) and the diffusion mechanism modelled in [article 5](#) can support the interpretation of the EU CBAM as climate-motivated trade weaponisation, either as an attempt to force other sovereign countries to adopt climate policies or as an instrument to hamper other countries from exporting to the EU market (Corvino 2023; Vuong, La, and Nguyen 2023). [Rodrigues Vieira \(2023\)](#) stresses the limits of weaponising trade in an increasingly multipolar world and the underlying risk for global cohesion.

Thereby, the broader literature opposes two competing interpretations of the EU CBAM. My thesis argues that the instrumentalisation of trade interdependences can contribute to overcoming the status quo of international negotiations, in line with the concept of social tipping points (Otto et al. 2020). From that perspective, the negative consequences of the EU CBAM on trade partners can be justified if they discourage free-riding and overcome the climate coordination dilemma. Alternatively, the EU CBAM can be perceived as an attempt to weaponize international trade under the pretext of climate mitigation. In that case, the consequences of the EU CBAM on trade partners would be ethically disputable (Corvino 2023), might trigger retaliation (Böhringer, Carbone, and Rutherford 2016) and threaten climate negotiations (Vuong, La, and Nguyen 2023).

3.3 Making the EU CBAM work

The question of which perception of the EU CBAM will eventually prevail is critical for the future of climate mitigation and largely transcends the academic discussion. Still, further research can chart a path towards a cooperative interpretation of the EU CBAM. Article 3 succinctly discusses the recycling of the fiscal revenue to dampen the effect of the EU CBAM on trade partners. Just like recycling the revenue of domestic carbon taxes is instrumental to increasing their acceptability, targeted recycling of the EU CBAM revenue to trade partners could favour a cooperative interpretation of that policy (Dechezleprêtre et al. 2022). However, this option raises crucial questions. Which normative foundations should underpin such recycling? What would be the distributional impacts of different options? What would be their effect on the incentive for trade partners to implement carbon pricing? What are the trade-offs and synergies between different dimensions? The methods introduced in article 5 provide a coherent framework for exploring this option space and ultimately designing cooperation-enhancing policies.

Developing relevant and robust science in that direction will demand efforts towards more interdisciplinarity, transparency and diversity. First, the last paragraphs discuss important insights from other disciplines that future research must reflect upon. Second, the (geo)political dimension of the EU CBAM cannot be understated, calling for dialogues between the scientific community and the broader society. A cooperative interpretation of the EU CBAM requires building international support through multilateral forums such as the Conferences of the Parties. Scientists willing to engage in related research must acknowledge the diverse perspectives involved. Third, the design of the EU CBAM has global consequences and relies upon normative value judgements. Including diverse cultural, social and political perspectives in the scientific processes allows explicit- ing and discussing these values, thereby improving the legitimacy and the significance of such research (Rolin 2019).

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Appendices

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Appendix for article 1:
Projecting the global trade network

Supplementary materials

S1. List of all operators, indices and variable names used

Operators	
e	Row wise sum operator
'	Transposition operator
I	Identity matrix
^	Diagonalization operator
'	Transposition operator
Indices	
$(r, s) \in \llbracket 1; n \rrbracket^2$	Region
$(i, j) \in \llbracket 1; m \rrbracket^2$	Sector
K, L	Trade zones, ensemble of regions
Superscripts	
in	Intermediate commodities
fi	Final commodities
*	Variable extracted from the base table
Variables	
Z	Inter-industry matrix (MRIO table)
Z_{rr}	Domestic inter-industry block
Z_{rs, r≠s}	International trade block
Y	Final demand matrix
c_r	Final demand (consumption) array for region <i>r</i>
y_{rr}	Array of domestic demand for final commodities from region <i>r</i>
y_{sr}	Array of final commodities from region <i>s</i> used in region <i>r</i>
v	Value added array
x	Gross output array
t_{rs}	Trade flow from region/zone <i>r</i> to region/zone <i>s</i>
ex_{rs}	Export array from region <i>r</i> to region/zone <i>s</i>
ex_r	Total exports value from region <i>r</i>
im_{rs}	Import array to region <i>r</i> from region/zone <i>s</i>
im_r	Total imports value to region <i>r</i>
δ_{rs}	Trade balance of region/zone <i>r</i> with regard to region/zone <i>s</i>
λ_{rs}	Intensity of the trade flow between regions/zones <i>r</i> and <i>s</i>
gdp_r	Gross domestic product of region <i>r</i>
θ_r	Sectoral shares in exports of region <i>r</i>
φ_r	Sectoral shares in domestic final demand of region <i>r</i>
α_r	Share of final commodities in imports to region <i>r</i>
ad_r	Aggregated demand array for region <i>r</i>
L_r	Domestic Leontief inverse
c	Number of countries covered for study cases
z	Number of economic zones defined for study cases
d_r	Volume of commodities domestically processed in region <i>r</i>
Supplementary Materials	
v₁	Income array
v₂	Net taxes and subsidies array
n_r	Number of countries forming the aggregated region <i>r</i>
h ∈ ⌊1; n_r⌋	Indices composing the aggregated region <i>r</i>
g_h	Country <i>h</i> in aggregated region <i>r</i>

Φ_r	Matrix of sectoral allocation of final demand of domestic commodities within aggregated region r
α_{gK}	Share of exports from country g in exports from region r to zone K
δ_{gr}	Trade balance of country g with regard to countries of region r
β_g	Share of imports to country g in imports to region r

Table S1 – List of all operators, indices and variable names used. Throughout the manuscript, arrays and matrices are designated with capital letters and scalars with lowercase letters.

S2. Supplementary figures

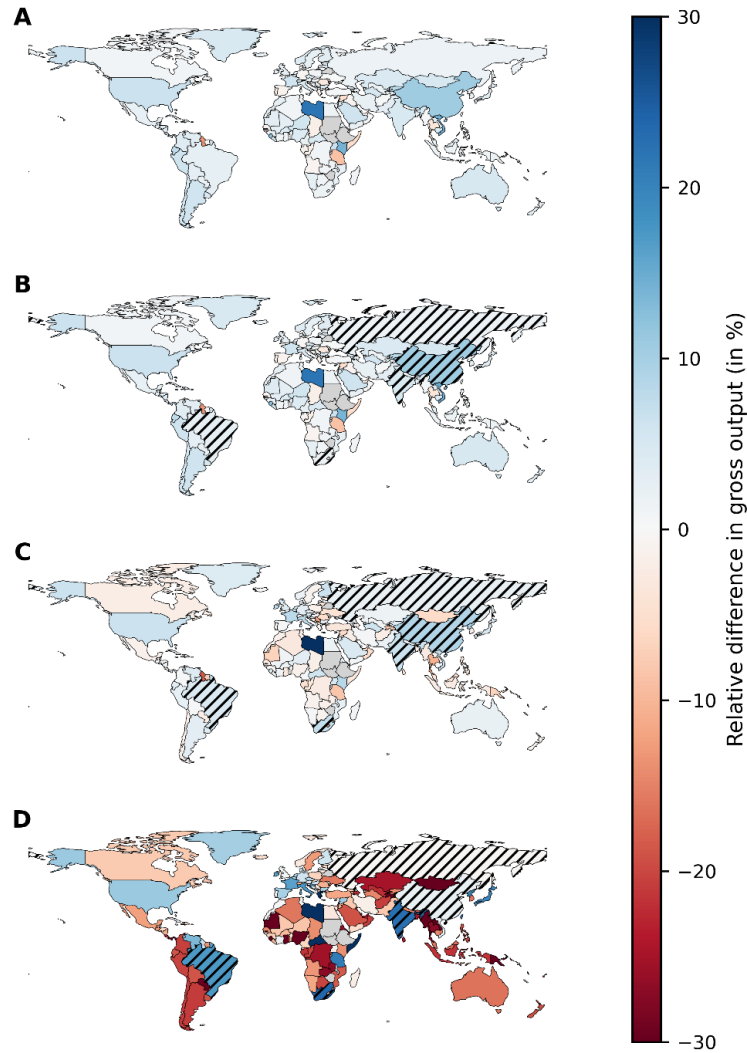


Figure S1 – Difference in gross output when constraints are applied at the level of large economic zones instead of at the national scale. Coloring of countries shows the percentage difference in national gross output compared to the reference EORA table for 2015. The BRICS countries are dashed. The base MRIO table corresponds to 2009 data; projections are made for 2015, using the global volume of trade between all the BRICS countries and the rest of the world. Panels A to D correspond to projections made using the corresponding settings (section 3.1, table 1). Gross output denotes the total output of all sectors in a country, encompassing both commodities that are further processed (intermediate commodities) and commodities that are consumed (final commodities). Heterogeneity in growth rates within economic zones cause large deviations in gross output compared to the reference scenario when constraints are prescribed at the scale of aggregated economic zones (C-D).

Here, the production in rapidly growing countries (South America, Africa) is generally underestimated, while it is overestimated in slowly growing countries, e.g. in European countries.

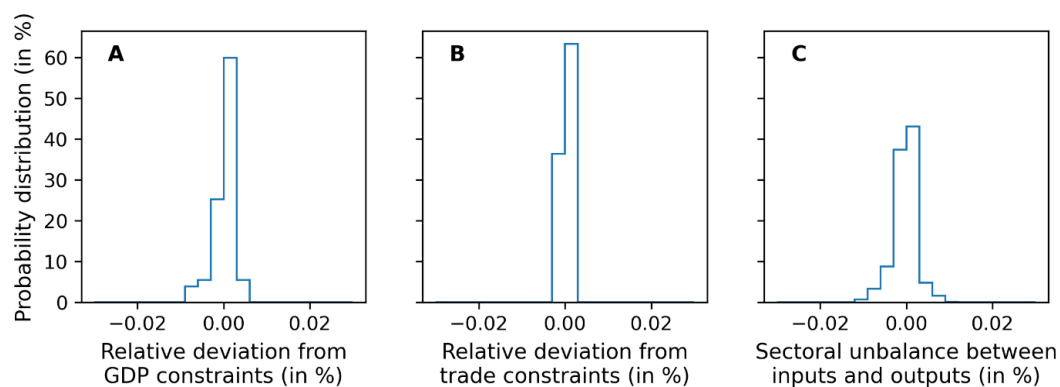


Figure S2 –Adherence of the SPIN projections to the prescribed constraints for 2015. The projected table is based on EORA 2009 and is iteratively projected for each year between 2010 and 2015. Trade and GDP constraints are extracted from the values observed in the EORA tables for the corresponding year. GDP constraints are prescribed for each country, and trade constraints are applied between each pair of countries (setting A). The termination threshold of the balancing algorithm is set at 0.01%. Panel A and B represent respectively the distribution of national GDP volumes and of bilateral trade flows observed in the projections in 2015, as compared to the constraints initially prescribed. Panel C represents the relative difference between sectoral outputs and sectoral inputs in the projected tables. All GDP and trade constraints are met with a precision consistent with the termination threshold of the balancing process. Similarly, balance is achieved for every sector with a very high precision.

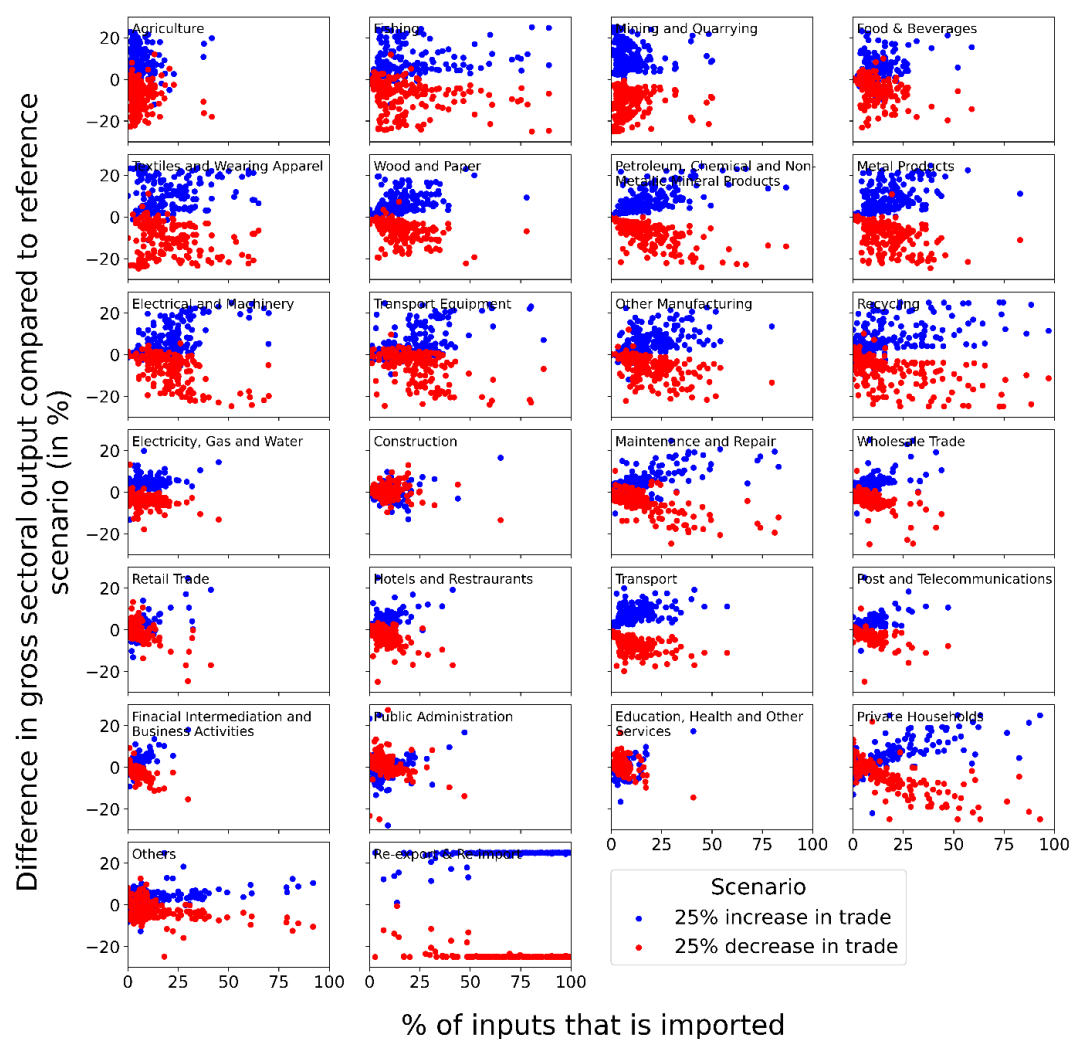


Figure S3 – Change in sectoral output induced by a hypothetical 25% change in trade relations related to sectoral dependence on imported inputs. Ordinates indicate the percentage change in sectoral gross output in each country compared to the reference table where trade between 2009 and 2015 evolved as observed. Abscissa refer to the percentage of inputs that is imported (intermediate imports) as share of national GDP observed in 2015. Red and blue dots refer to hypothetical scenarios of a 25% increase/decrease in trade during that period compared to the reference table. The three tables are based on EORA 2009 and projected iteratively up to 2015. GDP constraints are prescribed at the national scale following the values observed in the EORA time series from 2010 to 2015. Trade constraints are defined for each country with regard to the rest of the world (Setting B). In the reference table, trade constraints follow the volume observed in EORA time series. The two alternative scenarios, trade intensity is respectively increased/decreased by 25% for every country. Differences in sectoral output are unevenly correlated with relative importance of imported inputs. The link between dependence on intermediate imports and affectedness by changes in international trade is strongest for extractive and industrial sectors (rows 1-3).

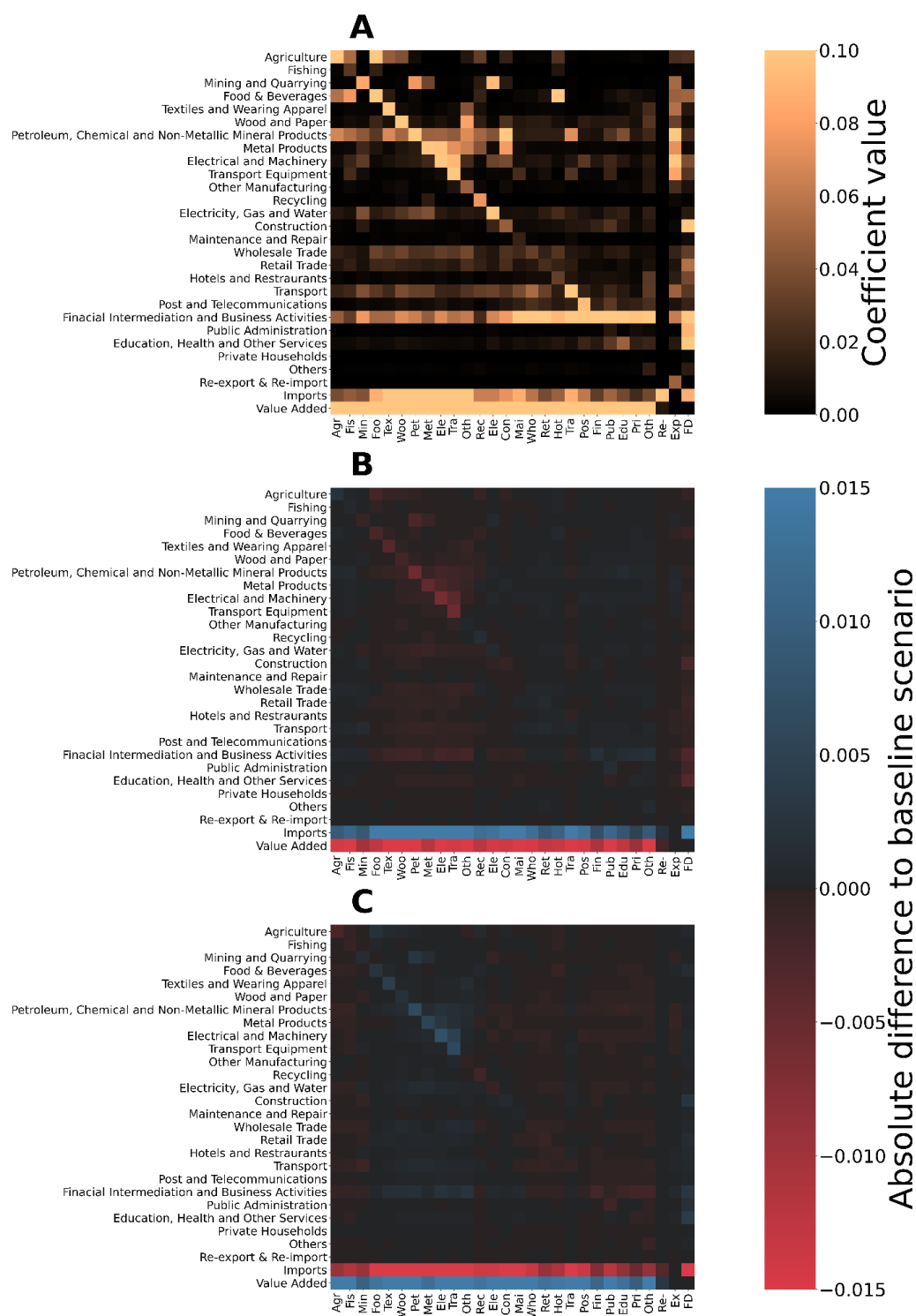


Figure S4 – Differences in the technical coefficient's matrix induced by a hypothetical 25% change in trade intensity. Technical coefficients represent the weight of a commodity (row) in the production process of an industry (column). Technical coefficients have a positive or null value, and the sum of the coefficients over one column always equals one. Panel A represents the matrix of technical coefficients observed in 2015 in the reference table, when trade evolved as observed from 2010 to 2015. Each pixel corresponds to a technical coefficient. Coloring of a technical coefficient indicates its absolute size.

Value added (corresponding to primary inputs in labor and capital) represents a large share of the inputs in every sector. Panel B and C compare the technical coefficients observed in the reference table for 2015 to the technical coefficients observed in the projections for 2015 where trade relations are increased by 25% (panel B) or decreased by 25% (Panel C). Coloring of each pixel represents the absolute deviation of the corresponding technical coefficient value induced by the increase/decrease of trade relations compared to the reference scenario. A 25% increase in trade translates simultaneously into an increase in the share of imported inputs, and a decrease in the share of value added in the production function of every sector. In other words, primary inputs (value added) are substituted by imported inputs when trade intensity is increased. Symmetrically, a decrease in trade volume is associated with a decrease of productivity (i.e. an increase in the share of value added in the production process), and a decrease in the share of imported inputs (Panel C). The three tables are based on EORA 2009 and projected iteratively up to 2015. GDP constraints are prescribed at the national scale following the values observed in the EORA time series from 2010 to 2015. Trade constraints are defined for each country with regard to the rest of the world (Setting B). In panel A, trade constraints follow the volume observed in EORA time series. In panel B and C, trade intensity is respectively increased/decreased by 25% for every country.

S3. Supplementary information

S3.1. Constraining net taxes and subsidies

In the basic setting of the SPIN method, net taxes and subsidies are handled as part of value added. We here propose an alternative formulation to handle net taxes and subsidies as a separate component of value added. This alternative is motivated by the fact that net taxes and subsidies are the only contributions to value added that may have large negative values (e.g. for highly subsidized sectors). Since the SPIN method is sign-conservative, a sector highly subsidized in the base table would remain virtually in deficit in every projected table. While this may be a reasonable assumption on short to medium time horizons, such assumption may become problematic in the longer term. The alternative formulation introduced here permits isolating negative elements from value added, hence permitting sign changes in overall value added. This alternative formulation can also be applied to further distinguish the components in value added (wages, profits, etc.). The main point of this alternative is to handle value added as two (or more) partly independent arrays instead of a single array. The first array, $\mathbf{v}_1$, contains the original elements of value added (incomes). The second array, $\mathbf{v}_2$, holds net taxes and subsidies (or any contribution to value added that should be distinguished).

In the basic setting of the method, regional value added v_r is directly identified with regional GDP, gdp_r (equation 11, section 2.1.4). In this alternative setting, regional value added is the sum of the two contributions, hence:

$$v_{1r} + v_{2r} = gdp_r. \quad (S1)$$

However, since value added is now considered as a matrix instead of an array, the scalar GDP volume is not sufficient to constrain value added during the balancing step anymore. This issue can be solved by introducing an additional closing relation for value added. For instance, one can assume that regional taxes and subsidies should balance each other (i.e. $v_{2r} = 0$), or that net taxes and subsidies should sum up to a constant share of value added. With that new relation, scalars v_{1r} and v_{2r} can be exogenously prescribed, and autonomous constraints can be imposed on the two arrays forming the value added matrix. The SPIN method can then be applied as detailed in sections 2.2. and 2.3., with a set of two constraints for regional value added instead of one in the basic setting.

S3.2. Aggregated regions

In the basic setting of the SPIN method, regions are identified as single countries. We present here an alternative formulation to model regions consisting of more than one country (as exemplified in settings C and D of section 3.1 and in section 3.3). Aggregated regional blocks are formed by

concatenating the trade blocks of the countries that compose it. A region r formed by n_r countries forms an inter-industry block of dimensions $(m * n_r, m * n_r)$, where m is the number of sectors per country. Diagonal blocks of the regional inter-industry matrix correspond to national inter-industry blocks, and non-diagonal blocks correspond to trade flows between countries within the same region. Similarly, final demand of domestic commodities $\mathbf{Y}_{rr}$ is now a matrix of dimensions $(m * n_r, n_r)$, instead of an array. Final demand of domestic commodities is in turn a block (instead of an array) from the regional matrix of final demand $\mathbf{Y}_r$. Columns of the final demand matrix are formed by concatenating final demand arrays of the corresponding countries:

$$\mathbf{Y}_r = (\mathbf{y}_{g_1}, \dots, \mathbf{y}_{g_{n_r}}), \quad (S2)$$

where $\mathbf{y}_{g_1}, \dots, \mathbf{y}_{g_{n_r}}$ are the final demand arrays referring to countries $g_1, \dots, g_{n_r}$.

This formal difference in the definition of regional consumption requires minor adjustments for allocating aggregated demand volumes to regional sectors (section 2.3.1). The array of sectoral shares for final demand of domestic commodities $\boldsymbol{\Phi}_r$ is now defined as a matrix, $\boldsymbol{\Phi}_r$. As in section 2.3.1, matrix $\boldsymbol{\Phi}_r$ describes the sectoral demand for final commodities produced within region r and consumed locally. It is defined by normalizing the matrix of domestic consumption of domestic commodities of the base matrix $\mathbf{Y}_{rr}$:

$$\boldsymbol{\Phi}_r = \frac{\mathbf{Y}_{rr}}{y_{rr}^*}. \quad (S3)$$

Hence, coefficient $\Phi_{ig_1 \rightarrow g_2}$ of $\boldsymbol{\Phi}_r$ describes the share of final demand for commodity i produced in country g_1 of region r and consumed in country g_2 of region r , with regard to the total consumption of domestic commodities in region r . Each coefficient of $\boldsymbol{\Phi}_r$ is of positive value, and the sum of all coefficients equals 1. The array of sectoral allocation of domestic final demand in region r , $\boldsymbol{\varphi}_r$, is obtained by aggregating $\boldsymbol{\Phi}_r$ by rows:

$$\boldsymbol{\varphi}_r = \mathbf{e}' \cdot \boldsymbol{\Phi}_r. \quad (S4)$$

The aggregated demand defined in equation (19) in section 2.3 is then deducted from GDP and trade inputs for region r , and the reconstructed array of sectoral shares for domestic demand of local final commodities.

Concerning the balancing step, a similar adjustment should be made with regard to final demand. Final demand is adjusted during the first sub-step of the balancing procedure (section 2.4.1). In the basic setting, final demand is constrained by the volume of regional consumption y_r . For regions composed of more than a single country, a final demand constraint should be defined for each country within the region. Without any other constraint being exogenously prescribed, regional constraint on domestic consumption is split between countries at the pro-rata of their contribution to regional final demand in the base table. Constraints on domestic consumption are then applied at the national level for balancing the regional inter-industry block (Figure S5).

Whenever constraints are applied at the scale of aggregated regions rather than individual countries, GDP can still be constrained at the sub-regional scale. In setting C in section 3.1, countries are aggregated into large economic zones but GDP is constrained at the national scale. That setting permits slightly improving the accuracy of the projected tables compared to the case where GDP is common to aggregated zone, by reflecting heterogeneity in growth rates of countries composing a region (see section 3.1). In that situation, national GDP growth rates are used for estimating both national final demand constraints (y_g) and the array of final demand for domestically produced

commodities (y_{rr}). In detail, national final demand arrays forming the demand matrix of region r are initially scaled up (or down) by their corresponding GDP growth factor. This preliminary scaled final demand matrix is then processed as introduced here before: sectoral allocation of domestic final demand Φ_r is computed by aggregating contribution of all countries, and domestic final demand y_r is allocated between countries at the pro-rata of their contribution in the base table.

The preliminary scaling step ensures that those economies within a region that grow fastest have their domestic consumption increase relatively more than slowly growing countries. As in section S3.1, the different GDP constraints within economic regions are handled in separate rows for the balancing procedure (figure S5).

	Region	r		Exports to trade zone K	Exports to trade zone L	Final demand		Constraints
Region	Country	g_1	g_2			g_1	g_2	
r	g_1	Z_{rr}^*		$ex_{rK}^* = Z_{rK}^* \cdot e + Y_{rK}^* \cdot e$	$ex_{rL}^* = Z_{rL}^* \cdot e + Y_{rL}^* \cdot e$	Y_{rr}^*		x_r
	g_2							
Imports from trade zone K		$im_{Kr}^{*in} = e' \cdot Z_{Kr}^*$		0	0	$im_{Kr}^{*fi} = e' \cdot Y_{Kr}^*$		im_{Kr}
Imports from trade zone L		$im_{Lr}^{*in} = e' \cdot Z_{Lr}^*$		0	0	$im_{Lr}^{*fi} = e' \cdot Y_{Lr}^*$		im_{Lr}
Value Added		$v_{g_1}^*$	0	0	0	0		gdp_{g_1}
		0	$v_{g_2}^*$	0	0	0		gdp_{g_2}

Constraints	x_r'	ex_{rK}	ex_{rL}	c_{g_1}	c_{g_2}
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Figure S5 -Example of regional MRIO table for the domestic optimization of the balancing step (see section 2.4.1). In this example, region r is formed by countries g_1 and g_2 , which are subjected to differentiated GDP constraints. Unlike in section 2.4.1, value added and final demand are not represented by arrays, but by matrices. Value added is now composed of two rows, associated each with the value added array of one country. Similarly, final demand contains two columns, corresponding to one country each. Value added rows are constrained using the GDP constraints associated with the corresponding country. Final demand columns are subjected to the consumption volumes computed during the projection step. Exports and imports constraints are defined at regional scale. They are hence common to both countries.

S3.3. Preparation of the EORA database for the performance assessment

The study cases exposed in section 3 use tables of the EORA time series as base and reference tables. The EORA database is a high definition global MRIO, covering 189 countries on a yearly basis from 1990 and 2015 (Lenzen et al. 2012; 2013). The basic database distinguishes from 26 to more than 300 sectors per country and combines both IO and Supply-Use Tables. For the sake of simplicity, our projections rely rather on EORA 26. This simplified version of EORA uses a homogeneous sectoral classification, distinguishing 26 sectors in 189 countries, for each year between 1990 and 2015. EORA 26 is made available as a sub product of the full EORA table and exhibits several consistency issues (e.g. discontinuous time series for some countries). In order to ensure the consistence of the baseline tables, the following routine is applied to each EORA tables from 2009 to 2015 before use.

First, rows and columns associated with countries exhibiting discontinuous time series are deleted:

- USSR does not exist in the projection period.

- Sudanese's and South Sudanese's time series are discontinuous since the latter become independent from the first in 2011.
- Belarus, Ethiopia, Moldavia and Zimbabwe present presumably flawed growth rates in the recent time period (at least one year with an annual GDP growth rate higher than 50%).

The "Statistical Discrepancies" sector is also deleted. Second, and as mentioned in section 2.1.1, changes in stocks and inventories are set to zero. The value added sector of EORA 26 does not include data on taxes and subsidies on product. We extrapolate net taxes and subsidies on products from available information, by setting net taxes and subsidies as the residual of the difference between outputs and inputs observed in EORA26. The outcome of this process is a balanced MRIO table covering 182 countries of 26 sectors each. The associated final demand and value added matrices are in line with our framework and internally consistent within the 2009-2015 time period.

Appendix for article 2:
Tracing externalities through the global trade network

Supplementary Material

Supplementary data

		Location of Final demand		
		Germany	EU	Non-EU
Location of CO ₂ emissions	Germany	273	104	171
	EU	74	31	51
	Non-EU	255	111	188

Table S.1 – Throughflow matrix of the CO₂ emissions associated with the German economy (Mt of CO₂). The throughflow matrix captures the upstream CO₂ emissions caused by the supply chains involving the German economy. Rows correspond to countries where emissions physically occur, columns correspond to the countries where the associated supply chains terminate. For instance, 51 Mt of CO₂ are caused in EU Member States to supply the final demand in non-EU countries through the German economy. The data correspond to those shown in fig. 3.

Supplementary figure

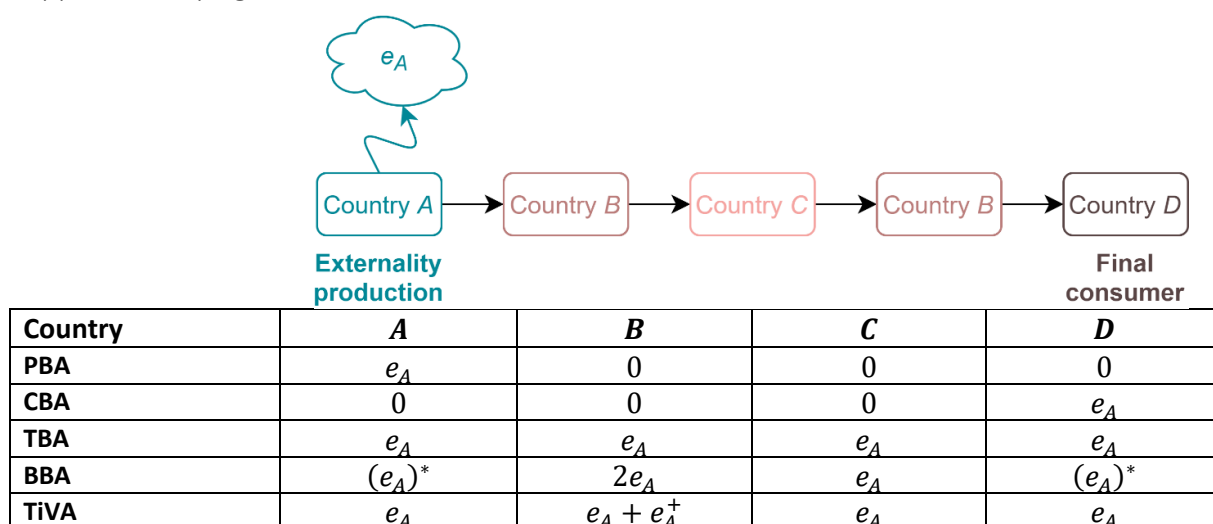


Figure S.1 - Allocation of an externality along an illustrative supply chain within different accounting frameworks. The table presents to which countries an externality is allocated to each of the countries involved in the supply chain represented above. This supply chain is causing an externality in country A, goes through countries B and C before traversing country B again. Finally, the supply chain reaches its' final user in country D. The Production Based Accounting (PBA) and Consumption Based Accounting (CBA) frameworks allocate the externality to the country directly causing them (A) and to the country where the final product is consumed (D), respectively. Both frameworks omit the involvement of countries B and C. The Throughflow Based Accounting (TBA) acknowledges the contribution of all countries equally, identifying the externality as exported for country A, traversing for countries B and C and imported for country D. The Betweenness Based Accounting (BBA) and Trade in Value Added (TiVA) frameworks also identify the contribution of intermediates (B and C) but count the contribution of country B's exports twice. Note that in the original definition of the BBA, the contribution of the producing and the consuming sectors are not included (Liang et al., 2016). Tokito et al. (2022) have proposed an alternative formulation of the BBA that accounts for these contributions. This alternative definition of the BBA entails the externality noted with an asterisk (*). The TiVA framework explicitly allows the isolation of the double counted component (Koopman et al., 2010, 2014), noted with a cross in the table (+).

Demonstrations and additional information

In what follows, we propose a formulation of the throughflow as a spatially explicit matrix and the decomposition of *local externalities* into two elements. We further provide the demonstration of the TBA decomposition and we detail the relation between the TBA and the decomposition proposed by

Hanaka et al. (2022). Finally, we expose the method used to map CO₂ emission data with the MRIO table. We ask the reader to refer to the main text for the notations.

Spatially explicit TBA matrix

The throughflow is introduced as a scalar quantity in equation (13). Using the elements of the TBA decomposition (equations (14-17)), the throughflow can also be expressed as a spatially explicit matrix $\mathbf{TBA}^c$, of dimensions $N \times N$. Element tba_{rs}^c of this matrix captures the volume of externalities caused in country r to supply the final users in country s through country c . Such element is generally defined as:

$$tba_{rs}^c = [\mathbf{q}^r \mathbf{L} \mathbf{Y}^s - (1 - \delta_{rc}) \mathbf{q}^r \bar{\mathbf{L}}^c \mathbf{Y}^s (1 - \delta_{cs})] \mathbf{e}, \quad (S.1)$$

where δ_{ij} denotes the Kronecker symbol, which equals 1 if and only if i and j are equal and 0 otherwise.

It is easy to show that the sum of the elements of such spatially explicit formulation of the throughflow equals the scalar throughflow. First, the sum of the elements of the $\mathbf{TBA}^c$ matrix is:

$$\sum_r \sum_s tba_{rs}^c = \left[\left(\sum_r \mathbf{q}^r \right) \mathbf{L} \left(\sum_s \mathbf{Y}^s \right) - \left(\sum_r (1 - \delta_{rc}) \mathbf{q}^r \right) \bar{\mathbf{L}}^c \left(\sum_s \mathbf{Y}^s (1 - \delta_{cs}) \right) \right] \mathbf{e}. \quad (S.2)$$

Then, using the properties of the Kronecker delta and equations (2), (3), (11) and (12), we have:

$$\sum_r \sum_s tba_{rs}^c = (\mathbf{q} \mathbf{L} \mathbf{Y} - \bar{\mathbf{q}}^c \bar{\mathbf{L}}^c \bar{\mathbf{Y}}^c) \mathbf{e} = tba^c. \quad (S.3)$$

Finally, such spatially explicit throughflow matrix intuitively displays the elements of the TBA decomposition. Using the properties of the Kronecker delta, it is trivial that, for any country r and s other than c :

$$\begin{cases} tba_{cc}^c = \mathbf{q}^c \mathbf{L} \mathbf{Y}^c \mathbf{e} = loc^c; \\ tba_{rc}^c = \mathbf{q}^r \mathbf{L} \mathbf{Y}^c \mathbf{e} = imp_r^c; \\ tba_{cs}^c = \mathbf{q}^c \mathbf{L} \mathbf{Y}^s \mathbf{e} = exp_s^c; \\ tba_{rs}^c = \mathbf{q}^r (\mathbf{L} - \bar{\mathbf{L}}^c) \mathbf{Y}^s \mathbf{e} = tra_{rs}^c. \end{cases} \quad (S.4)$$

Therefore, the c -th row of the TBA matrix shows the decomposition of the externalities caused in country c (PBA approach) and the c -th column of the TBA matrix contains the externalities caused by the final demand in country c (CBA approach). All externalities outside of the c -th row and column are *traversing* externalities.

Sub decomposition of the local supply chains

Local externalities are captured by equation (14). These can be further decomposed in *purely local externalities* ($ploc^c$) and *re-imported externalities* (rei^c). For that purpose, we introduce the matrix of input coefficients within country c , $\mathbf{A}^c$, being the block matrix associated with country c in $\mathbf{A}$ (i.e. the $(c-1)n$ -th to cn -th rows and columns of $\mathbf{A}$). Element $a_{ir \rightarrow js}^c$ is defined as:

$$\mathbf{A}^c = (a_{ir \rightarrow js}^c) = \begin{cases} a_{ir \rightarrow js} & \text{if } r = c \text{ and } s = c \\ 0 & \text{otherwise} \end{cases}. \quad (S.5)$$

From the matrix of input coefficients within country c , we build the Leontief inverse restricted to country c , $\mathbf{L}^c$ as:

$$\mathbf{L}^c = (\mathbf{I} - \mathbf{A}^c)^{-1}. \quad (S.6)$$

Element $l_{ic \rightarrow jc}^c$ captures how much inputs from sector i in country c are needed to produce one unit of output j in country c . Using these notations, we define *purely local externalities* ($ploc^c$) as the externalities caused in country c for supplying final users in country c along supply chains staying within country c :

$$ploc^c = \mathbf{q}^c \mathbf{L}^c \mathbf{Y}^c \mathbf{e}. \quad (S.7)$$

Conversely, *re-imported externalities* (rei^c) are caused in country c for the production of commodities finally used in country c but whose associated supply chain traverse other countries:

$$rei^c = \mathbf{q}^c (\mathbf{L} - \mathbf{L}^c) \mathbf{Y}^c \mathbf{e}. \quad (S.8)$$

The externalities captured as *re-imported* are similar to the ones captured as *purely local*, except that they are caused by supply chains involving other countries. From the perspective of the rest of the world, such externalities are *traversing externalities*. It is trivial that the sum of *re-imported* and *purely local externalities* corresponds to the *local externalities* introduced in equation (14).

Demonstration of the TBA decomposition

In order to demonstrate the equivalence between equation (13) and (18), we decompose equation (13) using the notations introduced in equations (11) and (12):

$$tba^c = [(\mathbf{q}^c + \bar{\mathbf{q}}^c) \mathbf{L} (\mathbf{Y}^c + \bar{\mathbf{Y}}^c) - \bar{\mathbf{q}}^c \bar{\mathbf{L}}^c \bar{\mathbf{Y}}^c] \mathbf{e}, \quad (S.9)$$

From equation (S.9), we decompose the throughflow into four elements:

$$tba^c = \mathbf{q}^c \mathbf{L} \mathbf{Y}^c \mathbf{e} + \bar{\mathbf{q}}^c \mathbf{L} \mathbf{Y}^c \mathbf{e} + \mathbf{q}^c \bar{\mathbf{L}}^c \bar{\mathbf{Y}}^c \mathbf{e} + \bar{\mathbf{q}}^c (\mathbf{L} - \bar{\mathbf{L}}^c) \bar{\mathbf{Y}}^c \mathbf{e}. \quad (S.10)$$

The first term of equation (S.10) corresponds directly to equation (14):

$$\mathbf{q}^c \mathbf{L} \mathbf{Y}^c \mathbf{e} = loc^c. \quad (S.11)$$

Applying equation (12) to the second term yields:

$$\bar{\mathbf{q}}^c \mathbf{L} \mathbf{Y}^c \mathbf{e} = \sum_{r \neq c} \mathbf{q}^r \mathbf{L} \mathbf{Y}^c \mathbf{e}. \quad (S.12)$$

And by comparing with equation (15):

$$\bar{\mathbf{q}}^c \mathbf{L} \mathbf{Y}^c \mathbf{e} = \sum_{r \neq c} imp_r^c = |\mathbf{imp}^c|. \quad (S.13)$$

Likewise, in the third term of equation (S.10), introducing equation (11) gives:

$$\mathbf{q}^c \bar{\mathbf{L}}^c \bar{\mathbf{Y}}^c \mathbf{e} = \sum_{s \neq c} \mathbf{q}^c \mathbf{L} \mathbf{Y}^s \mathbf{e}, \quad (S.14)$$

that is, in relation to equation (16):

$$\mathbf{q}^c \bar{\mathbf{L}}^c \bar{\mathbf{Y}}^c \mathbf{e} = \sum_{s \neq c} exp_s^c = |\mathbf{exp}^c|. \quad (S.15)$$

Finally, using equations (11) and (12) the fourth and latter term of equation (S.10) becomes:

$$\bar{\mathbf{q}}^c (\mathbf{L} - \bar{\mathbf{L}}^c) \bar{\mathbf{Y}}^c \mathbf{e} = \sum_{r \neq c} \sum_{s \neq c} \mathbf{q}^s (\mathbf{L} - \bar{\mathbf{L}}^c) \mathbf{Y}^s \mathbf{e}. \quad (S.16)$$

Comparing to equation (17), this corresponds to:

$$\bar{\mathbf{q}}^c(\mathbf{L} - \bar{\mathbf{L}}^c)\bar{\mathbf{Y}}^c\mathbf{e} = \sum_{r \neq c} \sum_{s \neq c} tra_{rs}^c = |\mathbf{TRA}^c|. \quad (S.17)$$

The TBA decomposition of equation (18) directly follows from the reintroduction of equations (S.11), (S.13), (S.15) and (S.17) into equation (S.10).

Comparison of the TBA with previous decomposition of the HEM

The TBA is the decomposition of the throughflow, which is itself the result of the Hypothetical Extraction Method applied to externality accounting. Hanaka et al. (2022) have proposed a comparable decomposition of the HEM into seven types of supply chains. This decomposition is different to ours in two aspects. First, the decomposition introduced here is defined at the country scale, while the decomposition of Hanaka et al. (2022) is applied at the sector scale. Second, Hanaka et al. (2022) differentiates between the trade of intermediate products and the trade of final products. Using the notations of Hanaka et al., our definition of *local externalities* coincides with their component (7), *importing externalities* gather components (2) and (5), *exported externalities* corresponds to the aggregation of elements (1) and (4) and *traversing externalities* are equivalent to component (3).

Besides this decomposition into seven terms, Hanaka et al. (2022) also define Production-, Betweenness- and Consumption-oriented emission's accounts. Each of these *emission types* is formed by the weighted sum of four of the seven terms of their initial decomposition. Given that these weights alter the elements of the initial decomposition, these *emission types* are not directly comparable to our definitions, nor to the canonical PBA, BBA or CBA frameworks.

Mapping of the CO₂ emissions in EORA

We apply a tailored procedure to assign emissions data from the PRIMAP datasets (J. Gütschow et al., 2020, 2021) to the economic sectors in the EORA 26 trade network dataset (Lenzen et al., 2012, 2013), referred to as Multi-Scale Mapping (MSM) method from now on. CO₂ emissions are reported in the PRIMAP databases using the 2006 hierarchical categorisation defined by the International Panel on Climate Change (IPCC) for the UNFCCC (Eggleston et al., 2006). IPCC emission categories form a nested list of emission categories, referred hereafter as an *emission tree*. We use a mapping table to associate IPCC emission categories to EORA sectors (Table S.2). As many aggregated IPCC emission categories relate to more than one economic sector, the construction of the mapping table requires to unfold the emission tree until a subcategory can be associated unambiguously with a single economic sector (referred to as *end-category*).

The PRIMAP-hist database reports aggregated emission categories for all IPCC countries (J. Gütschow et al., 2021) and PRIMAP-crf reports more detailed categories but only for Annex I countries of the UNFCCC (J. Gütschow et al., 2020). The MSM method exploits a two-step procedure to reconstruct an emission tree for each of the 182 countries included in both the PRIMAP-hist and EORA databases. End-categories' emissions are finally associated to economic sectors from EORA (fig. S.2) using the mapping table (table S.2). In the first step of the procedure, data from the PRIMAP-crf database are extrapolated to every country of the world using economic data from EORA 26 (fig. S.3). In the second step, estimated emission data are reconciled with the aggregated information contained in PRIMAP-hist (fig. S.4).

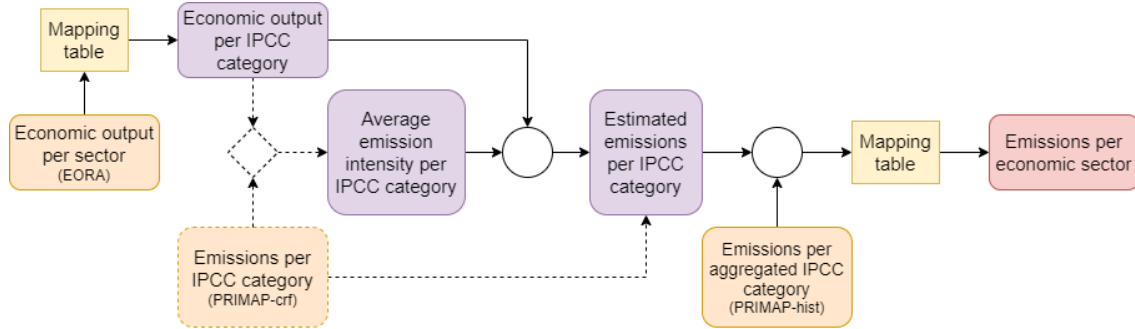


Figure S.2 - Overview of the MSM method that maps CO₂ emissions to MRIO data. First, the PRIMAP-crf emission database (J. Gütschow et al., 2020) is combined with sectoral economic output from EORA (Lenzen et al., 2012, 2013) to produce an initial estimation of emissions per IPCC category for each country. Second, these estimated emission data are reconciled with the aggregated information from the PRIMAP-hist database (J. Gütschow et al., 2021). Orange boxes represent inputs of the MSM method, the red box represents the output of the MSM method. Yellow boxes correspond to the table mapping EORA economic sectors to IPCC emission categories. Purple boxes represent intermediate data. Solid lines represent operations applied to all countries of the dataset. Dotted lines are only applied to countries covered in the PRIMAP-crf database (Annex I countries of the UNFCCC). Blank circles correspond to the two main steps of the algorithm. The dashed diamond corresponds to the initial estimation of the average emission intensities.

In the first step, average emission intensities are derived from PRIMAP-crf and EORA data for all end-categories. We note k the end-category from the IPCC emission tree and i the associated sector in the EORA database. For example, IPCC category 1A2A reports emissions associated with Fuel Combustion for Energy Production in the Iron and Steel Industry. This emission category is mapped with activities of the *Manufacturing of Metal Products* in the EORA 26 database. The world average emission intensity for end-category k , e_k^* , is defined as the volume of non-null emissions reported by countries c covered in PRIMAP crf for this category e_k^c , divided by the economic output of the associated national sectors x_{ic} , as reported in the MRIOT:

$$e_k^* = \frac{\sum_{c, e_k^c \neq 0} e_k^c}{\sum_{c, e_k^c \neq 0} x_{ic}}. \quad (S.18)$$

In our example, the PRIMAP-crf database contains data for the CO₂ emissions of category 1A2A for 38 countries, amounting to a total of 347 Mt of CO₂ in 2015. This figure corresponds to the numerator of equation (S.18). Reciprocally, the gross economic output of the *Metal products* industry in these 38 countries is valued in total to 3,34 trillion US\$ in 2015. Using the emission volume as the numerator and the economic output as the denominator, we estimate the average emission intensity of Fuel Combustion for Energy Production in the Iron and Steel Industry to 103g of CO₂ emitted per current US\$ of Metal Products.

Then, an estimated emission tree is created for every country covered in the EORA MRIOT (fig. S.3). The emission tree is first filled with data reported in PRIMAP-crf. Such values are labelled as *sourced*. In countries for which no emissions are reported in PRIMAP-crf, a volume of emissions $\overline{e_k^c}$ is estimated for country c using the average emission coefficient and the economic output of the corresponding sector x_{ic} :

$$\overline{e_k^c} = e^c * x_{ic}. \quad (S.19)$$

Such value is labelled as *estimated*. For instance, PRIMAP-crf does not include information on Chinese emissions. In absence of such *sourced* data, we assume provisionally that the Chinese *Metal products* industry has an emission intensity equal to the world average. The *Manufacturing of metal products* sector in China had an output value of 3,47 trillion US\$ in 2015. The world average emission intensity of Fuel Combustion for Energy Production in the Iron and Steel Industry is 103g of CO₂/US\$ according to equation (S.18). Following equation (S.19), Chinese emissions for category 1A2A are initially estimated to 229 MtCO₂ in 2015.

PRIMAP-crf also include information on aggregated categories. Aggregated categories are filled consecutively by “climbing” the emission tree, that is, starting from the most detailed category to the volume of national emissions (fig S.3). As for end-categories, categories for which emission values are reported into the PRIMAP-crf database are directly entered into the emission tree and labelled as *sourced*. Aggregated categories not covered in PRIMAP-crf are estimated from the sub-categories previously informed and labelled as *estimated*. For countries not reported in the PRIMAP-crf database, the emission tree built here is entirely estimated from national production data and from world average emission intensities.

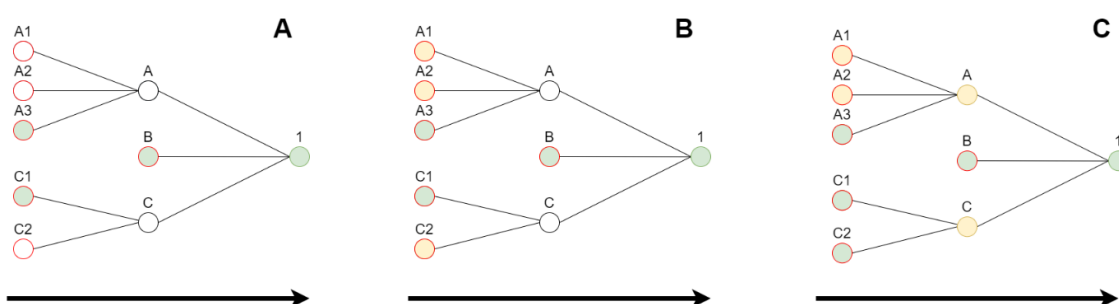


Figure S.3 – Description of the bottom-up aggregation process for the emission tree of a country. This procedure is applied to build an estimated emission tree using economic output from EORA, average emission intensity coefficients for each end-category and emission data from the PRIMAP-crf database. Panel A represents the emission tree of a country. Dots represent IPCC emission categories. The categories on the left-end of each branch correspond to end-categories, i.e. are associated with EORA economic sectors (red circles, A1-3, B, C1-2). Green dots correspond to categories available for this country in the PRIMAP-crf database. Blank dots are categories not covered for such country in PRIMAP-crf. In panel B, end-categories not covered in PRIMAP-crf are estimated using the average intensity coefficients of the corresponding category and the national economic output of the associated economic sector (A1, A2, C2, in yellow). In Panel C, emissions of subcategories are summed up to estimate the values of aggregated categories not reported in PRIMAP-crf (A, C, in yellow).

In the second step of the MSM method, estimated emission data are reconciled with the aggregated information contained in the PRIMAP-hist database. First, emission categories known from PRIMAP-hist are inserted into the national emission trees, replacing the data estimated or retrieved from PRIMAP-crf. Second, the emission tree of each country is browsed down to reconcile aggregated emission values with more detailed emission categories (fig. S.4). When aggregated emission volumes differ from the sum of the corresponding subcategories, *estimated* subcategories are scaled proportionally to meet the volume of emissions reported in the parent node. If such rescaling is not possible by rescaling *estimated* nodes, *sourced* nodes are also adjusted.

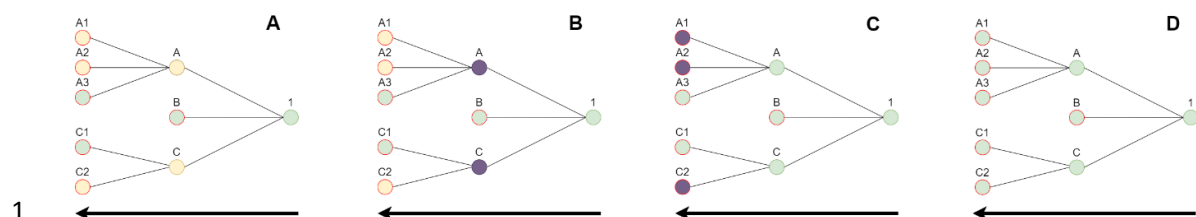


Figure S.4 – Description of the top-down adjustment process for the emission tree of a country. This procedure is applied to reconcile an estimated emission tree (see fig. S.3) with all data available, either from PRIMAP-crf or from PRIMAP-hist. Panel A represents the estimated emission tree of a country (see fig. S.3.C). The top-down balancing procedure is applied from the most aggregated node of the tree (node 1), down to end-categories (A1-3, B, C1-2). Panel B represents the first operation of the process. Nodes A and C (in purple) are proportionally adjusted so that the sum of nodes A, B and C corresponds to value of node 1. Node B is left unadjusted, because it was directly extracted from the PRIMAP-crf database (see fig. S.3.A). In panel C, the same procedure is applied at a lower level of the tree: nodes A1 and A2, and C2 are adjusted with regard to nodes A and C, respectively. Note that if nodes of a level cannot be adjusted consistently with the nodes of the upper level (i.e. if the total of sourced nodes is already exceeding the parent node), estimated nodes are set to 0 and sourced nodes are adjusted consistently with the parent node. The outcome of this procedure is shown in Panel D, where all nodes of the emission tree have been adjusted consistently with the most aggregated nodes.

For countries not covered in the PRIMAP-crf database, the estimated emission tree resulting from the first step of the MSM method assumed that their production technologies were identical to the world average. This assumption is relaxed during the second step of the algorithm when detailed emission categories are reconciled with aggregated values. For instance, the initial estimate of Chinese emissions for fuel combustion in Iron and Steel production is increased by 78% after introducing aggregated data from PRIMAP-hist.

Economic sectors can cause emissions through different processes, hence be mapped to different IPCC categories. For example, the *Metal Products* industry from EORA cause emissions due to fuel combustion for Iron and Steel (1A2A) and non-Ferrous Metals (1A2B) production, but also from direct reactions such as Iron smelting (2C). Hence, we simply sum all these contributions to obtain the total direct emissions related to the *Metal Products* sector. Reciprocally, an IPCC emission category may be associated with more than one economic sector. In that case, the economic output of all the corresponding sector is aggregated to compute the emissions intensity and the estimated emission volumes. Estimated emissions from this category are then allocated to all the associated sectors proportionally to their respective economic output.

IPCC Emission Category			Eora Sector	
0	Total emissions			
	Energy			
	Fuel Combustion Activities (Sectoral Approach)			
	Energy Industries			
	1A1A	Main Activity Electricity and Heat Production	Electricity, Gas and Water	
1	1A1	1A1B	Petroleum Refining	Petroleum, Chemical and Non-Metallic Mineral Products
		1A1C	Manufacture of Solid Fuels and Other Energy Industries	Petroleum, Chemical and Non-Metallic Mineral Products
		Manufacturing Industries and Construction		
	1A2	1A2A	Iron and Steel	Metal Products
		1A2B	Non-Ferrous Metals	Metal Products
		1A2C	Chemicals	Petroleum, Chemical and Non-Metallic Mineral Products
		1A2D	Pulp, Paper and Print	Wood and Paper
		1A2E	Food Processing, Beverages and Tobacco	Food & Beverages
		1A2F	Non-Metallic Minerals	Petroleum, Chemical and Non-Metallic Mineral Products
		1A2G	Transport Equipment	Transport Equipment
		1A2H	Machinery	Electrical and Machinery
		1A2I	Mining and Quarrying	Mining and Quarrying
		1A2J	Wood and Wood Products	Wood and Paper
		1A2K	Construction	Construction
		1A2L	Textile and Leather	Textiles and Wearing Apparel
		1A2M	Other	
1A3	Transport			
	1A3A		Civil Aviation	Transport
			Road Transportation	
	1A3B	1A3B1	Cars	Final Demand
		1A3B2	Light-Duty Trucks	Transport

IPCC Emission Category					Eora Sector		
1	1A	1A3	1A3B	1A3B3	Heavy-Duty Trucks and Buses	Transport	
				1A3B4	Motorcycles	Final Demand	
			1A3C	Railways		Transport	
			1A3D	Water-borne Navigation		Transport	
			1A3E	Other Transportation		Transport	
				Other Sectors (Fuel Combustion)			
		1A4A	Commercial/Institutional		Final Demand		
		1A4B	Residential		Final Demand		
		Agriculture/Forestry/Fishing/Fish Farms					
		1A4	1A4C1	Stationary	Agriculture		
			1A4C2	Off-road vehicles and other machinery	Agriculture		
			1A4C3	Fishing	Fishing		
		1A5	Non-Specified		Final Demand		
		1B	Fugitive Emissions from Fuels				
	1B1		Solid Fuels		Mining and Quarrying		
	1B2		Oil and Natural Gas		Mining and Quarrying		
			Oil				
	1B2A1		Venting		Mining and Quarrying		
	1B2A2		Flaring		Mining and Quarrying		
			All other				
	1B2A		1B2A31	Exploration		Mining and Quarrying	
			1B2A32	Production and Upgrading		Mining and Quarrying	
			1B2A33	Transport		Transport	
			1B2A34	Refining		Petroleum, Chemical and Non-Metallic Mineral Products	
			1B2A35	Distribution of Oil Products		Petroleum, Chemical and Non-Metallic Mineral Products	
			1B2A36	Other		Mining and Quarrying	
					Natural Gas		
	1B2B		Venting		Mining and Quarrying		
			1B2B1				

IPCC Emission Category		Eora Equivalent
4	Waste	Recycling
5	Other	
MOEL	Total CO2 equivalent emissions, without land use, land-use change and forestry, table10s1/s2/s6	
MAG	Total Agriculture, CRF table 3	Agriculture

Table S.2 – Mapping between the UNFCCC emission categories and the EORA production sectors. The columns on the left indicate the emission categories as defined by the IPCC (Eggleston et al., 2006) and the associated category codes. The column on the right shows the EORA production sector to which emissions have been allocated. Columns in grey indicate aggregated categories or categories which have not been classified. Indentations for the IPCC emission categories represent the hierarchy between emission categories, i.e. the structure of the emission tree (see fig. S2-3).

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Appendix for article 3:
The network effects of the EU CBAM

Supplementary Materials Information for:

Towards a comprehensive and inclusive European Carbon Border Adjustment Mechanism

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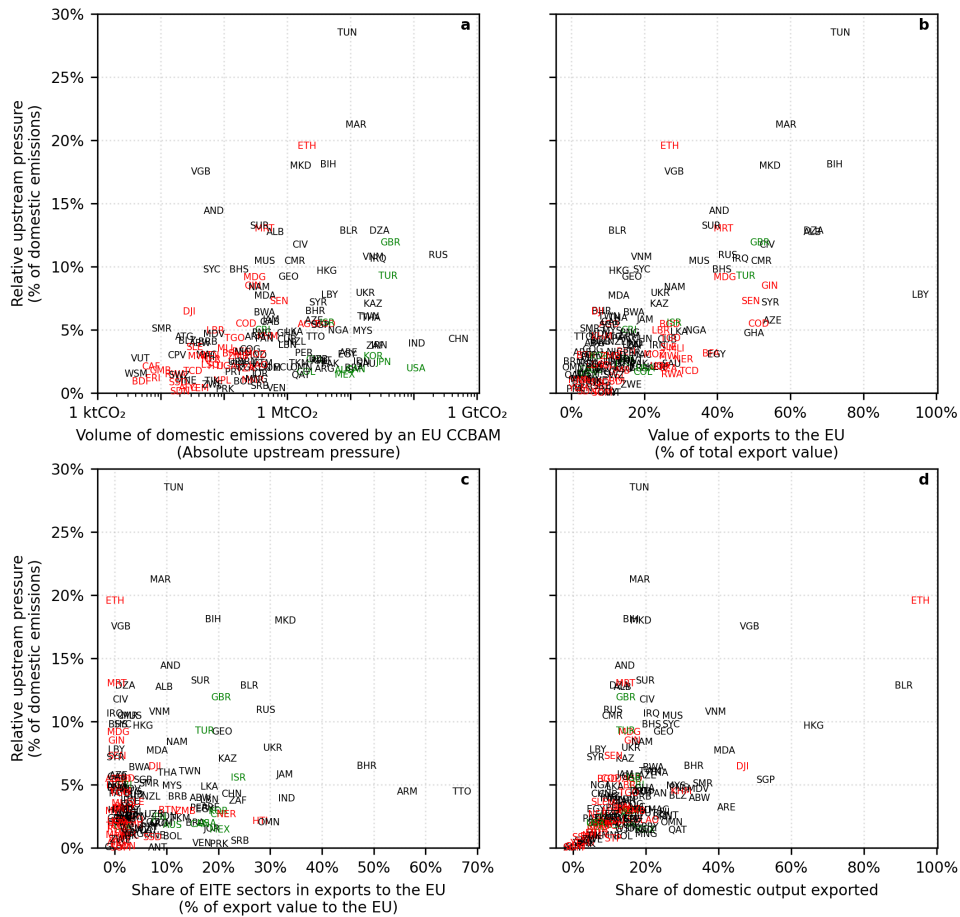
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This file includes:

Tables S.1-2

Figures S. 1-2



2

3 **Figure S.1. Trade characteristics of the countries exposed to an EU CCBAM.** Each panel shows the relation between
4 the relative upstream pressure a country is exposed to (vertical axis) with some trade characteristics (horizontal axis).
5 Countries members of the Organization for Economic Co-operation and Development (OECD) are shown in green. Least
6 Developed Countries (LDCs) are shown in red. The countries exposed to the strongest relative upstream pressure by the
7 EU CCBAM are all largely dependent on the EU for their exports (panel B) even though they don't necessarily export a
8 large share of emission-intensive products (figure C). EITE sectors here refer to the "Petroleum, Chemical and Non-Metallic
9 Mineral Products" and "Metal Products" sectors from the MRIO.

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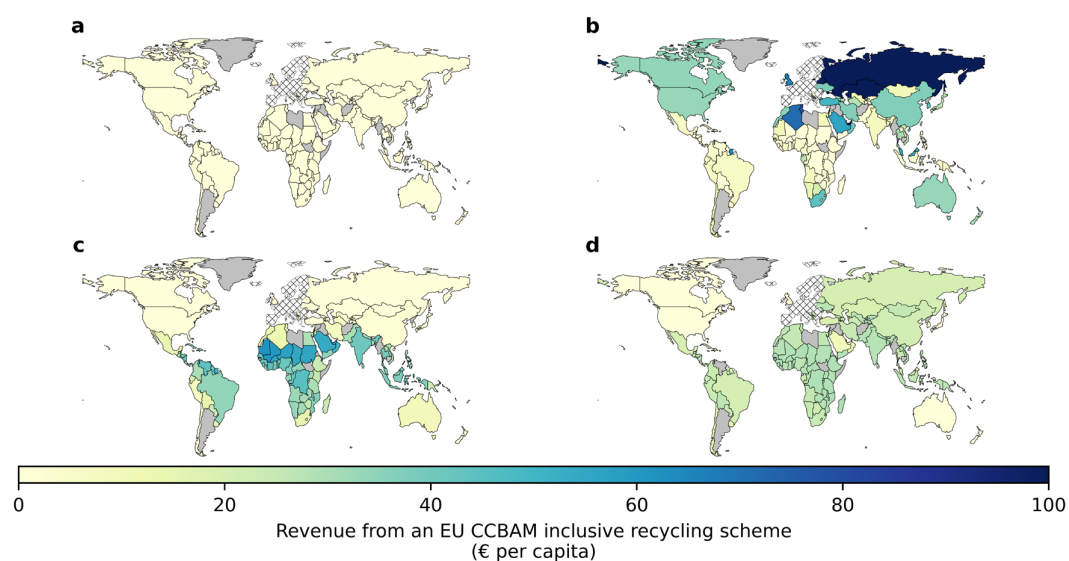


Figure 1.2 – Revenue recycled from an EU CCBAM without export rebates based on different allocation indicators. The proportion of the revenue each country receives is estimated based on the following indicators, assuming the full revenue of the EU CCBAM without export rebates is internationally recycled (see Materials and Data for details): a. No recycling; b. Emissions covered by the EU CCBAM; c. Historical impacts of anthropogenic warming on economic output²⁰; d. Difference in per capita Gross Domestic Product to the EU average. Grey indicates lack of data, hatching indicates member countries of the EU ETS.

	Scopes of emissions covered (vertical coverage)	Direct imports only (without export rebates)		Direct and indirect imports (comprehensive depth coverage)	
Sectors covered (horizontal coverage)	CO ₂ emissions covered (Mt CO ₂)	Scope 1 emissions	Scopes 1 and 2 and downstream products	With export rebates	Without export rebates
Conservative coverage	Electricity production	14	205	378	512
	Iron and steel	30	57	72	101
	Aluminium	4	7	9	13
	Fertilizers	4	7	8	11
	Cement	31	52	60	81
Ambitious coverage	Non-metallic minerals (Lime, Glass, Ceramics)	29	49	57	76
	Chemicals	18	30	35	48
	Refining and fuel manufacturing	46	76	89	120
	Pulp and paper	3	6	7	9
	Fugitive emissions from fuels	93	106	89	130
Comprehensive coverage	Other industrial emissions	182	245	249	314
	Inland transportation	46	84	101	134
	Agriculture and Waste	5	8	8	11

Table S.1. CO₂ emissions covered by an EU CBAM under different implementation options. Columns correspond to different vertical coverages (scopes of emissions covered) and rows correspond to different horizontal coverages (sectors and products covered). See Figure 1 for more information. IPCC emission categories considered for estimating the emissions from the different sectors are shown in table S.2. Numerical values correspond to MtCO₂ from the corresponding sectors covered by the corresponding CBAM implementation option.

Horizontal coverage	Sector name	IPCC code	Designation
Conservative coverage	Electricity production	1.A.1.a	Fuel combustion electricity and heat production
	Iron and steel	1.A.2.a	Fuel combustion Iron and Steel
		2.C.1	Process emissions for Iron and Steel production
	Aluminum	1.A.2.b	Fuel combustion for non-ferrous metals
		2.C.3	Process emissions for Aluminum production
	Fertilizers	2.B.1	Process emissions for Ammonia production
	Cement	2.A.1	Process emissions for Cement production
Ambitious coverage	Chemicals	1.A.2.c	Fuel combustion in the Chemical industry
		2.B.2-9	Process emissions from Chemical industry (excl. Ammonia production)
	Non-metallic minerals	1.A.2.f	Fuel combustion for non-metallic minerals
		2.A.2	Process emissions for Lime production
		2.A.3	Process emissions for Glass production
		2.A.4	Process emissions for other carbonates
	Refining and fuel manufacturing	1.A.1.b	Fuel combustion for refining
		1.A.a.c	Fuel combustion for the manufacturing of solid fuels
	Pulp and paper	1.A.2.d	Fuel combustion for the Pulp, Paper and Print industry
		2.H.1	Process emissions in the Pulp and Paper industry
Comprehensive coverage	Fugitive emissions from fuels	1.B	Fugitive emissions from fuels
	Inland transportation	1.A.3	Inland road, rail, air and water-borne transportation
	Other industrial emissions	1.A.2.e-m	Fuel combustion for other sectors
		1.C	CO2 transport and storage
		2.C.2,4-7	Process emissions other metals
		2.D-G	Process emissions other industries
		2.H.2	Process emissions food and beverage industry
		2.H.3	Other
	Agriculture and Waste	M.AG	Agriculture and forestry (excl. LULUCF)
		4	Waste

Table S.2 - IPCC emission categories considered in the different sectoral coverage settings. Emission categories defined by the International Panel on Climate Change (IPCC) are internationally agreed emission classification codes, used to associate Greenhouse Gases emissions to the process that generate them. In particular, reporting of Annex I countries to the United Nation framework Convention on Climate Change (UNFCCC) are based on this classification. We base our estimation of the CO₂ emissions generated to produce exports to the European Union (EU) on these IPCC emission categories (see Data and Methods).

Appendix for article 4:
Response options to the EU CBAM in Africa

Supplementary materials

PRIMAP contains emission data at the process level, which allows a fine description of the coverage of the EU CBAM. We model the EU CBAM as a tariff applied on the exports of the following sectors of the GTAP table: electricity, chemicals, ferrous metals, non-ferrous metals and non-metallic minerals. The EU CBAM has a finer coverage than the broad sectors covered in GTAP (namely fertilisers, iron and steel, aluminium and cement explicitly covered by the EU CBAM - hydrogen is not included here as it is not traded internationally yet). We use process-level emission data to account specifically for the goods covered by the EU CBAM within the GTAP sectors, in line with the approach used in (Beaufils et al. 2023). Namely, we use emission data from the IPCC fuel emission categories 1.A.1.a (fuel combustion for electricity production), 1.A.2.a,b,c and f (combustion of fuels for iron and steel, non-ferrous metals, chemicals and non-metallic mineral products); as well as the process emissions 2.B (Chemicals), 2.C.1 and 3 (Iron and steel, Aluminium) to compute more refined emission intensities for the exports covered by the CBAM. The volume of emissions covered by the CBAM is then computed by multiplying the exports of the corresponding sectors to the EU by the corresponding emission intensities.

As this approach involves some extrapolation and uncertainty, the results of the analysis should be interpreted with care. The use of more detailed bilateral trade data might in principle help refine the analysis at the product level but is challenging from a data availability and consistency perspective. Another limitation of our approach is its static nature. Our MRIO-based analysis is empirical and does not address adjustments to price changes that might affect the structure of trade between the African countries and the EU. While different model classes can be used to explore these dynamic effects, we chose for clarity and simplicity to focus on a first-order analysis of the drivers of the exposure of African countries to the EU CBAM, in line with the existing literature (Zhong and Pei 2022; Beaufils, Ward, et al. 2023).

Appendix for article 5:
The coalition-building potential of the EU CBAM

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 $\bar{J}$:

$$\begin{cases} \forall i \in \bar{J} & \gamma_{\bar{f}}^{ir} = \gamma_f^{ir}; \\ \forall i \in \tilde{J} & \gamma_{\bar{f}}^{ir} = 0; \end{cases} \quad (21)$$

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

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

- 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:

$$\begin{cases} \gamma_{\tilde{f}}^{\bar{f}r} = 1; \\ \gamma_{\bar{f}}^{\tilde{f}r} = 0; \end{cases} \quad (23)$$

- Only the regulated sector $\bar{f}$ in country r provides the domestic supply of regulated fuel:

$$\begin{cases} \pi_r^{\bar{f}r} = 1; \\ \forall s \neq r, \pi_r^{\bar{f}s} = 0. \end{cases} \quad (24)$$

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 ($\tau_{\bar{f}r}^s = \tau_{\tilde{f}r}^s; \tau_{\tilde{f}r}^s = 1$), 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 $\bar{\Omega}$ 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'^f_{js} . 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:

$$\varphi'_{js} = \sum_f \frac{\gamma_f^{js}}{\hat{p}_f^s} e_f^s + e_{js}. \quad (25)$$

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 , $\beta_{ir}^{'js}$:

$$(\eta'^1)_{js}^{ir} = \beta_{ir}^{'js} \varphi_{ir}' \quad (26)$$

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 , $\widehat{p}_i^s$, 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 , $\gamma_{ir}^{'js}$:

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

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:

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

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 $r \in \bar{\Omega}$ in the case of Import Adjustments, or regulated countries $r \in \Omega$ in the case of export rebates:

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

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:

$$H'^1 = B' \Phi' \quad (30)$$

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

$$H'^k = (B')^k \Phi' \quad (31)$$

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 :

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

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:

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

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} (25)
Rank n coverage	η'_{js} (31)
Comprehensive coverage	$\eta'_{js}{}^{\infty}$ (33)
Comprehensive coverage with import adjustments and in absence of export rebates	$\varphi'_{js} + \eta'_{js}{}^{*\infty}$ (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:

$$\eta'_{js}{}^{\infty} = \sum_{i,r} ((l'^*)_{ir}^{js} - 1) \varphi'_{ir}. \quad (34)$$

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:

$$\sum_s \hat{v}_s v_s = \sum_s v_s. \quad (35)$$

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 $\hat{\rho}^s$:

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

where the national price index changes are defined as:

$$\hat{\rho}^s = \prod_i (\hat{p}_i^s)^{\alpha_i^s}. \quad (37)$$

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

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

797 The emissions caused by burning fuel f in sector i of country s , E_f^{is} , derive from fuel input share in monetary terms
 798 (γ_f^{is}), the gross production of the sector and the nominal fuel intensity (e_f^{is} , see 10):

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

799 The process emissions from the sector i in country s , E_p^{is} similarly derive from the gross production of the corresponding
 800 sector and the process-specific emission intensity (e_{ir}^{is} , see 13):

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

801 S.4 Additional figures

802 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 (European Commission, 2023)	Sector in the MRIO table (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.

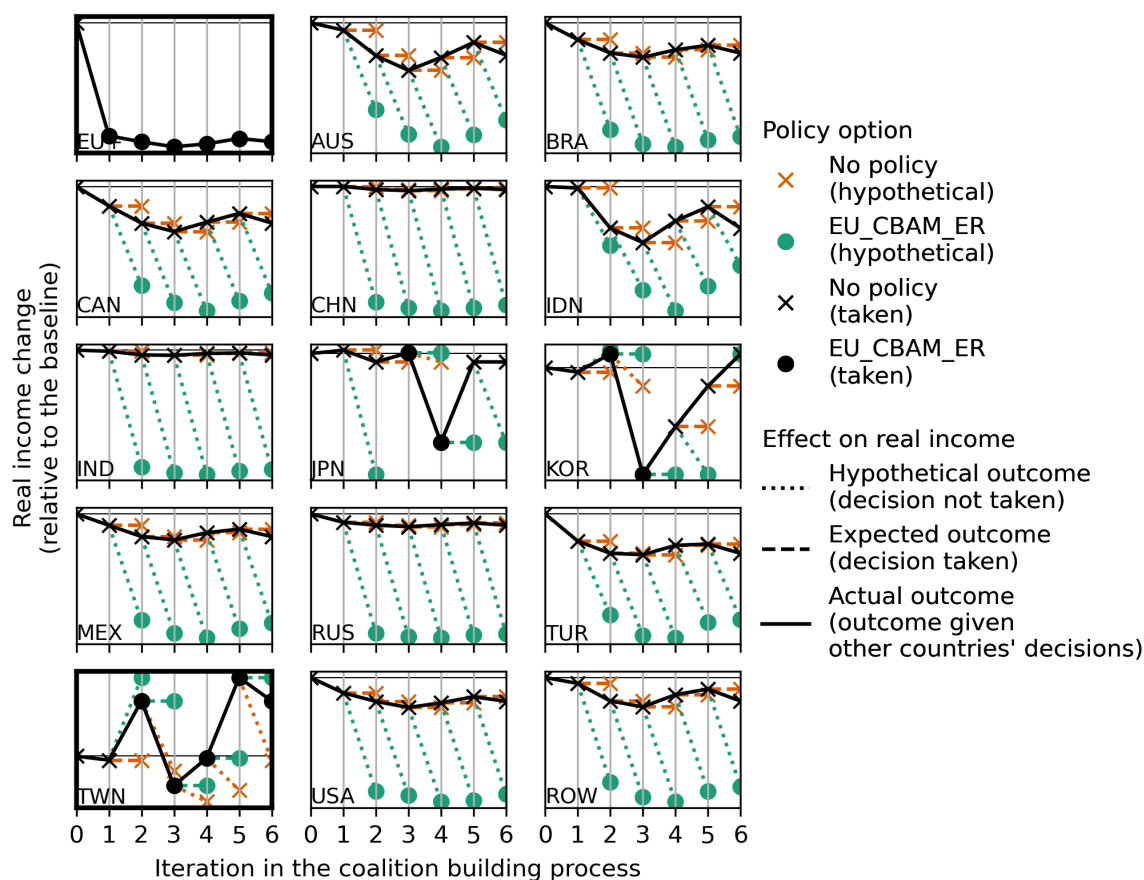


Figure S.1: Coalition-building process under an EU CBAM with Export Rebates. In this scenario, the EU and Taiwan are committing to joining a climate club. At step 2, Korea decides to join the coalition, which triggers the decision of Japan to join the coalition too at step 3. In turn, the Japanese decision to join the coalition forces Korea out of it at step 4, which in turn motivates 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 vehicleless		
1.A.2.h	computer, electronic and optical products		other transport equipment
1.A.2.i	Mining and quarrying		electrical equipment
1.A.2.j	wood and of products of wood and cork		
1.A.2.k	Construction		
1.A.2.l	textiles		
1.A.2.m	rubber and plastic products		
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		
1.A.4.c.ii	Crop and animal production		Forestry and logging
1.A.4.c.iii	Fishing and aquaculture		Forestry and logging
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		
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	Mining and quarrying		coke and petroleum
1.B.2.a.iii.4	Land transport and transport via pipelines		
1.B.2.a.iii.5	coke and petroleum		
1.B.2.a.iii.6	coke and petroleum		
1.B.2.a.iii.6	Mining and quarrying		coke and petroleum

machinery and equipment n.e.c.

furniture; other manufacturing

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

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

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I dedicate this work to Romy. Your birth was a ray of light.

