EU in Search of a WTO-Compatible Carbon Border Adjustment Mechanism*

Cecilia Bellora (CEPII)† Lionel Fontagné (Bank of France, CEPII and PSE)‡

This version: July 7, 2022

Latest version of the paper available here:

http://www.lionel-fontagne.eu/uploads/9/8/3/3/98330770/cblf_cba_2021.pdf.

Abstract

To meet the targets of the EU's *Fit for 55* package, the European Commission proposes to implement a Carbon Border Adjustment Mechanism (CBAM) to replace free emission allowances for the most trade-exposed emitting industries. The CBAM is firstly intended to avoid carbon leakages, but it also deals with the thorny issue of the compliance by European producers in carbon-intensive industries. Its design, as voted by the European Council in March 2022, and amended by the European parliament three months later, questions the compatibility with the rules of the World Trade Organization (WTO). This paper aims to quantify the economic and environmental impacts of different choices regarding this design in the face of the dilemma between compliance with WTO rules and acceptability of the new regulation. Using a dynamic general equilibrium model featuring imperfect competition, global value chains, greenhouse gas emissions and endogenous price of emission quotas, we evaluate the various options. We show that the CBAM is effective in reducing carbon leakages. But its design leads to an increase in the price of carbon quotas in the European Emission Trading System (ETS) market. Losses in competitiveness on export markets are expected, even in the presence of rebates to the European exporters and also for downstream sectors not covered by the EU ETS nor the CBAM. Eventually, offsetting the difference in carbon prices at the border comes at a cost to the enforcing jurisdiction, suggesting that the CBAM was not designed as a beggar-thy-neighbour policy.

Key Words: Carbon Border Adjustment, International Trade, Climate Change.

JEL Codes: F14, F13, F17, Q56.

---

*Lionel Fontagné thanks the support of the EUR grant ANR-17-EURE-0001. The views expressed in this paper are the authors' and do not necessarily reflect those of the institutions they belong to. We thank participants to various seminars and conferences for their helpful comments and suggestions.

†CEPII, 20 avenue de Ségur 75007 Paris. Email: cecilia.bellora@cepii.fr. Declarations of interest: none

‡Banque de France, 31 rue Croix des Petits-Champs 75049 PARIS cedex 01 (France). Email: lionel.fontagne@banque-france.fr. Declarations of interest: none

Introduction

Climate is a global public good that deserves global action. There is however a tension between ambitious commitments to reduce global greenhouse gas (GHG) emissions and the maintenance of the open multilateral trading system. First, action comes up against inherent difficulties such as the diversity of instruments to tackle climate change, the different levels of development of countries and the potential impact of measures taken by one country or a group of countries. The Paris Agreement has initiated a cooperative approach but ambition is running out of steam, thus the call for an international carbon price floor differentiated by income level (Parry, Black & Roaf 2021). But even if the latter solution were considered, international differences in carbon prices would still imply carbon leakage at the expense of the most ambitious countries. What would be the economic consequences of offsetting these price differences at the border? How to determine the reference carbon price used for such compensation when different jurisdictions rely on different instruments (carbon tax, cap-and-trade, regulations)? How to take into account the special case of least developed countries, which are highly exposed to the consequences of climate change but have limited resources to mitigate their emissions?

Beyond the diversity of instruments or development levels, a second issue – international cooperation – has to be addressed. The benefits of GHG reduction are immense for each country, but none of them has an individual incentive to act in the right direction, which is an illustration of the "tragedy of the commons" (Gollier & Tirole 2015). This lack of incentive resorts to the political economy: governments have to make GHG taxation acceptable to their constituents and bearable by their companies in the absence of international coordination.[1]

In the absence of a globally coordinated and cooperative policy, the European Commission's ambitious goal of climate neutrality by 2050, will be undermined by carbon leakage. To avoid leakages, the EU initially exempted some industrial installations from paying for (part or all of) their GHG emissions. These installations belong to energy-intensive manufacturing industries that are most exposed to trade. Practically, selected installations received emissions permits for free. This kind of approach avoid leakages but also drastically reduce the incentive to abate GHG emissions. The proposed Carbon Border Adjustment Mechanism (CBAM), included in the regulatory package announced in mid-July 2021, is specifically intended to replace these exemptions while preventing leakage.[2] Offsetting carbon

[1] "Should differences in levels of ambition worldwide persist, as the EU increases its climate ambition, the Commission will propose a carbon border adjustment mechanism, for selected sectors, to reduce the risk of carbon leakage. This would ensure that the price of imports reflect more accurately their carbon content. This measure will be designed to comply with World Trade Organization rules and other international obligations of the EU." *Communication from the Commission to the European Parliament, the European Council, the Council, the European economic and social committee and the Committee of the regions – The European Green Deal.* COM/2019/640final, Brussels.

[2] The purpose of this regulation was set as follows: "A carbon border adjustment mechanism ("CBAM"), announced in the European Green Deal, is part of that package and will serve as an essential element of the EU toolbox to meet

price differences at the European border will raise both the difficult question of its compatibility with multilateral international trade rules and the opposition of European exporters that will no longer be exempted from paying for their emissions, while at the same time not being protected from competitiveness losses on third markets by the CBAM in the absence of export rebates. The research question addressed in this paper is which CBAM design can best meet these potentially conflicting objectives.

The CBAM comes as a complement to the central tool of the European Union's climate policy, the European Emission Trading Scheme (ETS), which in mid-July 2021 the European Commission proposed to extend to other activities (maritime and road transport, and heating) on a distinct market. The ETS, set up in 2005, is a carbon market[3] that covers 43% of EU emissions generated by EU based firms of certain sectors during their production process. The existing European legislation, consistent with the old version of EU's National Determined Contribution under the Paris Agreement, presently sets a cap on these emissions so as to reduce them by 43% by 2030, with respect to 2005. The *Fit for 55* package proposes a more ambitious target, −61%, inline with the new overall ambitions of the European climate policy. Of course, efforts on other sectors are also set to reach the most recent commitment taken by the EU to reduce by 55% its GHG emission in 2030, with respect to 1990.

The CBAM will add to this carbon market a carbon price on imported products whose production-related emissions have not been taxed (or not at the same level as in the EU) by the exporter's country. The related legislative procedure is in progress. After a first announcement by the Commission while it has been settled, the European Parliament voted in plenary session on the principle and the contours of a CBAM on 10 March 2021,[4] with a view to the presentation of the Commission's draft, which finally occurred in July 2021. The European Council reached an agreement on these CBAM outlines on March 15, 2022, while keeping the discussions open on the thorny issues of the termination of free allowances of emission quotas[5] and of the compensation for exporters' losses in competitiveness. The European Parliament adopted an amended text on June 22, 2022, reintroducing rebates to exporters, while shortening the transition period to phase out free allowances of emission quotas to ETS industries exposed to international competition. Given than the project of Regulation is following the Ordinary Legislative Procedure (meaning an adoption of the regulation jointly and on an equal footing by

the objective of a climate-neutral EU by 2050 in line with the Paris Agreement by addressing risks of carbon leakage as a result of the increased Union climate ambition." (Art. 1.1).

[3] GHG covered by the ETS are: carbon dioxide (CO_2), nitrous oxide (N_2O) and perfluorocarbons (PFC). In the following, we loosely refer to this as carbon, hence "carbon market" and "carbon taxation". The overall emissions are measured in CO_2 equivalents, noted CO_2eq.

[4] The European Parliament resolution of 10 March 2021 *Towards a WTO-compatible European mechanism for border carbon emission adjustments* – procedure 2020/2043(INI) – was adopted with 444 votes for, 70 against and 181 abstentions.

[5] In absence of adjustment at the border, free allowances of emission quotas to energy intensive industries reduced the risk of carbon leakage (Böhringer, Carbone & Rutherford 2012).

Parliament and the Council), the exact design of the instrument is not yet stabilized.

The Commission's proposal foreshadowed a scheme combining 1) the purchase of allowances by importers on a specific market, price taker with respect to the ETS; 2) a taxation base equal to the emissions of the exporter, possibly inclusive of indirect emissions associated to the energy mix of the electricity consumed in the production process; 3) a compensation for the carbon content of the product, net of the carbon price paid by the exporter in its own country;[6] 4) the phasing out of free allowances over a ten years period, progressively replaced by the CBAM; 5) the absorbtion in the European budget of the resources generated by the CBAM in order to "(...) address the challenges posed by the COVID-19 pandemic and, therein, support investment in the green and digital transitions".

The European Council introduced some amendments concerning the administration of the system, the reference to the social cost of the measure, and the aim to flank the CBAM with a Climate club inspired by the proposal supported by Germany.[7] Importantly, the statement accompanying this agreement stresses that "work on the [free allowances and leakages associated with export losses] needs to have progressed sufficiently before negotiations with the European Parliament can begin." In plain English this statement of the Council leaves the door open to export rebates, as opposed to the views of the Commission.[8] The Parliament eventually extended the coverage of ETS industries subject to CBAM and reintroduced rebates for exports to third countries with no carbon pricing similar to ETS in the second reading of June 2022.

The proposed compensation mechanism raises three questions: i) to what extent does it reduce direct and indirect international carbon leakage induced by EU climate policy? ii) does it restore a level playing field for EU producers having to buy emission allowances in the ETS? iii) and is it designed to minimize the likelihood of WTO panels or even the prospect of retaliation by trading partners?

Regarding the first question, a distinction has to be made between direct and indirect leakages. The emitting European industries may displace part of their production in regions where the climate policy is less tight than the new European ambitions. Imports from non-taxing countries may partly substitute for European production, an this would widen the gap between national inventories and

[6] "An authorised declarant may claim in its CBAM declaration a reduction in the number of CBAM certificates to be surrendered in order for the carbon price paid in the country of origin for the declared embedded emissions to be taken into account." (COM(2021) 564 final, Chapter 2, Art. 9.1).

[7] See Bundesministerium der Finanzen "Steps towards an alliance for climate, competitiveness and industry – building blocks of a cooperative and open climate club", August 2021.

[8] The wording of the initial text adopted by the Parliament remained ambiguous but reflected limited support for the idea of a refund to European exporters that could be interpreted as an export subsidy for carbon products. Art. 29 of 2020/2043(INI) "urges the Commission, therefore, to consider the possible introduction of export rebates, but only if it can fully demonstrate their positive impact on climate and their compatibility with WTO rules". The Commission proposal disregards export rebates to ensure WTO compatibility.

carbon footprints. The fact that production techniques in less constrained countries are more carbon intensive also adds to this leakage. Overall, such direct leakages would jeopardize European efforts. A second type of leakage (Felder & Rutherford 1993) may impair the outcome of European ambitions: the lower demand for fossil fuels in Europe will in turn depress their price, leading *indirectly* to higher consumption by non-constrained countries, hence higher GHG emissions.[9] CBAM can have an impact on direct leakages but is inefficient in curbing indirect ones. Furthermore, the impact on direct leakages is complex: CBAM reduces them by increasing the price of imports of carbon intensive goods but also increases them as European exports become less competitive and are replaced by (possibly dirtier) competitors' exports to third markets. The total impact on direct leakage will be the net of these two mechanisms. Finally, CBAM is expected to replace the mechanism presently in place to reduce leakages, namely free allowances, which raises the question of the efficiency of these two instruments in relation to each other. Against this background, it is worth quantifying the share of leakages (both direct and indirect) that will be avoided due to the CBAM. To do so, we need a global model taking account of emissions in all countries, and of the reaction of carbon price in Europe to the substitution of European goods to imported goods and thus a higher demand for emission allowances on the ETS market.

Regarding the second question, a distinction must be made between the level playing field for carbon intensive sectors, and the level playing field for downstream sectors. At first sight, carbon intensive sectors should benefit from the protection of the CBAM on the European internal market, but not on third markets in absence of exports rebates, especially as the price of allowances in the ETS will increase due to CBAM, as demonstrated in this paper. But the more subtle mechanism here is that CBAM does not come in isolation: it is the counterpart to the elimination of free allowances that currently (partially) protect the ETS sectors from carbon leakage. In the end, the impact on the ETS sectors of the introduction of CBAM and the phasing out of free allowances is the net result of the protection offered by the former and the disappearance of the latter. As for downstream sectors that use carbon intensive products as inputs, partial product coverage of the CBAM implies that European downstream manufacturers will have to pay a higher price for their inputs,[10] regardless of whether those inputs are sourced in Europe or in third Countries. In total, the compensation should distort value added to the benefit of European upstream producers, although this would be somehow counterbalanced by the gradual phasing out of free allowances, at the expense of their European clients. To have a sense of these complex mechanisms and the resulting variations in the value added

[9]This problem has been identified by Markusen (1975), who suggested a simple solution consisting in capping national emissions by a tax and introducing a tariff at the border.

[10]Think of the steel used in the car industry for instance.

of the different industries, it is essential to have a model in which the value chains are duly represented.

Finally, with regard to compliance with WTO rules and the potential reaction of third countries, a compromise must be found between the effectiveness of the mechanism and legal certainty. Imports from different countries will have to purchase different amounts of allowances, which does not necessarily violate the non-discrimination principle given that a common mechanism will be used. The potential problem is that the only criterion taken into account is the price of carbon, whereas there is a continuum of policies to reduce emissions, ranging from carbon price only to regulation only or subsidies. An exporter country may well claim that it will reach the same goal with a different instrument. The thorny issue here is how to compute an implicit price of different instruments, and whether this implicit price should be taken into account in the calculation of the compensation at the EU border.[11] Another issue is the reference chosen for offsetting emissions. Charging third country competitors on the basis of their own emissions will penalise countries in the developing world with limited resources to combat climate change in absence of special and differential treatment (SDT). Finally the allocation of the revenues generated by the compensation mechanism will be a signal sent to commercial partners. The legal logic is that the resources should be allocated to support climate change mitigation, and the economic logic is that they should be allocated where the effectiveness of decarbonisation expenditure is greatest, namely in developing countries.

This paper aims to assess the effectiveness of the various possible designs of the CBAM in meeting its environmental and economic impacts. To proceed, we use a dynamic, multi-sector and multi-regional model of the world economy, featuring a detailed representation of energy use and taking stock of Global Value Chains (GVCs), imperfect competition, substitution among energies and substitution among capital and energy. Here, as it is standard in energy-oriented models, energy is not considered as an intermediate consumption but directly substitutes with capital in the production function. This representation captures the possibility to invest in order to reduce energy use, while impeding to replace energy by any other intermediate consumption when energy is taxed.[12] GHG emissions due to both energy use (carbon dioxyde) and production processes (methane, nitrous oxyde and fluorinated gases) are explicitly reported. Such calibrated multi-sector and global dynamic general equilibrium model allows to trace production displacements across sectors and regions and, as a consequence, account for carbon leakages.[13] Relying on a model taking explicitly into account GVCs is also important when emissions related to intermediate consumptions have to be embarked. Climate

[11] The calculation of effective carbon prices raises difficult methodological issues. OECD (2021) is a first attempt.

[12] In addition, energy is subject to independent productivity improvements, specifically calibrated.

[13] While the mechanisms underlying the impacts of an unilateral environmental policy and the potential for reducing its undesirable consequences in the absence of effective international cooperation have been documented (Felder & Rutherford 1993, OECD 2020, Böhringer, Fischer, Rosendahl & Rutherford 2022), the magnitude of the leakages remains an empirical question.

policies are represented, based on Nationally Determined Commitments (NDCs). For regions assumed to respect their commitments, we compute the implicit price of policies making it possible to reach the target settled by NDCs. We pay specific attention to the European cap-and-trade market, with a focus on free allowances. Based on such modelling, we ask whether a European CBAM can efficiently curb global emissions in a context where not all countries adopt a cooperative behavior.

First, we consider a reference path for the world economy till 2040 in terms of GDP and the induced emissions in the absence of any abatement policy.[14]

Then, we construct our baseline scenario taking stock of the targets announced by countries as a follow up of the Paris agreement, based on their *unconditional* NDCs. For the EU, in the baseline, we maintain free emission allowances in the ETS for industries exposed to international competition. Free allowances represent 43% of total allowances on the ETS market until 2040. We then consider that *if CBAM were not implemented, free allowances would be preserved* in order to reduce leakage induced by the ambition of the *Fit for 55* package. Yet the ETS is subject to an emission cap that is binding in our modelling. We complement the emission reduction with the implicit price of all measures (price or non-price based) imposed on non-ETS sectors and the rest of the economy. In summary, we are in this reference scenario with a growing world until 2040, in which a subset of countries, including the EU, reduce their emissions in line with their NDCs.

Finally, in three scenarios, we implement a CBAM at the border of the EU. For each product covered, CBAM requires the importer to hold emission allowances corresponding to a certain reference emission level (EU sector average in Scenario 1 versus exporter's sector average in Scenarios 2 and 3), allowances purchased at a carbon price equal to the ETS market price (minus any carbon price already paid in the exporter's country).[15] CBAM replaces the free allocation of allowances to European producers in ETS sectors exposed to international competition. This replacement is gradual, with CBAM being phased in as free allowances are phased out over a ten-year period. In the third scenario export rebates (progressively introduced as free allowances are phased out) address the problem of competitiveness of EU exporters of ETS products.

In Scenario 1, the CBAM takes as reference the European average GHG intensity by sector. Free allowances are phased out over a ten-year period as the CBAM comes into force. There is no export rebate, i.e. there is no refund of allowances purchased by EU exporters in the ETS sectors. This first scenario is not the most ambitious in terms of offsetting, but it is the least risky at the WTO insofar as foreign products are granted national treatment in terms of reference emissions. It also minimizes

[14]The long-term trajectory is consistently projected by the macro-economic model MaGE (Fouré, Bénassy-Quéré & Fontagné 2013, Fontagné, Perego & Santoni 2021).

[15]We consider direct emissions by sake of simplification. Introducing indirect energy-related emissions based on the EU average reference would not affect our conclusions as shown in earlier versions of this paper.

the collection of information on foreign technologies and the need for controls. The drawback is that it does not provide a strong incentive for foreign countries to adopt a less emissive production technology, nor is it expected to reduce leakages the most.

In Scenario 2, we replicate Scenario 1 but using the emissions of the *exporter's* country as a reference for the compensation. This scenario is more ambitious in terms of offsetting emissions and providing incentives to non-participating countries. The drawback is the risk of being challenged at the WTO. The administrative burden associated with the collection of information on foreign emissions is also a potential source of costs. This scenario is close to the one envisaged for the EU regulation, although it covers all ETS products, not a subset.

In Scenario 3, we explore the thorny issue of export rebates. In theory, combining a cap-and-trade system (the ETS) with a carbon compensation at the border and a rebate on exports very much resembles a consumption tax (Elliott, Foster, Kortum, Munson, Perez Cervantes & Weisbach 2010). There is actually equivalence if and only if the mechanism at the border taxes carbon at the exact same price as the domestic tax, if the carbon tax is fully passed onto the consumer by producers and if there is full rebate for exporters. Then domestic producers and foreign producers pay the carbon tax when selling their products to domestic consumers, while no producer (domestic or foreign) pays the tax when serving foreign consumers. In practice however, rebates raise a risk of WTO compatibility. Any tax rebate would provide a competitive advantage to European producers exporting to markets taxing carbon domestically (or enforcing regulations having an implicit carbon price) without imposing a CBAM. We explore in scenario 3 the economic and environmental consequences of export rebates by adding those to Scenario 2.

In all scenarios we apply the CBAM to all ETS sectors which goes beyond the initial stage of the proposed regulation restricted to cement, aluminium, fertilisers, electric energy production, iron and steel. This choice has three main reasons. First, a CBAM extended to all ETS sectors decreases the exposure of the EU to legal challenges at the WTO for "cherry-picking" excluded industries, i.e. industries that will continue to receive free allowances. Second, this choice is consistent with the Commission's longer-term objective and with the project adopted by the Parliament and, finally, it also allows the identification of the main mechanisms. Our results should therefore be understood as the long-term impact of a CBAM extended to all ETS industries. All scenarios also provide for special and differential treatment for the Least Developed Countries (LDCs), in order to facilitate WTO acceptance of the new European regulation and to align with the European Parliament's initial recommendation.[16]. The revenues of the CBAM are not strictly earmarked: they are allocated to the

[16]Art. 8 of (2020/2043(INI)): "Least Developed Countries and Small Island Developing States should be given special treatment in order to take account of their specificities and the potential negative impacts of the CBAM on their

European budget, as envisaged by the Commission.

We are not the first to quantify the economic and environmental efficiency of a compensation at the border in general equilibrium. Elliott et al. (2010) perform a quantitative analysis of scenarios of compensating carbon taxes at the border of Annex B countries (before the US opt out).[17] Babiker & Rutherford (2005) quantify the effectiveness and consequences of various CBA schemes (Voluntary Export Restraints, compensating tariff, free allowances, export rebates) under the Kyoto protocol after the US opt-out. Böhringer, Bye, Fæhn & Rosendahl (2012) consider alternative designs for compensating *tariffs*, and analyze their effects on global welfare within a multi-region model of the global economy.[18] Compensation is applied alternatively on Emission Intensive and Trade Exposed (EITE) sectors only or on all sectors.

Weitzel, Hübler & Peterson (2012) and Antimiani, Costantini, Martini, Salvatici & Tommasino (2013) examine the consequences of a CBA modelled as a tax compensating for internal carbon prices at the borders of a coalition comprising Europe, USA and other Annex I countries.[19] Manders & Veenendaal (2008) quantify the outcomes of two scenarios (ETS imposed in Europe only versus coalition with other Annex I countries, plus Brazil, India and China) combined with different instruments.[20] Kuik & Hofkes (2010) quantify the impact of two CBA-type policies in presence of the European ETS: obligation of purchasing allowances for importers of EITE products based on reference direct emissions in the EU *versus* in the exporting country. They do so considering a reduced coverage for the ETS and, more importantly, that the cap imposed on it is the one that corresponds to a carbon price of EUR 20, while the rest of the world implements no climate policy. Mörsdorf (2022) compares three designs of the CBAM proposed by the European commission (scope 1 versus scope 2 emissions and rebate to exporters) compensating for an exogenous price of carbon of USD 50 in the EU. Böhringer, Carbone & Rutherford (2018) quantify the consequences of compensating carbon at the borders of OECD, with OECD applying a taxation of its emissions and possibly compensating non-OECD with lump-sum transfers. Fouré, Guimbard & Monjon (2016) take a slightly different perspective and explore the impacts of a CBAM in the presence of retaliatory measures that trade

development". In the version adopted by the Parliament in 2022, LDCs would rather benefit from financial help to decarbonization in proportion of the income generated by the CBAM.

[17]We refer here to Annex B of the Kyoto protocol. This Annex sets binding emission reduction targets for 36 industrialized countries and the European Union, over the period 2008-2012. The countries *not* listed in the Annex B have no binding commitment, under the principle of the "common but differentiated responsibility and respective capabilities".

[18]The carbon content for compensation at the border includes indirect emissions associated with intermediate non-fossil inputs corresponding to indirect carbon from electricity use and indirect carbon from non-electric and non-fossil intermediate inputs. The tax rate is either based on the average of the coalition or on the average of opting-out countries or alternatively on the actual emissions of the exporting country.

[19]We refer here to Countries that are listed in Annex I to the UN Framework Convention on Climate Change.

[20]Namely, a tax levied on the carbon content of EITE imports; an export refund; a redistribution of auctioning receipts to emitting sectors; Clean development Mechanisms with the EU investing in clean technologies in the developing world (as an alternative to more expensive emission reductions in their own countries).

partners could take if considering the mechanism as not compliant with WTO rules.

Lanzi, Mullaly, Château & Dellink (2013) start from the OECD global mitigation scenarios of the OECD Environmental Outlook to 2050 (OECD 2012) and show that carbon leakages and competitiveness are the two issues faced by countries adopting ambitious mitigation policies in isolation and that such risk can not be fully addressed by carbon compensation at the border. Böhringer, Carbone & Rutherford (2012) assess three proposals for leakage reduction: CBA, industry exemptions, and output-based free allowances. The coalition comprises either Europe only, or Annex I countries, or the latter countries plus China. The CBA is implemented as tariffs levied on the carbon content (direct emissions plus indirect emission from electricity use) of imported EITE products. Böhringer, Garcia-Muros, Cazcarro & Arto (2017) performs the same type of analysis but focused on the US initial NDCs under the Paris agreement. McKibbin, Morris, Wilcoxen & Liu (2018) quantify the economic and environmental impact of a taxation of carbon in the US in presence of a CBA. Böhringer, Schneider & Asane-Otoo (2021) assess the impact of carbon tariffs by combining WIOD data with a static model. They show a sharp increase in emissions embodied in OECD countries' imports from developing economies. While this pattern reinforces the impact of carbon taxation at the border (with a 64-80% leakage reduction due to carbon tariffs depending on scenarios), it somehow shifts the burden of adjustment to developing countries.

Lastly, the proposed regulation was issued by the Commission accompanied by an evaluation of different options (import tax, regulation using either the EU reference emissions of the exporters' reference, phasing out of free allowances and different scopes of emissions) using the JRC-GEM-E3 computable general equilibrium model. However, in this exercise there are no exemptions for countries putting an explicit price on their carbon emissions, there is no sequencing of the introduction of the measure, there is no rebate. The privileged reference situation with full auctioning of emission quotas (no free allowances), is also different from ours.[21] Another reference used is the situation with 100% free allowances which does not correspond to the current situation either.

We contribute to this literature by i) focusing on the core element of the CBAM, meaning the substitution of the compensation at the border to the existing allocation of free allowances to ETS sectors exposed to international competition; ii) contemplating a reference scenario in which the EU is not the only region or country respecting the pledges it took during COP 26, although not all countries are assumed to do so; iii) avoiding double taxation, i.e. granting exemptions (or reductions)

[21]This modelling choice is justified as follows: "In modelling terms, for this impact assessment it would be impossible to illustrate how the CBAM adjusts if it was not compared also to a situation where full auctioning is introduced but the border adjustment is absent. Without such a comparison the move to full auctioning (...) would blur the impact of the border measure thus making it impossible to fairly assess its contribution."Impact assessment report. SWD(2021)643-final p. 43.

to countries charging a price to carbon; iv) shedding light on how the induced increase in the price of ETS allowances and the increase in the price of certain imported intermediate inputs propagates throughout the value chains in Europe. Importantly, carbon price is *endogenous* in our modelling and set to respect the cap of emissions associated with the unconditional NDCs in the baseline and in the different scenarios.

The remainder of this paper is organised as follows: section 1 provides the details on the model we use and the data we rely on, as well as on the scenarios that we implement. Then, section 2 presents the economic and environmental results. The last section concludes.

1 Our modelling assumptions

Our approach combines three tools: i) a global and multi-sector general equilibrium model featuring recursive dynamics and emissions of GHGs; ii) a dynamic baseline of the world economy up to 2040 and iii) a rich set of data to implement detailed trade and climate policies. We present sequentially these three elements.

1.1 The General Equilibrium model

MIRAGE-VA (Bellora & Fouré 2019) is a multi-sector and multi-region computable general equilibrium model of the world economy that aims to assess the impact of trade policies and the interactions between trade and climate change. It innovates by featuring GVCs and an improved representation of GHG emissions.[22]

In the model, firms interact either in a monopolistic competition (a number of identical firms in each sector and region compete one with another and charge a markup over marginal costs) or in a perfect competition framework (a representative firm by sector and region charges the marginal cost), depending on the sector that is considered. Production combines value-added plus energy and intermediate consumption, while demanding five primary factors (labor with two different skill levels, capital, land, natural resources), fully employed (see Appendix A.1.3).

In each region, a representative consumer gathers households and the government. It maximizes its utility under its budget constraint. This representative agent saves a part of her income and spends the rest on commodities, according to a LES-CES functional form.

[22] MIRAGE-VA is the extension of MIRAGE-e documented in Fontagné, Fouré & Ramos (2013) that did not differentiate the demand of goods according to their use, whether for final or intermediate consumption, and that did not consider GHGs other than carbon dioxyde produced by burning fossil energies. More information on the version used here is available on the MIRAGE wiki: https://wiki.mirage-model.eu. MIRAGE stands for Modelling International Relationships in Applied General Equilibrium.

Trade is represented with two different Armington structures, one for final consumption and one for trade in intermediates (see Appendix A.1.1). This double structure explicitly accounts for GVCs. In both structures, domestic and imported goods are imperfectly substitutable, as are imported goods from different origins.[23] What the double Armington structure indeed captures is the difference in the preferences in the base year for a given sector (e.g. Vehicles) since, for instance, the share of imports coming from a given country is not the same whether they are of final (e.g. cars) or intermediate goods (e.g. components). Furthermore, it allows to apply policy shocks differentiated by the use of goods. Trade can be impacted by a wide range of measures, systematically differentiated according to the use of the affected goods. We explicitly consider tariffs and export taxes. Trade restrictiveness of non-tariff measures (NTMs), both on goods and on services, is also taken into account, under three possible different forms: tariff equivalents, export tax equivalents and iceberg costs. Section 1.3 provides details on data sources for each of these measures. International transportation is explicitly modelled: transportation demand is *ad volumen*, it can be satisfied through different transport modes, supplied by different countries.

Finally, MIRAGE-VA is a recursive dynamic model: agents optimize their choices intra-temporally and the model is solved each year until the last year considered in the simulation. A putty-clay formulation captures the rigidity in capital reallocation across periods: the stock of capital is immobile, while investments are allocated each year across sectors according to relative return rates. In other words, structural adjustments result from the inertial reallocation of the stock of capital via depreciation and investment. The baseline required for dynamic simulations is calibrated in close relationship with the MaGE model and the resulting EconMap database (see section 1.4) to deal with world structural change at medium-run horizon (2040).

The model is calibrated using the GTAP 10.1 MRIO database, that features a decomposition of trade in goods and services by final or intermediate use that is consistent with GTAP 10.1 standard database.[24] The 10.1 release of the GTAP database features 2014 as the last reference year. It represents the world economy considering 65 sectors in each of the 147 regions of its geographic

[23]Elasticities of substitution across origins do not differ according to the use of goods, meaning that we actually assume that the behavior of an importer is the same whatever the kind of good (for final or intermediate use). These elasticities were estimated by Fontagné, Guimbard & Orefice (2022). They are higher than the elasticity of substitution between domestic and foreign goods.

[24]Since the goods traded in the former versions of GTAP were aggregated within sectors over numerous HS-6 products categories, a given resulting sector provided the same category of good to final consumer and to other sectors that use it as an intermediate product. Combining COMTRADE and the Broad Economic Categories of the UN, GTAP MRIO fixes this problem: each bilateral flow in a GTAP sector is split into final and intermediate use. The outcome is a database of value of imports of commodities purchased by sectors (intermediate), households (final), government and investment (final), by source and destination country/region, at market, agent and world prices. Notice that although the database also provides the tariffs aggregated along the same dimensions, we do not rely on the latter as we proceed with our own aggregation of the MAcMap HS6 database. Since tariffs differ by HS6 category, with a simple combination with the BEC classification, followed by an aggregation at the GTAP sector level, for each GTAP sector we obtain tariffs differentiated by main use of the output of the sectors, as well as by the source and destination of the good.

decomposition. We aggregate this data into 23 sectors and 28 regions or countries (see Tables A1 and A2 in the Appendix for the detailed aggregations).

1.2 GHG emissions and related data

To account for GHGs emissions, MIRAGE-e explicitly considers the consumption of five energy goods (electricity, coal, oil, gas, refined petroleum). In firms' consumption, the bundle of these five goods substitutes with capital, in the value added structure, instead of substituting with intermediate consumptions. Within the energy bundle, oil, gas and refined petroleum are more substitutable than coal or electricity (see Appendix, section A.1.3). To avoid unrealistic results, energy production sectors other than electricity deserve a special structure: a constant Leontief technology is assumed, to avoid, for instance, to produce refined petroleum from gas and electricity. Improvement in energy efficiency is embedded, at the level of the capital-energy bundle, its growth follows the growth rate of the energy productivity projected by the MaGE model (see below, section 1.4).

Endogenous technical progress is also present in the model. It is implicit, as producers can substitute capital for energy when they renew their capital stock, according to a nested CES production function. Given the depletion rate used in MIRAGE, this leaves the possibility of renewing 90% of the installed equipments at the 2040 horizon considered here. This mechanism, which mimics a technical progress induced by the increase in the carbon price, limits endogenously the increase in this latter price.

Carbon dioxyde emissions are proportional to the consumption of the energy goods corresponding to fossil energy (coal, oil, gas, refined petroleum), based on fixed parameters determined in the initial year. They arise from the intermediate consumption (use in manufacture production processes) as well as the final consumption (e.g. domestic heating fuel) of fossil fuels.

GHGs other than carbon dioxyde, namely nitrous oxyde, methane and fluorinated gases are considered as emitted during the production process. More precisely, these three GHGs are treated as production factors within the production functions. Their position in the production function, i.e. their relative substitutability with respect to other factors and intermediate consumptions, varies across sectors, following Hyman, Reilly, Babiker, De Masin & Jacoby (2003).[25]. Their substitution elasticity is taken from the literature.

The climate policy instrument present in our framework is a tax on GHG emissions, which is GHG-sector-region and time specific. It can be interpreted as the shadow price of the regulations aiming at curbing the emissions. This is how countries implement their unconditional commitments

[25] See details in Appendix A.1.2

in the Paris Agreement. The level of the tax is calculated endogenously in order to respect the target imposed on the GHG emissions of each country: an upward pressure on the emissions increases the tax so as to respect the cap defined by the NDC, at each date.

Two exceptions to this general framework are worth mentioning. First, for the European Union, a separate tax that mimics the cap-and-trade carbon market is calculated endogenously for industries participating in the EU ETS.[26] More specifically, in order to reach the target of −55% of economy-wide emissions by 2030 set in the EU new NDCs, we consider one specific tax to the ETS, and one that applies to all other sectors and to final consumers. The cap imposed to the emissions of the sectors covered by the ETS is the one proposed by the EU Commission in July 2021, i.e. 61% in 2030 with respect to 2005. The level of the tax supported by sectors not covered by the ETS and by households is set to achieve the Paris target, conditional on the reductions undertaken in the ETS sectors. Finally, we represent the free allowances allocated to some sectors among those covered by the ETS. Over the period 2013-2020, 57% of the allowances on the ETS were auctioned, while the remaining 43% were freely allocated to sectors "deemed to be exposed to a significant risk of carbon leakage".[27][28] Free allowances are preserved until 2040 in our baseline scenario and phased out when CBAM is introduced in our scenarios (the dynamics of the phasing out depends on the scenario we consider and is detailed in section 1.5).

Second, the level of the tax is imposed exogenously in the case of China: it is determined by applying the rate of increase observed in the ETS market to the price of allowances in the Chinese carbon market at the end of 2021. China announced the implementation of its national carbon market two days after the presentation of the *Fit for 55* package by the European Commission. Such announcement made in July 2021 is a sign of good will, however counterbalanced by the low level of the carbon price recorded on the Chinese national market (on average, USD 7 per ton in 2021), which is not sufficient to reach the targets announced in the Chinese NDC – hence the specific treatment adopted for China.[29]

For all other countries we consider all the *unconditional* commitments, and disregard conditional

[26]The ETS market actually concerns the EU Member States and a few other countries. Norway (the ETS represents only a small part of the taxation of this country), Liechtenstein and Iceland. The United Kingdom left the ETS during the Brexit and now implements its own system to reach its commitments. Our modelling restrains the European ETS only to EU27 members. Norway, Liechtenstein and Iceland implement their commitments but in a parallel system, not connected to the EU ETS.

[27]Directive 2003/87/EC provides this general principle of free allowances to some specific sectors. Then, the Commission Decision 2014/746/EU determines the list of the sectors deemed as exposed to leakage for the period 2015 to 2019.

[28]Considering the aggregation retained in our simulation exercise, we consider that all sectors covered by the ETS but the power generation benefit from free allowances. Actually, in the model, these sectors pay a reduced carbon price (the precise amount of the reduction is detailed in sections 1.4 and 1.5), while the power generation sector fully pays for the GHGs it emits. See Appendix A.2 for details on the representation of free allowances in the MIRAGE model.

[29]This results in the reduction of China's GHG emissions by 15% in 2040.

ones, as reported in the National Determined Contribution interim registry of the United Nations Framework Convention on Climate Change (UNFCC) at the COP26.[30] We add here another important restriction, to stick to the spirit in which the European Commission conceived the CBAM, i.e. considering that its trading partners have developed climate policies which lack of ambition. We consider that only those countries that have already implemented, by the end of 2021, a *national* carbon market are going to fulfill the commitments they have taken in the Paris Agreement. We therefore assume that those countries that have not priced nationally the carbon they emit will not be able, or will not have the political willingness, to reach their target in terms of GHG emission reduction. Based on the *Carbon Pricing Dashboard* developed by the World Bank,[31] only 17 countries other than EU had national carbon pricing systems in 2021: Argentina, Canada, Chile, Colombia, Iceland, Japan, Kazakhstan, Korea, Mexico, Montenegro, New Zealand, Norway, Singapore, South Africa, Switzerland, United Kingdom and Ukraine.[32]

We translate all the considered commitments, whether formulated in absolute or in intensity terms or formulated with respect to a business as usual reference, in a relative reduction with respect to 2014, the base year in our simulations. We then apply this reduction linearly from 2014 to the horizon retained in NDCs. If this horizon occurs before 2040, which is the case for the majority of the commitments considered, we keep the commitment unchanged until 2040. Technically speaking, the commitments translate in a yearly cap on GHG emissions, imposed to each committed region of our regional aggregation, and the model then endogenously adjusts the level of a tax on GHGs to meet this target.[33] In other words, we consider here that countries fulfill their commitments based on a cap-and-trade system, while they are actually free to choose the policy instruments they prefer. As far as the CBAM is concerned, consistently with the European planned CBAM, only exporting countries that have introduced a national carbon market will be allowed to deduct this price from the compensation at the border. In other words, the implicit price of carbon regulations is not integrated in the calculation of border adjustment.

Unless otherwise specified, emission data are taken from the GTAP-E database and the satellite data on non-CO_2 emissions provided by GTAP.

[30] We represent the commitments as reported in the NDC register at the end of December 2021.

[31] https://carbonpricingdashboard.worldbank.org/map_data#price

[32] South Africa made conditional commitments, and as such is not considered in our simulations as implementing a carbon pricing scheme.

[33] By construction, the GHG cap is *always* reached in our setup, it is not possible to be more virtuous than planned in the NDCs. Unless differently specified, the carbon tax covers all the emissions, included those due to the burning of fossil fuels by final consumers, with the exception of the emissions caused by the transportation of international freight, which are excluded from the Paris agreement. China is not considered here, as we assume a time-varying exogenous carbon price rather than a fixed cap.

1.3 Protection data

Market Access Map (MAcMap-HS6) provides a disaggregated, exhaustive and bilateral measurement of applied tariff duties at the product level. It takes regional agreements and trade preferences exhaustively into account. The raw source data is from ITC (UNCTAD-WTO). The HS6 data set used here was constructed by the CEPII (Guimbard, Jean, Mimouni & Pichot 2012) for analytical purposes and provides an *ad valorem* equivalent (percentage) of applied protection for each triplet importer-exporter-product. To minimize endogeneity problems (when computing unit values or when aggregating data), it relies on "reference groups" of countries: bilateral unit values and bilateral trade are replaced by those of the reference group of countries in the weighting scheme (Bouet, Decreux, Fontagné, Jean & Laborde 2008). MAcMap-HS6 treats specific duties (per unit) as well as TRQs and offers MFN for all WTO members; we use the year 2014 consistent with the GTAP data. *Ad valorem* equivalents of NTMs affecting goods are taken from Kee, Nicita & Olarreaga (2008), they are split across import taxes, export taxes and iceberg costs in an equally proportional way. *Ad valorem* equivalents of NTMs applying to services are from Fontagné, Mitaritonna & Signoret (2016) and are taken into account in the form of iceberg trade costs. These data provide the overall inital protection for all the sectors and regions retained for our exercice. The CBAM is going to add to these trade frictions although this instrument is not designed as a carbon tariff.

1.4 The dynamic baseline

The effects of the EU CBAM are measured in terms of deviation from a dynamic baseline, using a 27 years horizon in order to fully capture the dynamic adjustments of the economies. The baseline is build in two steps. First, it relies on a macroeconomic model of the world economy, MaGE (Fouré et al. 2013), used in projection up to 2040 (Fontagné et al. 2021). This three-factor model (labor, capital and energy) details the working population by education level, age group and gender. It represents a dual process of international convergence of technological levels and energy efficiency. It includes a life cycle determining the level of savings according to the demographic pyramid, a Feldstein-Horioka mechanism determining the international mobility of capital and a Balassa-Samuelson real exchange rate appreciation mechanism. It consistently projects, for each country, the GDP, the savings rate, the current account, and the energy efficiency.

The MIRAGE model uses the same exogenous variables as MaGE, as well as the current account targets, the investment rate and the GDP trajectories provided by MaGE for each country in a first simulation (step 1 of the reference) that reconciles the two models (given the chosen aggregation of countries in regions). The endogenous variable is the TFP in the manufacturing sector conditional on the agricultural TFP (exogenous) and on a constant difference in TFP between manufacturing and services. This first reference trajectory of the world economy is accordingly defined in absence of any commitment in terms of abatement of GHG emissions.

The next step consists in constraining this reference trajectory to be consistent with unconditional commitments of countries or regions of the world economy. As said, we restrict the perimeter of countries achieving their unconditional NDCs to those having managed to set a carbon price at the national level in 2021.

In the second step of the baseline, the GDP becomes endogenous and the caps on emissions are binding while the price of carbon adjusts in each country in that step.[34] Free allowances in the ETS market are maintained throughout the exercise at their 2021 level in this baseline.

To sum up, the general equilibrium model is first run to calibrate the TFPs; a second run, implementing the Paris Agreement in selected countries, then constitutes what we consider our baseline. We then build policy scenarios, in which we implement the policies we are interested in. The only element that differs between the baseline and a policy scenario is the simultaneous introduction of CBAM and phase-out of free allowances, as detailed in the next section.

1.5 Scenarios

To build the policy scenarios, our starting point is the climate policy that the EU applied in 2021. The central tool of European policy today is the ETS. This market is referred to as a cap-and-trade market. A cap on emissions is set, which decreases over time to reach the EU target; industrial companies trade emission permits on the market thus constituted in proportion to their emitting activity. The emissions of more than 10,000 industrial emitters are covered (steel industry, cement plants, fossil fuel power generation, domestic airlines in the European area). In total, 40% of European emissions are covered.[35] Importantly, sectors exposed to international competition receive free allowances of emission quotas. The purpose is to avoid carbon leakages. The drawback of free allowances is to reduce the incentives to reduce emissions.

The question raised by the proposed CBAM regulation is how best to articulate an efficient ETS market with border compensation that should remain WTO compatible while addressing the competitiveness problems faced by the ETS sectors. The practical implementation issues concern i) the maintenance or termination of the free allocation of allowances to the industries of the ETS;

[34] This treatment indeed introduces a constraint in terms of geographic aggregation of the model: regions of the world economy must be consistent in terms of their NDCs. The existing aggregation in GTAP imposes slight departures from this consistency for certain "Rest of" regions. We also aggregated a couple of small size economies to larger groups for computational purposes. As detailed in section 1.2, China is an exception in the sense that in our simulations the trajectory of the tax is given, and the GHG emissions evolve accordingly.

[35] Remaining emissions must be curbed using other mechanisms.

ii) the industrial scope covered; iii) the tax base (i.e. reference emissions); iv) the instrument of compensation (customs duty, tax, emission allowance purchased by the EU importer); v) the allocation of revenues (general European budget, revenue allocated to decarbonization, international transfer); vi) the possible return to European exporters of the rights acquired on the ETS; vii) ; and finally, vii) the possible Special and Differential Treatment (SDT) of the imports from Least Developed Countries (LDCs).

Is the CBAM a substitute to free allocation of allowances? On that front, the Commission, in the proposal made in July 2021, was more affirmative than the Parliament was in March 2021. It proposed to implement the CBAM gradually over ten years, while free allowances would be progressively phased out in parallel. However, WTO compatibility of such approach is an open issue and this approach may evolve after consultations with main trading partners.

What scope? The European Parliament initial draft proposed two stages: firstly, industries covered by the ETS, and secondly, all products, according to their indirect content in products covered by the ETS, in order to avoid a toll on the competitiveness of downstream European industries.[36] The proposal of the Commission goes in the same direction and consider it is "prudent to start with a selected number of sectors with relatively homogeneous products where there is a risk of carbon leakage".[37] Accordingly, it restricts the perimeter of concerned ETS products (iron and steel, aluminium, cement, fertilizers, electricity) but extending it to tubes and pipe fittings in order to avoid circumvention of the regulation. The indirect emissions induced by the consumption of electricity in the production process of ETS sectors are covered by the CBAM in the Commission proposal, based on the energy mix of electricity generation in the exporter country. The difficulty here is that the production of electricity might be subject to carbon taxation in the exporter country, which adds to the complexity of the compensation. Moreover, green electricity is heavily subsidized in Europe, which would open the Pandora box of subsidies in case of a panel at the WTO. In June 2022, the amendments voted by the European Parliament extend the scope of the products potentially covered by the CBAM to organic chemicals and plastics, as well as some other chemical compounds.[38]

Which base? To ensure the effectiveness of the CBAM, it would be appropriate to use the actual emissions of the exporter country. But how to know the carbon content of imported products? It is in

[36] "Art. 12 of (2020/2043(INI)): In order to prevent possible distortions in the internal market and along the value chain, a CBAM should cover all imports of products and commodities covered by the EU ETS, including when embedded in intermediate or final products; (...) as a starting point (already by 2023) and following an impact assessment, the CBAM should cover the power sector and energy-intensive industrial sectors like cement, steel, aluminium, oil refinery, paper, glass, chemicals and fertilisers (...)".

[37] COM(2021) 564 final by the European Commission, *Proposal for a Regulation of the European Parliament and of the Council establishing a carbon border adjustment mechanism*, page 39, paragraph 28.

[38] All the amendments are detailed in *Amendments adopted by the European Parliament on 22 June 2022 on the proposal for a regulation of the European Parliament and of the Council establishing a carbon border adjustment mechanism*, https://www.europarl.europa.eu/doceo/document/TA-9-2022-0248_EN.html.

the exporting country's interest to reveal this content only if it is lower than the content of equivalent European products (thus avoiding the tax), which should not happen in countries where carbon is not taxed, since the production units there are less efficient. There are two possible solutions: to apply a carbon "package" for comparable products and comparable countries, or to consider the European carbon content and apply it to imported products. Using the "package" approach, the EU runs the risk of a dispute before the Dispute Settlement Body (DSB) of the WTO. This was anyway the solution envisaged by the European Parliament, with reference to average global emissions.[39] The solution proposed by the Commission is to apply a default reference for emissions if the European importer is not in position to provide the requested information. An alternative solution would be to consider the average EU content. It would secure WTO-compatibility, but only part of the carbon content of imports would be covered, such that the CBAM would compensate only *partially* the competitive differential for European producers. Hence, it would avoid only a small amount of leakages. This solution is not envisaged by the Commission.

Which instrument? How to financially compensate for the difference in carbon content between European and imported products? A first solution is to impose a customs duty calibrated to this difference. Here again, the prospect of difficulties at the WTO arises: this customs duty would be discriminatory (not all exporters would pay the same customs duty), which may contravene one of the founding principles of the WTO, not to say that the duty would vary daily like the price of carbon. A second solution is to impose a tax at the border. The difficulty is then not in Geneva but in Brussels, because taxation issues are decided unanimously by the member countries. Faced with these difficulties, one might prefer to ask European importers to acquire carbon permits on the ETS market, in the same way as producers located in the EU. However, it would be necessary to modify the fundamental parameters of the ETS, i.e. the supply of permits and the emission cap, in order to reintegrate the substantial "imported" European emissions into the market. The European Parliament, the Commission and the Council agree on the purchase of emission allowances by European importers. But, very cleverly, to avoid unbalancing the ETS, the Parliament proposes the creation of a *second* market, reserved for importers, on which the price is set by the first market.[40] If the price is fixed, then the quantities of allowances on the second market adjust accordingly.

However, this system raises a difficult problem of acceptability: replacing free allocation of ETS allowances by the CBAM will ultimately penalise the ETS industries in their export markets. The

[39] Art. 13 of (2020/2043(INI): If data is not made available by the importer, account should be taken of the global average GHG emissions content of individual products.

[40] Art. 16 of (2020/2043(INI): "importers should buy allowances from a separate pool of allowances to the EU ETS whose carbon price corresponds to that of the day of the transaction in the EU ETS". Garicano (2021) details the choices of the Parliament and explains the envisaged gradual phasing-out of free allowances.

CBAM by itself cannot address competitiveness issues on third markets, unless it embeds a rebate of the allowances paid by the exporters. The Council has left this issue open: export rebates are the logical solution, but could be considered as subsidies and therefore open to challenge in the WTO. Combining border compensation for imports and refunds to exporters is very similar, from the point of view of economic analysis, to a consumption tax, without the problems of acceptability that this would raise.[41] Aside WTO compatibility, rebating has an undesirable consequence: European exporters would no longer have an incentive to reduce their emissions, or a smaller incentive if they also sell on the European market, which is still subject to obtaining permits.

What allocation of revenues? Finding a satisfactory answer (from the point of view of WTO rules) to the question of the use of the revenues is an important point. The terms of the WTO environmental exception on which the European CBAM could be based would not necessarily allow the revenues generated by the CBAM to be used to fund the European budget indiscriminately, contrary to what has been suggested in the Commission's first communications. At the very least, these funds should be directed towards financing decarbonization projects in the EU. Their use to finance decarbonation in developing countries would indeed be preferable, although more challenging from a political economy perspective: these countries use less efficient techniques and therefore the gain in terms of decarbonation of a euro invested is greater; and these countries do not necessarily have the financial means to make these investments, so there would be no windfall effect. The text adopted by the European Parliament insists on the need to have resources earmarked for decarbonation in the EU or in the LDCs, and not to increase European resources without precise allocation.[42] The proposal of the Commission is to not earmark the revenues of the CBAM and to allocate them in the general budget of the EU. In the text voted in June 2022, the European Parliament proposes that i) the revenues are allocated to the general budget and ii) an amount equivalent to these revenues is devoted to support climate change mitigation and adaptation in LDCs.

Finally, will imports from LDCs benefit from a SDT, for instance with an exemption of compensation? This option is disregarded at this stage by the Commission, while we think this element is central for WTO-compatibility, while it comes at a very low economic and environmental cost.

Against this background, we consider 3 scenarios summarized in Table 1. In all scenarios the

[41] A CBAM combined with a refund is generally considered equivalent to a consumption tax if it taxes carbon at exactly the same price as the domestic tax; if the carbon tax is fully passed on to the consumer by producers; and if exporters receive a full refund. Thus, European producers and their foreign third-country competitors pay the carbon tax when selling to European consumers, while no producer (European or not) pays the tax when serving third-country consumers.

[42] Art. 16 of 2020/2043(INI) "asks the Commission to ensure full transparency about the use of those revenues; (...) those new revenues should allow for greater support for climate action and the objectives of the Green Deal, such as the just transition and the decarbonisation of Europe's economy, and for an increase in the EU's contribution to international climate finance in favour of Least Developed Countries and Small Island Developing States, which are most vulnerable to climate change.

Table 1: Scenarios

Scen.	Scope	Emissions	Tax base	SDT	Rebate
S1	All ETS sect.	Direct	EU	Yes	No
S2	All ETS sect.	Direct	**Exporter**	Yes	No
S3	All ETS sect.	Direct	**Exporter**	Yes	**Yes**

CBAM is applied on all sectors covered by the ETS.[43] Whatever the scenario, CBAM is gradually introduced – and free allowances are phased-out – over a period of 10 years, from 2026 to 2035. There is no double taxation of carbon embodied in imported products: importers are exempted from EU emission allowances in proportion to the carbon price incurred by the exporter in its country. And we systematically apply a SDT to LDCs, exempting them from the compensation. The outcomes of these three scenarios will be compared to a baseline in which 43% of the total allowances are freely allocated and this share is kept constant.

In the first scenario, we use as reference only emissions directly induced by the production process of the sectors covered by the European ETS. In order to maximise the chances of WTO compatibility, we rely on the average EU emissions by sector as a reference. This is the safest design of the CBAM with respect to WTO compatibility but also the one that potentially reduces leakages of the European policy the least.

The second scenario differs from the first in terms of reference emissions: we consider the emissions by sector in the exporter country. The complex modalities envisaged for tracing the carbon content of products in the EU proposal are here justified by a more effective reduction in leakages. However, such increased complexity, among others, endangers WTO-compatibility. Indeed, the necessity for the importer to document the emissions in the origin country of the product, or conversely the need for exporters to register on a centralised database maintained by the Commission may be interpreted as additional non-tariff barriers. In short, the reference to the exporters' emissions favours the reduction of leakages over WTO compatibility.

The third scenario adds to the second a rebate to exporters. European exporters get a refund of the allowances they have actually paid for to produce the goods they export. The refund does not cover the allowances bought to produce the goods sold on the European market.

In the following section, we detail the economic and environmental impacts of each these versions of the CBAM and discuss in more detail their compatibility with WTO rules.

[43]It will be difficult to justify at the WTO an exemption of certain ETS sectors that would be still subject to free allowances, hence this choice. Notice that the proposal of the Commission envisages a two-year implementation period – from 2023 on – whereby importers notify the embedded emissions of the imported products without having to purchase allowances.

2 Results

Provided that the ultimate goal of CBAM is to curb the carbon leakages induced by the ambitious target of reducing EU emissions by 55% by 2030 with respect to 1990, let us start by focusing on the environmental impact of the CBAM. We use the reduction in EU GHG *leakages* as a metric of the efficiency of the instrument. European leakage results from the increase in GHG emissions in unconstrained countries caused by the implementation of the European climate policy. These leakages are both direct, i.e. caused by the displacement of production activities outside the EU, and indirect, i.e. channeled through the changes induced on international energy markets by the European policy. In medium to long term scenarios as those we are considering, indirect leakages are expected to be significant, contrary to what has been observed in the past years, because the carbon price is expected to be much higher in the coming years (see Appendix, Figure A6). Leakages are present in our baseline, despite free allowances: the EU climate policy covers all sectors while free allowances cover only the sectors most exposed to direct leakages. Furthermore, free allowances do not cover the electricity generation: the increasing price of electricity is fully passed to all firms. In our three scenarios, the net effect on leakages (compared to the baseline) results from two contrasting drivers. On the one hand, direct leakage could increase because of the loss of competitiveness of European industries in their export markets: their products, which are relatively low intensive in carbon, are replaced by goods produced outside Europe with higher intensive non-European technologies. On the other hand, European demand for products covered by the ETS is going to be satisfied by a larger share of domestic low intensive production, and will also be reduced because of increased prices. The leakages presented here encompasses both direct and indirect leakages, and their variation is the net result of the two mechanisms detailed, plus one additional adjustment. Actually, global emissions and therefore leakage from the *Fit for 55* package decrease due to the reduction of international transport (international bunkers are included in our calculation despite their absence from national inventories).

Practically, we compute in Table 2 leakages as the difference in the emissions occurring in unconstrained countries under the scenario of interest (with the CBAM in place) and under a scenario in which the EU does not implement any climate policy, everything else being equal (in particular, the implementation of carbon policies in the countries that have taken unconditional commitments under the Paris Agreement and implemented as of end 2021 a carbon pricing at the national level). The leakage rate is the leakage so defined divided by the reduction of European emissions associated with the *Fit for 55* package. We consider cumulated emissions (and therefore cumulated leakages) over the period 2021-2040. We calculate the leakages associated with the package but without free allowances, the package combined with free allowances, and the package combined with Scenarios 1 to 3.

Table 2: Focus on the environmental impact of the CBAM

	EU leakage ($Gt\ CO_2$ eq)	EU leakage rate (%)
Paris Ag., no free allowances in EU ETS	20.7	76.1
Paris Ag., free allowances in EU ETS	14.6	53.7
Scenario 1	9.7	35.6
Scenario 2	8.6	31.5
Scenario 3	8.5	31.0

Note: cumulated emissions over the period 2021-2040.
Source: MIRAGE-VA, calculations by the authors.

The implementation of the European NDCs, *without* free allowances generates cumulated leakages amounting to 20.7 Gt of CO_2 eq. over the period 2021–2040. This significant amount corresponds to one year and 8 months of emissions by China, based on its 2018 emissions, excluding land use and forestry. As we take as a reference a situation without any mitigation policy in Europe and we consider the very ambitious *Fit for 55* package, the leakage rate we find is much larger than the one usually presented in *ex ante* studies (for instance Branger & Quirion 2014, find an average leakage rate of 12%). Free allowances reduce these leakages by 30%. Substituting CBAM for free allowances, regardless of its design, further reduces leakage, by 40%. The comparison of the leakage *rate* in a situation with the *Fit for 55* package and free allowances, with the one where the CBAM replaces free allowances sheds light on the issue faced by the Commission. With free allowances, half of the costly effort of mitigation would be jeopardized by leakages; CBAM reduces the leakage rate to one third.

However, achieving this environmental goal of mitigation has an economic cost, the complex mechanisms of which we now detail. Table 3 provides a summary of the main macroeconomic impacts of our three scenarios, with a focus on the European economy. The baseline is the world economy in 2040, with all countries with unconditional NDCs and national carbon pricing in place by 2021 capping their emissions according to these NDCs. Free allowances on the ETS market are maintained in this baseline (recall that 43% of allowances are allocated for free). Therefore, the economic and environmental impacts of the modelled CBAM are the result of the substitution of CBAM for free allowances.

The first column in Table 3 is showing the impact of the introduction in 2023 of the CBAM with no rebate to exporters, compensating only direct emissions and using EU average emissions by sector as reference, and exempting LDCs in the name of SDT. The second column replicates the first, but using as a reference the average emission in the exporter country.[44] The third column further adds a

[44] In the proposal of the Commission individual exporters' emissions are targeted, which is out of reach with the data

Table 3: Impact of the CBAM in EU

	CBAM (1)	+ ref. exp. (2)	+ ref. exp & rebate (3)
GDP	−1.2	−1.3	−1.3
Imports			
Imports int. goods	−3.6	−8.3	−7.4
Imports final goods	−2.7	−3.0	−1.5
Exports			
Exports int. goods	−6.3	−8.6	−6.6
Exports final goods	−2.6	−6.0	−6.4
Carbon price ETS	5.2	10.4	14.1

Notes: relative changes in % compared to the baseline, in 2040, excl. price effect, excl. intra-EU, results in volume. International freight included. Source: MIRAGE-VA, calculations by the authors.

rebate to the exporters covering the allowances they buy to produce goods exported to third markets, as free allowances are progressively removed. All figures are in percentage deviation from the baseline in 2040, at constant prices. The first five rows report variations in economic variables, the last one reports variations in the carbon price on the ETS market.

In the new equilibrium of 2040 there are no more free allowances and the CBAM is fully implemented since 2035. Across the three scenarios, we expect differences in economic impacts to proceed mainly from the reference emissions used for compensation and from exporter rebates. The use of the emissions of the exporting country instead of the EU average emissions should make Scenario 2 more effective in reducing EU imports of carbon intensive products. The differences between scenarios 2 and 3 are expected to come mainly from the partial restoration of the competitive advantage of European exporters subject to the ETS on extra-EU markets.

The starting point to analyse the results is the change in European imports of intermediate goods. Although this macroeconomic variable aggregates imports in ETS sectors and in other intermediate products, we already see that Scenario 2 imposes a much larger toll on European intermediate imports (−8.3%) than Scenario 1 (−3.6%). The reason is that in Scenario 2, GHG emissions of the exporter (instead of European ones) are used as a reference for compensation, where GHG emission intensity is on average higher in extra-EU countries than in the EU. We will see below which exporters and sectors are most affected.

In contrast, Scenario 3 is not more effective than Scenario 2 in reducing imports. The reason is twofold. First, third markets are now relatively more attractive for EU ETS producers benefitting from rebates. EU producers export more and leave a relatively larger share of the European market to

at hand, which justifies our approach. Considering the national average would also have the advantage to avoid that some exporters specialize their clean production for the European market, while other dirtier exporters reach other markets, leading to a kind of trade diversion, with no impact on the overall emissions of the exporting country.

their foreign competitors. Second, ETS products are more costly for European downstream producers, due to the higher price of ETS allowances which we now detail. As a result, downstream producers lose competitiveness in their home market.

The next step in the comparison of scenarios is to examine the impact of the CBAM on the carbon price in the ETS market. Scenario 1 leads to a 5.2% increase in the price of carbon quotas *on the main ETS market* (as opposed to the market for allowances intended for importers). This result deserves attention. Since importers buy emission allowances on a separate market, an increase in the price of emission quotas for European *producers* was not necessarily expected by the designers of the mechanism. This outcome results from two opposing effects. On the one hand, EU ETS producers benefit from the protection of CBAM in the European market. They therefore expand their production to meet the new demand. As a result, EU ETS producers increase demand for allowances, which are capped to meet NDC targets – and thus the price of carbon rises in the main ETS market. And in turn, this price increase is passed on to the allowance market for importers.

On the other hand, the removal of free allowances tend to *reduce* the price of allowances on ETS markets, since without free allowances, the burden is optimally shared among the sectors covered by the EU ETS, between sectors exposed to leakage (thus not paying the full ETS price in the interim phase or thereafter protected by the compensation at the border) and power generation not exposed to leakage but having to cope with the increase in price of ETS allowances. In scenario 3, ETS exporters put additional pressure on the demand for allowances when they export, without bearing the cost, as opposed to allowances they must purchase for their domestic sales. In the end, whatever the scenario, the first effect dominates and the price of allowances increases when CBAM replaces free allowances. The rise is more substantial in the more protective Scenario 2 (10.4%) than in Scenario 1. In Scenario 3 the increase is even larger (14.1%) since domestic demand is even larger, the EU exporters being more competitive in the third markets than in the other Scenarios.

The increase in the price of electricity, induced by higher carbon prices, is an additional cost for European producers in all sectors (and for households). European producers who import ETS products as inputs, such as steel or aluminum, also see the price of their intermediate consumption increasing due to border compensation. And the price of European ETS products substituting for imports also increases due to the increase in the price of ETS allowances. This increase in European production costs translates into a loss of competitiveness for European intermediate and final products on third-country markets (despite the rebate in scenario 3). In short, European producers in the ETS market enjoy a higher market share in a smaller European market (demand for ETS products decreases in the Single Market due to their higher price), and a lower share in third markets.[45] A more restrictive CBAM, using as a reference the exporter country emissions, will increase by more this price. Downstream, European producers of final goods lose market share on third country markets, but also on their domestic market, as their products lose competitiveness compared to imported products whose carbon content is neither priced in their country of origin nor offset at the European border. Rebates to exporters amplify the previous mechanisms.

In scenarios 1 and 2, intermediate good producers find it more profitable to sell their products on the European market given the restriction on competing imports and given their loss of competitiveness on third countries markets. They accordingly reorient their sales towards their domestic market at the expense of their exports, on the top of their loss of external competitiveness. At the horizon of the simulation, the cumulation of the two effects leads to large variations in European exports of intermediate goods, which end up −6.3% to −8.6% below the baseline in our two first scenarios. But the drop in exports in Scenario 1 (resp. Scenario 2) reaches −34.5% (−38.9%) for the chemical industry, −28.6% (−29.8%) for metal products and −34.1% (−35.6%) for other energy intensive manufactured products. Downstream producers of final goods are also affected, although the declines in exports are smaller, but spread across several industries, and increase with the stringency of the carbon adjustment at the borders, so that the overall impact on exports of final goods to third countries is −6% in Scenario 2. These drops in exports will partially offset the reduction in leakages obtained on the import side as a result of the CBAM (production being less GHG intensive in the EU than in the majority of countries). Exports from extra-EU countries, which are more carbon intensive, are going to replace EU exports.

In Scenario 3, export rebates partially restore the competitiveness of ETS producers on third markets. The drop in exports of intermediate goods in this scenario is reduced to −23.0% for the chemical industry, −22.1% for metal products and −21.4% for other energy intensive manufactured products. The explanation is simple: ETS sectors are energy intensive and pay their electricity or alternative sources of energy at a higher price due to the increased price of carbon quotas. Rebates do not compensate for increased production costs, only for the value of purchased allowances. Accordingly, export rebates are only a partial fix of the competitiveness problem of ETS producers on third markets.

The CBAM (similar to a tax from the modelling point of view although this is formally a regulation) is a distortion introduced to correct another distortion (of competition). In such second best situation, the outcome may be positive or negative. The −1.2 to −1.3 percent drop in the EU

[45] A simpler interpretation tells us that ETS products are rather homogenous: a tax at the border accordingly inflates indifferently the price of imported and domestic affected products.

GDP is the outcome of the reduced value added in sectors using ETS products as inputs, which is not compensated by the protection offered by the CBAM to European producers of ETS products.[46] This loss of downstream value added cannot be offset by gains in the upstream ETS sectors because free allowances are being phased out as CBAM is introduced. The *upstream sectors were already protected by the free allowances*, CBAM simply substitutes one protection for another while reducing overall competitiveness in export markets and domestic consumption of ETS products due to their higher price. Adopting a different design of the CBAM changes the degree of protection the CBAM offers but does not change dramatically this conclusion, although using the exporter's emissions as a reference in Scenario 2 and 3 impose a higher toll on imports. In Scenario 2, the net negative impact on ETS sectors is simply alleviated as shown below.

The impact of changes in domestic demand, combined with the change in exports and imports, subsumes in variations in the value added by sector. In brief, the mechanisms behind these changes are the following. Higher price of carbon in domestic products as well as in imported products reduce domestic demand. The higher cost of electricity and of carbon intensive intermediate consumptions, combined with the end of free allowances in ETS sectors, overall decrease exports. As far as imports are concerned, two opposite effects are at play: CBAM reduces imports in the sectors it covers, while the loss of competitiveness of downstream sectors increases the imports of the goods produced by these industries. Other mechanisms have an impact on value added by sector. The energy mix changes in the EU, both in industry and in the rest of the economy, and the whole economy moves toward services, which is the other side of the transition to a low-carbon economy. In a word, we expect an "electrification" of the economy and an increase in the value added of services.

The impacts of a CBAM maximising WTO compatibility (our first scenario) are shown in Figure 1. Each bar represents the variation in 2040 (with respect to the baseline) of the value added generated by sectors for which this variation exceeds USD 1.5 bn and 0.2% in relative terms. There is a large increase in the value added generated by the electricity sector (+33.3%) because of higher demand and higher prices. The negative impact on downstream industries, intensive in intermediate products sourced from ETS sectors, such as vehicles (−1.1%), electronics (−1.5%), textile (−1.2%), or other manufactured products (−1.6%), was expected because of competitiveness losses on the European and export markets. Recall that foreign competitors do not pay (or pay less) for emitted carbon at home

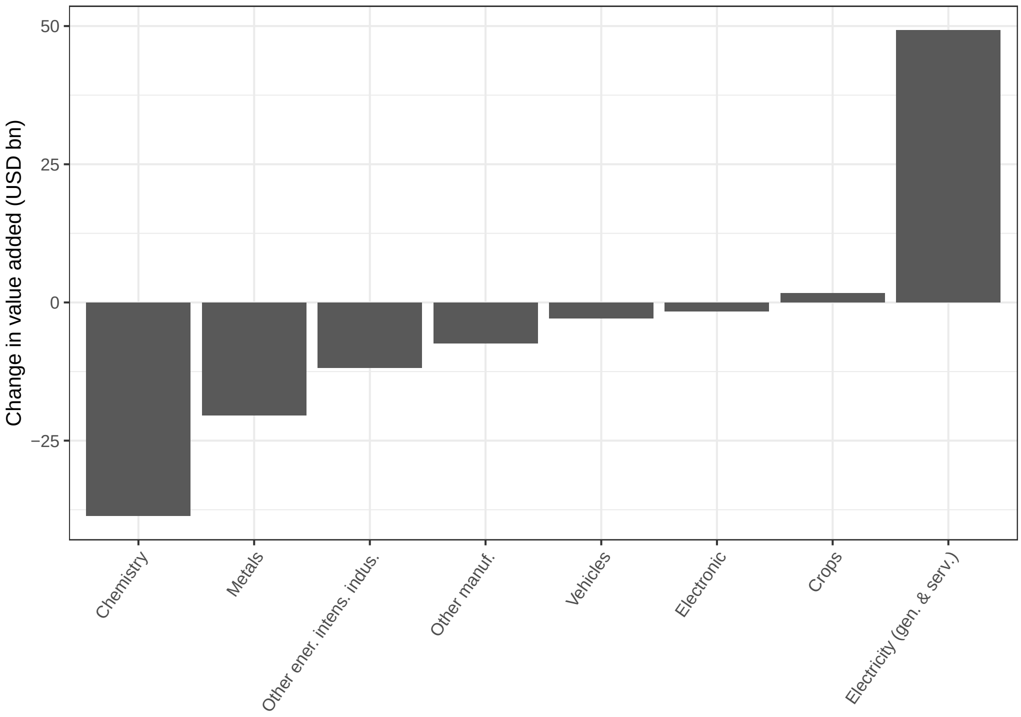
[46]Note that our model does not integrate a damage function to map the changes in GHG emissions into economic impacts, as it can be done in integrated assessment models. Two reasons motivate this choice. First, there is considerable uncertainty about the magnitude of these costs, and the more so that the permanent impact of climate change on economic activity should take into account extreme events with low probability. Second, according to Auffhammer (2018) the damage functions are often "outdated" and based on estimation methods raising identification issues. For example, regressing GDP growth rates across countries on temperature fluctuations to extrapolate the impact of future global warming on global productivity is only valid under the assumption that the intensity of adaptation efforts does not increase with rising temperatures.

and are not subject to the CBAM, while EU competitors pay their intermediate consumptions at a higher price because of CBAM. Rather unexpected is the deleterious impact of the CBAM on carbon intensive industries (metals: -10.3%, chemicals: -20.5%, other energy intensive industries: -7.2%). This large negative impact on upstream industries is the net of two opposing effects: on the positive side, the protection offered by the CBAM on the European market (which is possibly smaller than the one by free allowances, in particular in Scenario 1); on the negative side, the loss of competitiveness in export markets due to the higher price of ETS allowances and the loss of free allowances as well as the decrease in demand within the EU for ETS products due to the higher carbon price. The latter result can be summarised by concluding that, in the absence of an export rebate, carbon offsetting at the border *using European emissions as basis for compensation* does not ultimately protect the ETS sectors.

We now compare these results with a different design of CBAM where the reference emissions are those of the exporter and the CBAM comprises a rebate to European exporters on the allowances they bought to produce the goods they exports. This is done in Figure 2 which compares the outcome of Scenario 3 with Scenario 1. The figure shows that the above conclusion must be reconsidered when the emissions by the exporter are taken as reference for the border adjustment: *compared to Scenario 1*, the value added of Metal products, Chemical products, and Other energy-intensive products sectors increases significantly, although not enough to erase the overall negative impact of a CBAM that replaces free allowances. The value added in the Chemical sector still records a -9.5% drop compared to the baseline, which is above the loss of value added of metal products (-3.4%) and other energy-intensive products (-2.5%). In short, even with such design, CBAM fails to replace free allowances with border compensation without imperiling the industries that currently receive free allowances. Moreover, limiting the losses upwards comes at a cost sown along the value chain: because the border adjustment and ETS allowance price increases are greater in Scenario 3 than in Scenario 1, sectors using ETS products as inputs are now more severely affected by CBAM in Scenario 3 as shown in the left part of Figure 2. Compared to Scenario 1, the losses are much larger for Other industries, for the Vehicle sector or in the Electronic sector.

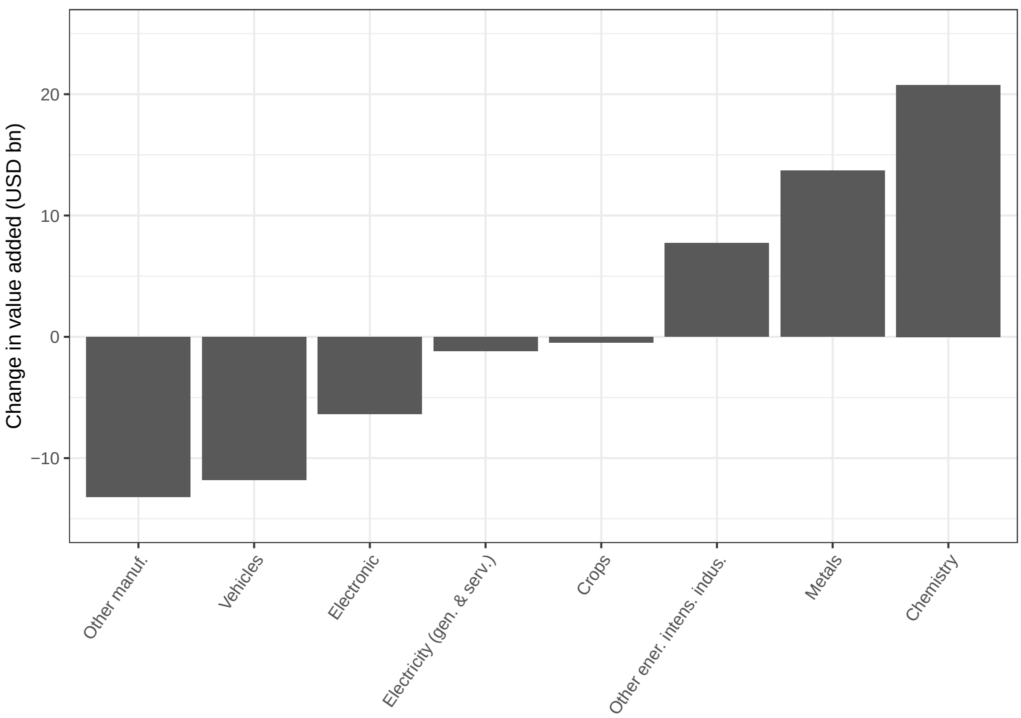
If we now turn to the possible impacts of the European CBAM on third countries, we first notice that the EU enjoys a positive terms of trade effect when introducing the CBAM. It varies between 0.6% in the first scenario and 0.8% in Scenario 2 where the emissions of the exporter country are chosen as reference. This effect, where the lower demand for carbon-intensive imports from a large country (the EU) results in lower import prices and therefore a positive terms-of-trade effect for this importer, is consistent with the theoretical prediction that the taxing country is extracting a rent

Figure 1: Impact of the CBAM on value added by sector (*vs* baseline, in 2040). Scenario 1



Source: simulations with MIRAGE-VA, calculations by the authors. The figure only shows sectors for which the absolute value of absolute variation is greater than USD 1.5 bn and the absolute value of relative variation is larger than 2 percent.

Figure 2: Impact of the CBAM *based on the emissions by the exporters and complemented with a rebate* on value added by sector (Scenario 3 *vs* Scenario 1, in 2040)



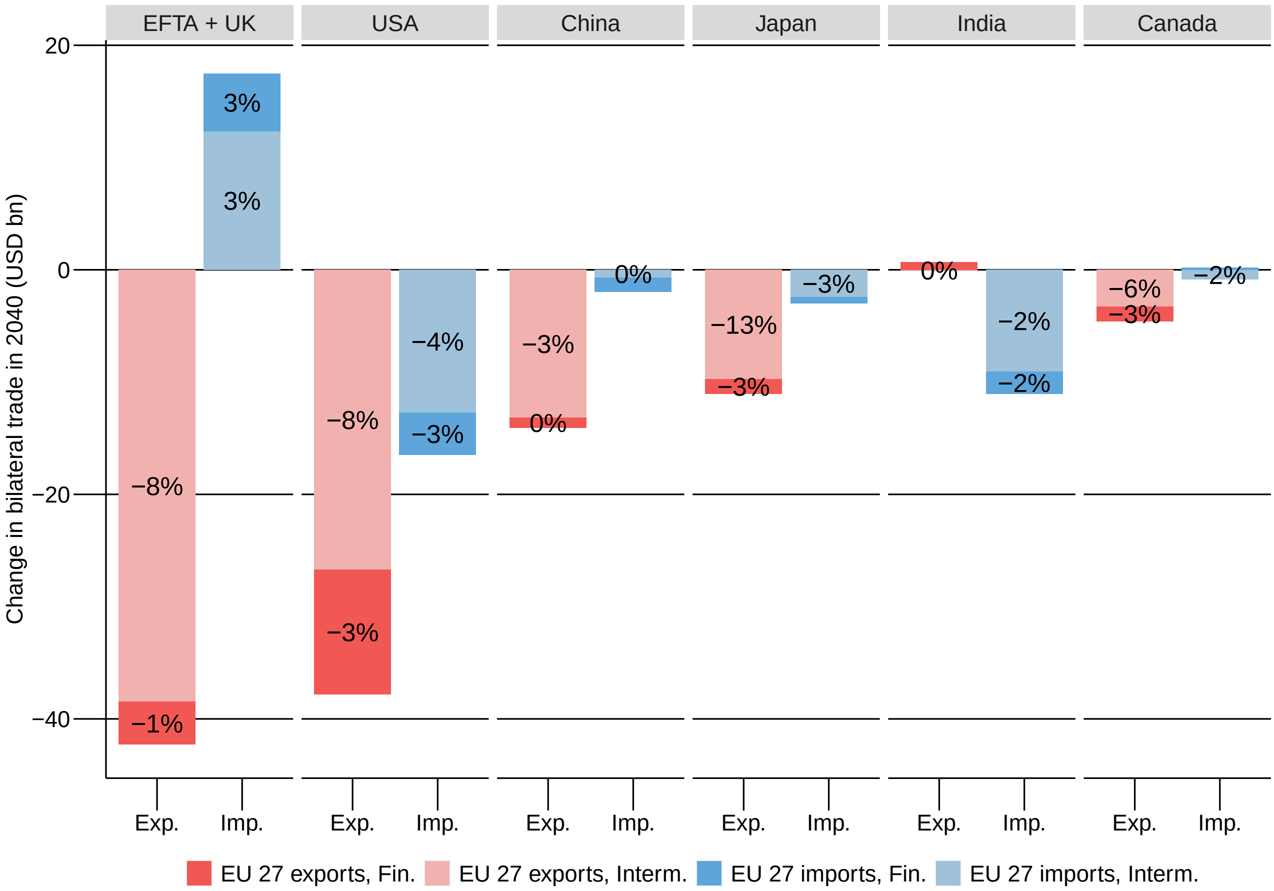
Source: simulations with MIRAGE-VA, calculations by the authors.The figure only shows sectors for which the absolute value of absolute variation is greater than USD 1.5 bn and the absolute value of relative variation is larger than 2 percent.

from the exporters (Balistreri, Kaffine & Yonezawa 2019). This may also pose difficulties for the acceptance of the CBAM by WTO members.

Another possibly contentious issue in the WTO arena is the impact of CBAM on bilateral exports of main European trading partners of carbon intensive products. Figure 3 shows the impact of CBAM on EU bilateral exports and imports to (from) selected countries. Imports are in blue and exports in red, with a darker shade for final products: the figure shows the absolute variation in billion USD on the vertical scale, while relative changes in percentages are indicated on the bars. Considering Scenario 1, the most affected country in absolute and relative terms is the USA, with a -3.6% cut in exports towards the EU. However, EU exports to the USA are also down, by -5.8%, with CBAM being ultimately the source of changes in the bilateral trade balance *favourable* to the USA. A similar pattern is observed with China or Japan, although of a much smaller magnitude. India is negatively affected with an absolute deterioration of its trade balance of USD -10 bn mostly due to a drop in exports of intermediate goods. Finally, EFTA and the United Kingdom are the main beneficiaries of CBAM, as they are among the countries that benefit from a low carbon border adjustment once the carbon price they apply to their producers is taken into account, giving them a relative cost advantage: their bilateral exports to the EU are increasing, while their bilateral imports decrease.

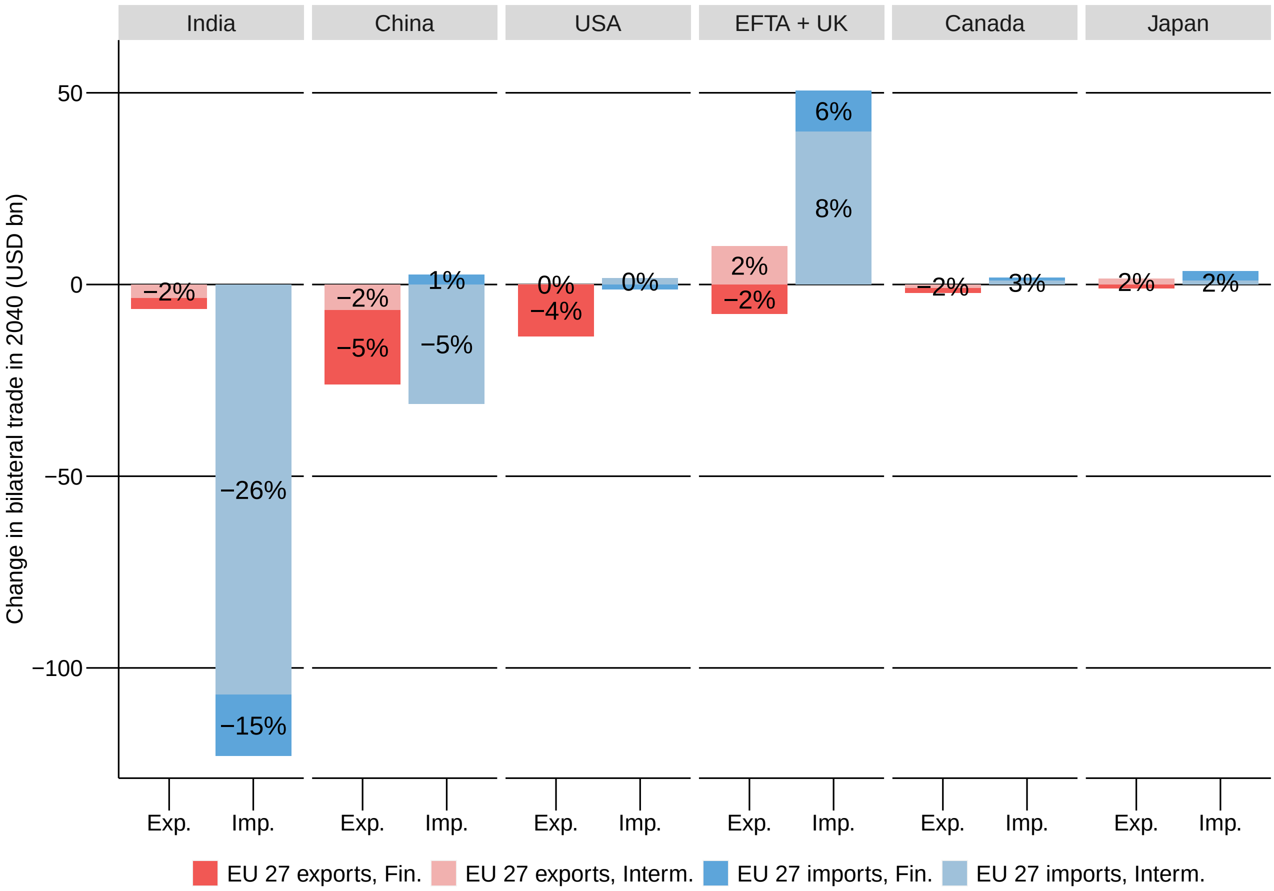
Figure 4 compares Scenario 3 to Scenario 1, Scenario 3 having potentially the largest impact on trade. The results for Scenario 2 are provided in the Appendix. The main finding is that India is deeply affected by the change in baseline emissions, with an additional drop of its exports of intermediate products towards the EU, which amounts to USD 100 billion.

Figure 3: Impact of the CBAM on EU27 bilateral trade (*vs* baseline, in 2040). Scenario 1



Source: simulations with MIRAGE-VA. Values are in constant USD of 2014. Trade is reported in volume, i.e. excluding price effects. Absolute and relative variations are expressed with respect to the baseline.

Figure 4: Impact of the CBAM on EU27 bilateral trade (Scenario 3 *vs Scenario 1*, in 2040).



Source: simulations with MIRAGE-VA. Values are in constant USD of 2014. Trade is reported in volume, i.e. excluding price effects. Absolute and relative variations are expressed with respect to Scenario 1.

Conclusion

The European Parliament, the Commission and the Council are moving towards a compensation of carbon price at the borders of the EU. This mechanism would replace the free allocation of emission allowances that presently benefit to the industries most exposed to leakage. It would increase the incentive for these industries to curb their emissions while keeping in place a form of protection against leakages. Taking stock of the ongoing discussions, this paper simulates the environmental and economic impact of different options to implement this mechanism. We explore the impacts on leakages, GDP, trade, value added by sector. We discuss into details the options that could be problematic for the trade partners of the EU and could induce their retaliation. To do this, we evaluate possible designs against WTO rules. Although the Dispute Settlement Body is at a standstill, the regulation envisaged by the European institutions aims at WTO compatibility. A WTO-compliant mechanism would indeed generate a much weaker incentive for retaliation.

Considering the trajectory of the world economy in terms of GDP and induced emissions in absence of any abatement policy, we impose the caps on emissions corresponding to the (updated) unconditional NDCs of the Paris agreement for countries having managed to enforce a pricing of carbon at the national level in 2021. This is our reference, in which the EU freely allocates carbon allowances to ETS sectors exposed to carbon leakage. The counterfactuals consider a CBAM that replaces free allowances. They consist in i) a CBAM limited to direct emissions and taking EU emissions by sector as reference, gradually replacing free allowances between 2026 and 2035; ii) alternatively augmented by the choice of the exporter country's emissions by sector as reference (and still gradually implemented), and iii) further augmented by a rebate of emission quotas to EU exporters. We assume that all ETS industries, in the broad sense, are covered by the CBAM, which goes ways beyond the initial step of the proposed regulation. This choice is consistent with the long-term objective of the Commission, and also helps identifying what are the main mechanisms at play. Our results must therefore be understood as the long-term impact of a CBAM extended to all ETS industries.

We show that the CBAM is more efficient than free allowances in reducing carbon leakages, which is the purpose of the tool as announced by the European Commission. It also better shares the burden of the climate policy among the sectors covered by the ETS, in particular between the production of electricity and the rest of the emission intensive sectors. The cumulated leakages associated with the Paris agreement in our last scenario are reduced by the equivalent of 2 years of European emissions over the period 2021–40 considered here. This however comes at a cost, and not only for sectors covered by the ETS: the price of ETS allowances increases, ETS products used as intermediate consumptions by downstream industries are more expensive, and ETS producers are no longer protected by free allowances on their export markets in absence of rebates. Our work shows that there is a tension between two polar approaches in designing the European CBAM: on the one hand, a more conservative approach that minimises the risk of retaliation by trading partners but has a smaller environmental impact (Scenario 1); on the other hand, a more complex design that reduces the leakages to a much greater extent, that limits the cost for EU exporters of ETS products, but discriminates more between trading partners (Scenario 3). In between, a third solution is possible, without any rebate to ETS sectors, that has a cost similar to the most complex design, but shares the burden differently across sectors and trading partners.

Bibliography

Antimiani, A., Costantini, V., Martini, C., Salvatici, L. & Tommasino, M. C. (2013), 'Assessing alternative solutions to carbon leakage', *Energy Economics* **36**, 299–311.

Auffhammer, M. (2018), 'Quantifying economic damages from climate change', *Journal of Economic Perspectives* **32**(4), 33–52.

Babiker, M. H. & Rutherford, T. F. (2005), 'The economic effects of border measures in subglobal climate agreements', *The Energy Journal* **26**(4).

Balistreri, E. J., Kaffine, D. T. & Yonezawa, H. (2019), 'Optimal environmental border adjustments under the general agreement on tariffs and trade', *Environmental and Resource Economics* **74**(3), 1037–1075.

Bellora, C. & Fouré, J. (2019), Trade, global value chains and the Paris Agreement. mimeo.

Böhringer, C., Bye, B., Fæhn, T. & Rosendahl, K. E. (2012), 'Alternative designs for tariffs on embodied carbon: A global cost-effectiveness analysis', *Energy Economics* **34**, S143–S153.

Böhringer, C., Carbone, J. C. & Rutherford, T. F. (2012), 'Unilateral climate policy design: Efficiency and equity implications of alternative instruments to reduce carbon leakage', *Energy Economics* **34**, S208–S217.

Böhringer, C., Carbone, J. C. & Rutherford, T. F. (2018), 'Embodied carbon tariffs', *The Scandinavian Journal of Economics* **120**(1), 183–210.

Böhringer, C., Fischer, C., Rosendahl, K. E. & Rutherford, T. F. (2022), 'Potential impacts and challenges of border carbon adjustments', *Nature Climate Change* pp. 1–8.

Böhringer, C., Garcia-Muros, X., Cazcarro, I. & Arto, I. (2017), 'The efficiency cost of protective measures in climate policy', *Energy Policy* **104**, 446–454.

Böhringer, C., Schneider, J. & Asane-Otoo, E. (2021), 'Trade in carbon and carbon tariffs', *Environmental and Resource Economics* .

Bouet, A., Decreux, Y., Fontagné, L., Jean, S. & Laborde, D. (2008), 'Assessing applied protection across the World', *Review of International Economics* **16**(5), 850–863.

Branger, F. & Quirion, P. (2014), 'Would border carbon adjustments prevent carbon leakage and heavy industry competitiveness losses? Insights from a meta-analysis of recent economic studies', *Ecological Economics* **99**, 29–39.

Elliott, J., Foster, I., Kortum, S., Munson, T., Perez Cervantes, F. & Weisbach, D. (2010), 'Trade and carbon taxes', *American Economic Review* **100**(2), 465–69.

Felder, S. & Rutherford, T. (1993), 'Unilateral CO_2 reductions and carbon leakage: the consequences of international trade in oil and basic materials', *Journal of Environmental Economics and Management* .

Fontagné, L., Fouré, J. & Ramos, M. P. (2013), MIRAGE-e: A general equilibrium long-term path of the world economy, Working Paper 2013-39, CEPII.

Fontagné, L., Guimbard, H. & Orefice, G. (2022), 'Tariff-based product-level trade elasticities', *Journal of International Economics* **137**, 103593.

Fontagné, L., Mitaritonna, C. & Signoret, J. E. (2016), Estimated tariff equivalents of services NTMs, Working Paper 2016-20, CEPII.

Fontagné, L., Perego, E. & Santoni, G. (2021), MaGE 3.1: Long-term macroeconomic projections of the world economy, Working paper 2021-12, CEPII.

Fouré, J., Bénassy-Quéré, A. & Fontagné, L. (2013), 'Modelling the world economy at the 2050 horizon', *Economics of Transition* **21**(4), 617–654.

Fouré, J., Guimbard, H. & Monjon, S. (2016), 'Border carbon adjustment and trade retaliation: What would be the cost for the European Union?', *Energy Economics* **54**, 349–362.

Garicano, L. (2021), Towards a feasible carbon border adjustment mechanism: Explanation and analysis of the European Parliament's proposal. Mimeo, European Parliament.

Gollier, C. & Tirole, J. (2015), 'Negotiating effective institutions against climate change', *Economics of Energy & Environmental Policy* **4**(2).

Guimbard, H., Jean, S., Mimouni, M. & Pichot, X. (2012), 'MAcMap-HS6 2007, An exhaustive and consistent measure of applied protection in 2007', *International Economics* **130**, 99–121.

Hyman, R. C., Reilly, J. M., Babiker, M. H., De Masin, A. & Jacoby, H. D. (2003), 'Modeling non-CO_2 greenhouse gas abatement', *Environmental Modeling & Assessment* **8**, 175–186.

Kee, H. L., Nicita, A. & Olarreaga, M. (2008), 'Estimating trade restrictiveness indices', *The Economic Journal* **119**(534), 172–199.

Kuik, O. & Hofkes, M. (2010), 'Border adjustment for European emissions trading: Competitiveness and carbon leakage', *Energy policy* **38**(4), 1741–1748.

Lanzi, E., Mullaly, D., Château, J. & Dellink, R. (2013), Addressing competitiveness and carbon leakage impacts arising from multiple carbon markets, Environment Working Papers 58, OECD. **URL:** *https://www.oecd-ilibrary.org/content/paper/5k40ggjj7z8v-en*

Manders, T. & Veenendaal, P. (2008), Border tax adjustments and the EU-ETS. A quantitative assessment, CPB Document 171, Netherlands Bureau for Economic Policy Analysis.

Markusen, J. R. (1975), 'International externalities and optimal tax structures', *Journal of international economics* **5**(1), 15–29.

McKibbin, W. J., Morris, A. C., Wilcoxen, P. J. & Liu, W. (2018), 'The role of border carbon adjustments in a U.S. carbon tax', *Climate Change Economics* **09**(01), 1840011.

Mörsdorf, G. (2022), 'A simple fix for carbon leakage? Assessing the environmental effectiveness of the EU carbon border adjustment', *Energy Policy* **161**, 112596.

OECD (2012), *OECD Environmental Outlook to 2050*, Organisation for Economic Co-Operation and Development (OECD).

OECD (2020), *Climate Policy Leadership in an Interconnected World – What role for Carbon Border Adjusments?*, Organisation for Economic Co-Operation and Development (OECD).

OECD (2021), *Effective Carbon Rates 2021:Pricing Carbon Emissions through Taxes and Emissions Trading*, Organisation for Economic Co-Operation and Development (OECD).

Parry, I., Black, S. & Roaf, J. (2021), Proposal for an international carbon price floor among large emitters, Staff Climate Note 2021/001, International Monetary Fund.

Weitzel, M., Hübler, M. & Peterson, S. (2012), 'Fair, optimal or detrimental? Environmental vs. strategic use of border carbon adjustment', *Energy Economics* **34**, S198–S207.

A Appendix

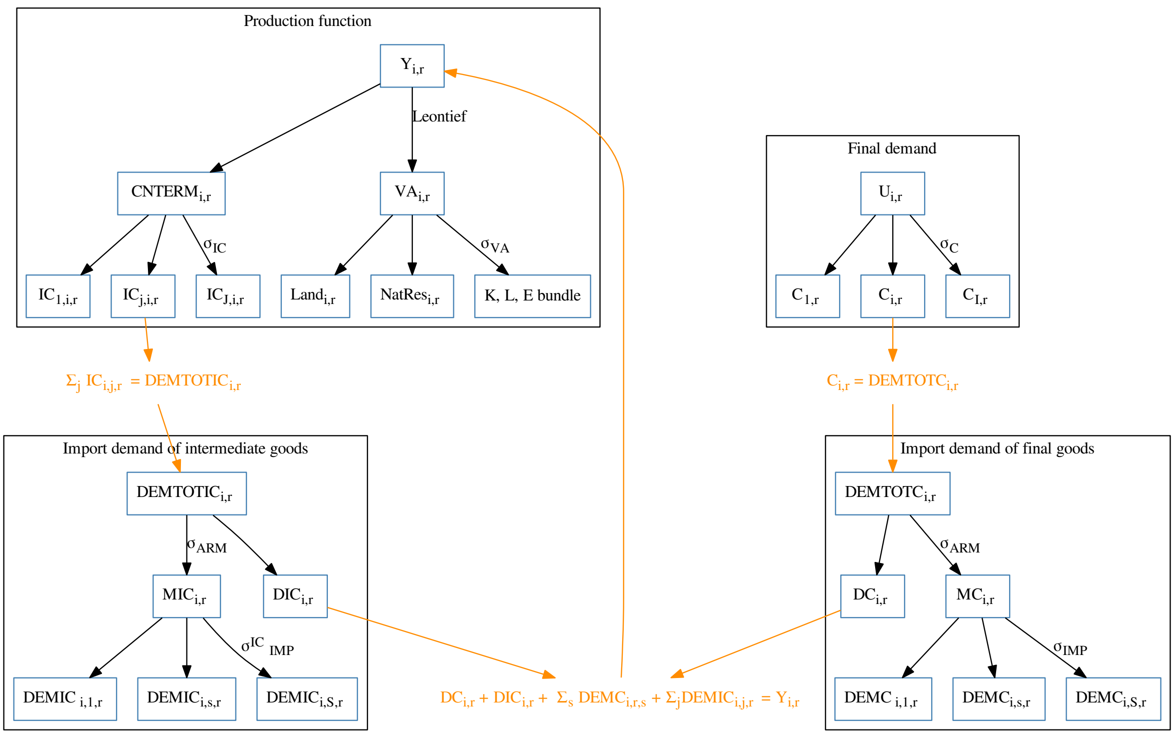
A.1 Structure of the MIRAGE-VA model

A.1.1 Overall structure of the model

Figure A1 shows the overall structure of the model and the way consistency is ensured across the production, demand and trade blocks. In the production function, perfect complemetarity is assumed between value added and overall intermediate consumption. The sectoral composition of the intermediate consumption aggregate stems from a CES function, with an elasticity σ_{IC}. Value-added is a CES bundle of land, natural resources, unskilled labour and a CES bundle of capital, skilled labour and energy (for the details on this bundle see section A.1.3).

For final demand, preferences across sectors are represented by a LES-CES (Linear expenditure system - Constant elasticity of substitution) function. Then, within each sector, we assume that products are differentiated according to their geographic origin and represent this Armington assumption with a nesting of CES functions. Two different Armington structures allow to differentiate the demand structure according to the use of the good considered, whether for final or intermediate consumption.

Figure A1: Overall structure of MIRAGE-VA



The notations are the following regarding subscripts:

- i and j denote sectors
- r and s denote regions

As far as variables are concerned (here we omit their time dimension):

- $Y_{i,r}$: production of good i in region r,
- $CNTERM_{i,r}$: intermediate consumption bundle to produce good i in region r,
- $VA_{i,r}$: value added bundle to produce good i in region r,
- $IC_{j,i,r}$: intermediate consumption of from sector j to produce good i in region r,
- $Land_{i,r}$: land to produce good i in region r,
- $NatRes_{i,r}$: natural ressources (other than land) to produce good r in region i,
- $DEMOTOTIC_{i,r}$: total demand of good i in region r, to be used for intermediate consumption,
- $MIC_{i,r}$: demand of good i to be used for intermediate consumption adressed to the domestic market, in region r,
- $DIC_{i,r}$: total demand of good i to be used for intermediate consumption adressed to foreign markets, in region r,
- $DEMIC_{i,s,r}$: demand of good i to be used for intermediate consumption adressed to region s by region r,
- $DEMTOTC_{i,r}$: total demand of good i in region r, to be used for final consumption,
- $DC_{i,r}$: total demand of good i to be used for final consumption adressed to the domestic market, in region r,
- $MC_{i,r}$: total demand of good i to be used for final consumption adressed to foreign markets, in region r,
- $DEMC_{i,s,r}$: demand of good i to be used for intermediate consumption adressed to region s by region r,
- U_r: total final consumption in region r,
- $C_{i,r}$: final consumption of good i in region r.

A.1.2 Representation of GHGs emitted during the production processes

Figure A2 shows the way GHG other than CO_2 emitted during the production processes are represented in the production functions. GHGs are introduced as production factors, based on the approach developed by Hyman et al. (2003). In red,we show differences with respect to this latter approach to ensure the consistency with the historical specification of the MIRAGE model.

A.1.3 The production function in MIRAGE-VA – Manufacture

Figure A3 shows the detailed nesting of the CES and Leontief functions used to represent the production function of industrial goods that are not considered as energy intensive and of services.

A.2 Free allowances

In MIRAGE-e, the price of GHG emissions, without free allowance, is given by

$$P^{GHG}_{g,j,r,t} = \tau_{m,t} \times EF_{g,j,r} \times PU_{R,t} \tag{1}$$

with

- $P^{GHG}_{g,j,r,t}$: price of the emissions of gas g caused by the production of good j in region r at time t
- $\tau_{m,t}$: price of an emission quota on the emission market m at time t
- $EF_{g,j,r}$: emission factor of gas g by the production of good j in region r (in USD per ton of CO_2)
- $PU_{R,t}$: shadow price of utility in the reference region R at time t

Based on this formulation, we add free allowances as follows.

$$P^{GHG}_{g,j,r,t} = (\tau_{m,t} - \tau^{FA}_{m,j,t}) \times EF_{g,j,r} \times PU_{R,t} \tag{2}$$

with

- $\tau^{FA}_{m,j,t}$: reduction in the price of the emissions of sector j in market m due to free allowances

How to define $\tau^{FA}_{m,j,t}$?
$\forall j \neq Elec$,

$$\tau^{FA}_{m,j,t} = \frac{\beta^{FA}_{m,t-1}(\sum_{g,i,r\in m} EmGHG_{m,t-1} \times \tau_{m,t-1})}{\sum_{g,i,r\in m,\ i\neq Elec} EmGHG_{g,i,r,t-1}} \tag{3}$$

with

- $EmGHG_{m,t-1}$: total emissions covered by market$m$ at time $t-1$ (in tons of CO_2eq)
- $\beta^{FA}_{m,t-1}$: share of free allowances in market m at time $t-1$

With the proposed formulation, $\tau^{FA}_{m,j,t}$ is an exogenous parameter, its value is fixed at the beginning of the each period during the simulation.

The policy scenario is then determined by the exogenous value of parameter $\beta^{FA}_{m,t}$: 43% btw 2013 and 2020, 0 after 2036 in the CBAM, for instance.

A.3 The regional and sectoral aggregation

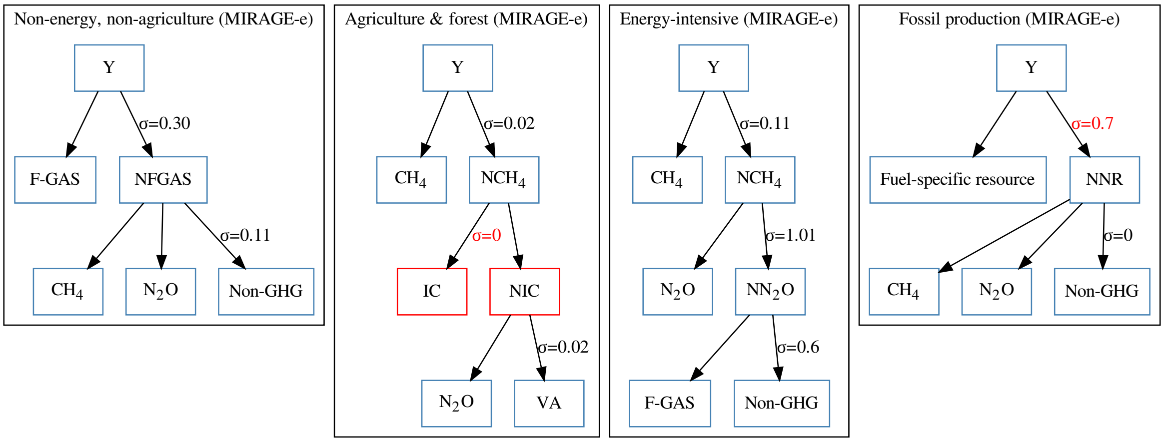
Tables A1 and A2 respectively report the aggregation retained to move from the 147 regions and 65 sectors of the GTAP 10.1 MRIO database to the 27 regions and 23 sectors of our simulations.

Table A1: Regional aggregation

MIRAGE	Aggreg. code	GTAP region
Argentina	Argentina	ARG
Asia (NDC BAU)	AsiaBAUA	BGD, IDN, LKA, MNG, THA, VNM
Asia (NDC Intensity)	AsiaInt	MYS, SGP
Australia	Australia	AUS
Canada	Canada	CAN
Chile	Chile	CHL
China	China	CHN
Colombia and Mexico (NDC BAU)	ColMex_BAU	COL, MEX
EFTA and UK (NDC Absolute)	EFTA_UK	CHE, GBR, NOR, XEF
European Union 27	EU27	AUT, BEL, BGR, CYP, CZE, DEU, DNK, ESP, EST, FIN, FRA, GRC, HRV, HUN, IRL, ITA, LTU, LUX, LVA, MLT, NLD, POL, PRT, ROU, SVK, SVN, SWE
India	India	IND
Japan (NDC Absolute)	Japan	JPN
Kazakhstan and Ukraina (NDC Absolute)	KazUkr_Abs	KAZ, UKR
Latin America (NDC Absolute)	LACAbs	BRA, CRI, GTM
Latin America (NDC BAU)	LACBAUA	ECU, JAM, PER, PRY
Middle East and North Africa (NDC BAU)	MENABAUA	GEO, IRN, JOR, KGZ, MAR, ARE, KWT, LBN, OMN, QAT
NewZealand (NDC Absolute)	NewZealand	NZL
Others (NDC Absolute)	OthAbs	AZE, ISR, TUN
Rest of America	OthAm	BOL, DOM, HND, NIC, PAN, PRI, SLV, TTO, URY, VEN, XCA, XCB, XNA, XSM
Rest of Asia and Oceania	OthAsiaOce	BRN, HKG, KHM, LAO, NPL, PAK, PHL, TWN, XEA, XOC, XSA, XSE, XTW
Rest of Europe	OthEur	ALB, XER, SRB
Rest of Europe (NDC Absolute)	OthEurAbs	RUS, BLR, XEE
Rest of MENA	OthMENA	ARM, BHR, EGY, IRQ, PSE, SAU, SYR, TJK, TUR, XNF, XSU, XWS
Rest of SubSaharan Africa	OthSSA	BWA, CIV, MDG, MOZ, SDN, TZA, XAC, XCF, XEC, XSC, XWF, ZAF, ZMB, ZWE, GHA
South Korea	Korea	KOR
SubSaharan Africa (NDC BAU)	SSABAUA	CMR, ETH, GIN, KEN, MUS, MWI, RWA, TGO, BEN, BFA, NAM, NGA, SEN, UGA
United States	USA	USA

Notes: The *Aggregation code* column reports the short names used during the simulations. These names may be used in some figures and tables of the paper.

Figure A2: Emissions of GHG occuring during the production processes - representation in MIRAGE-VA



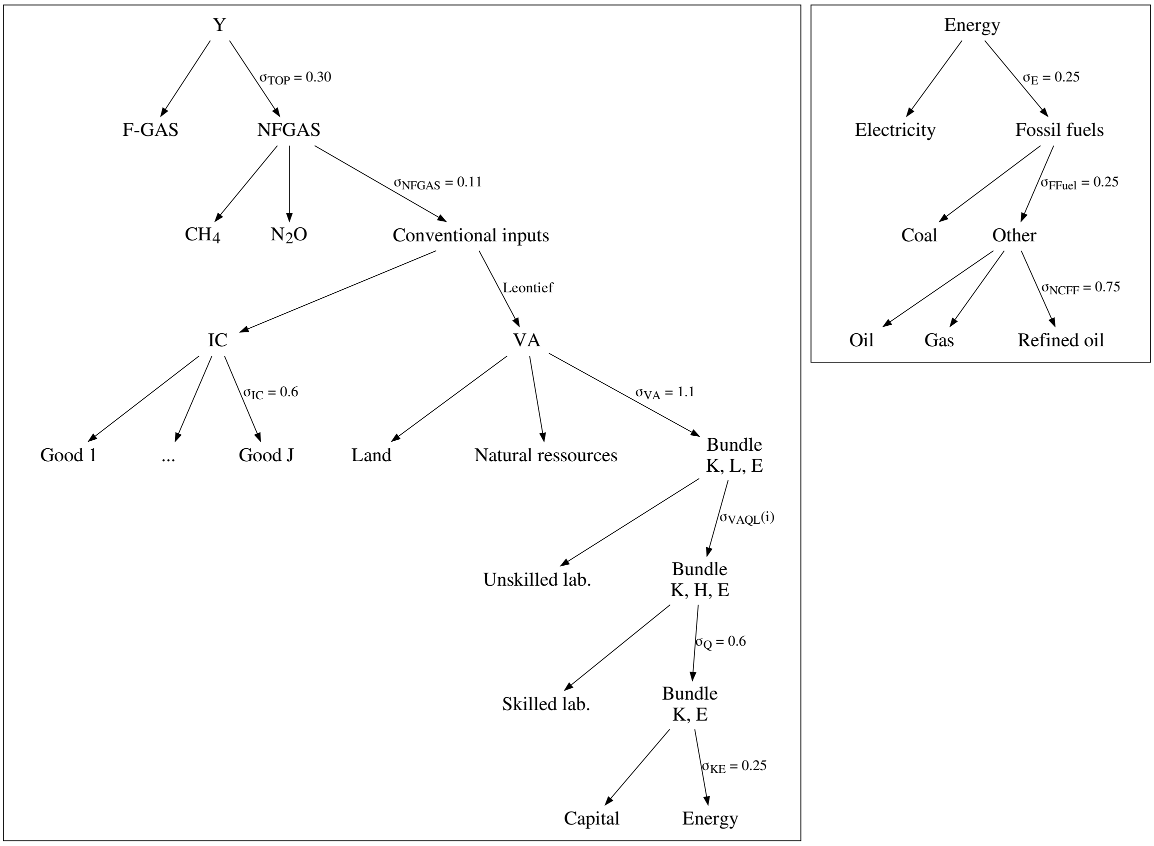
Note: Subscripts i and r are omitted to ease the reading. $F-GAS$ stands for fluorinated gases, $NFGAS$ for non fluorinated gases (which is a CES bundle of CH_4, CO_2 and the standard aggregation of intermediate consumption and value added). NCH_4 is a bundle of intermediate consumptions, N_2O and value added. NN_2O is a CES budnle of fluorinated gases and the standard aggregation of intermediate consumption and value added. NNR is a Leontief bundle of CH_4, N_2O and the standard aggregation of intermediate consumption and value added.

Table A2: Sectoral aggregation

MIRAGE	Aggreg. code	GTAP sector
Air transp.	AirTransp	atp
Beverages and tobacco*	BevTob	b_t
Cattle and other animal productions	AnimProd	ctl, oap, rmk, wol, fsh, cmt, omt, mil
Chemistry*	**Chemistry**	**chm, bph**
Coal	Coal	coa
Crops	Crops	pdr, wht, gro, v_f, osd, c_b, pfb, ocr
Electricity (incl. distribution)*	**Electric**	**ely**
Electronics*	Electronic	ele, eeq
Forestry	Forestry	frs
Gas	Gas	gas, gdt
Metal products*	**Metals**	**i_s, nfm, fmp**
Oil	Oil	oil
Oth. transp.	OthTransp	otp, whs
Other food products*	OthFood	vol, pcr, sgr, ofd
Other manuf. – energy intensive*	**OthEI**	**ppp, nmm**
Other manufactured products*	OthManuf	lum, rpp, ome, omf
Other primary products	OthPrimary	oxt
Other services*	OthServ	wtr, cns, afs, ros, osg, edu, hht, dwe
Refined oil	RefinedOil	p_c
Services to businesses*	BusiServ	trd, cmn, ofi, ins, rsa, obs
Textile*	Textile	tex, wap, lea
Vehicles*	Vehicles	mvh, otn
Water transp.	SeaTransp	wtp

Notes: The *Aggregation code* column reports the short names used during the simulations. These names may be used in some figures and tables of the paper. Asterisks identify sectors in which competition is imperfect in our modeling setup. In the simulations, the ETS covers the sectors marked in bold. Taking the sectors in GTAP 10.1 as the basic blocks of our aggregation, the sectors covered by the ETS have been identified based on the list of sectors and activities reported in the Annex I of the Directive 2003/87/EC of the European Parliament and of the Council and in the Annex of the Commission Delegated Decision 2019/708. The Directive lists the activities covered by the ETS and the Decision supplements the Directive with the list of the sectors deemed at risk of carbon leakage.

Figure A3: Detailed structure of the production function for manufacture sectors and services in MIRAGE-VA



A.4 Additional results

A.4.1 Sectoral impacts on trade and production costs

Table A3: Impact of the CBAM on European sectors – Scenario 1

	Imports		Exports	
	(USD bn.)	(%)	(USD bn.)	(%)
Sectors covered by the CBAM				
Chemistry	−57.9	−6.2	−251.5	−28.4
Electricity (incl. distribution)	−156.5	−73.3	11.7	76.2
Metal products	−2.7	−0.4	−107.7	−20.0
Other manuf. – energy intensive	−1.6	−0.8	−59.7	−21.3
Primary sectors				
Cattle and other animal productions	−0.7	−0.5	4.8	2.5
Crops	−0.9	−0.7	2.9	2.2
Forestry	−0.2	−2.8	0.3	2.6
Other primary products	−5.1	−8.6	4.4	3.3
Secondary sectors				
Electronics	−13.1	−1.4	−22.4	−1.7
Other food products	−3.8	−1.4	3.1	1.2
Other manufactured products	−16.2	−1.6	−27.0	−1.8
Refined oil	−5.0	−1.9	−1.6	−1.9
Textile	−6.7	−1.3	−4.9	−1.1
Vehicles	−13.0	−1.1	−7.2	−1.2
Tertiary sectors				
Air transp.	−1.5	−1.6	1.6	1.2
Oth. transp.	−4.4	−2.7	5.7	3.0
Other services	−6.3	−2.4	11.5	2.8
Services to businesses	−27.4	−2.6	38.0	3.0
Water transp.	−0.6	−0.9	1.0	1.3

Notes: Changes are in volume (price effects excluded), with respect to the reference scenario, in 2040. Sectors are ranked by decreasing relative change in their sectoral value added. The table does not report results for the sectors in which the absolute change in value added is smaller than USD 50 Mn.
Source: MIRAGE-VA, calculations by the authors.

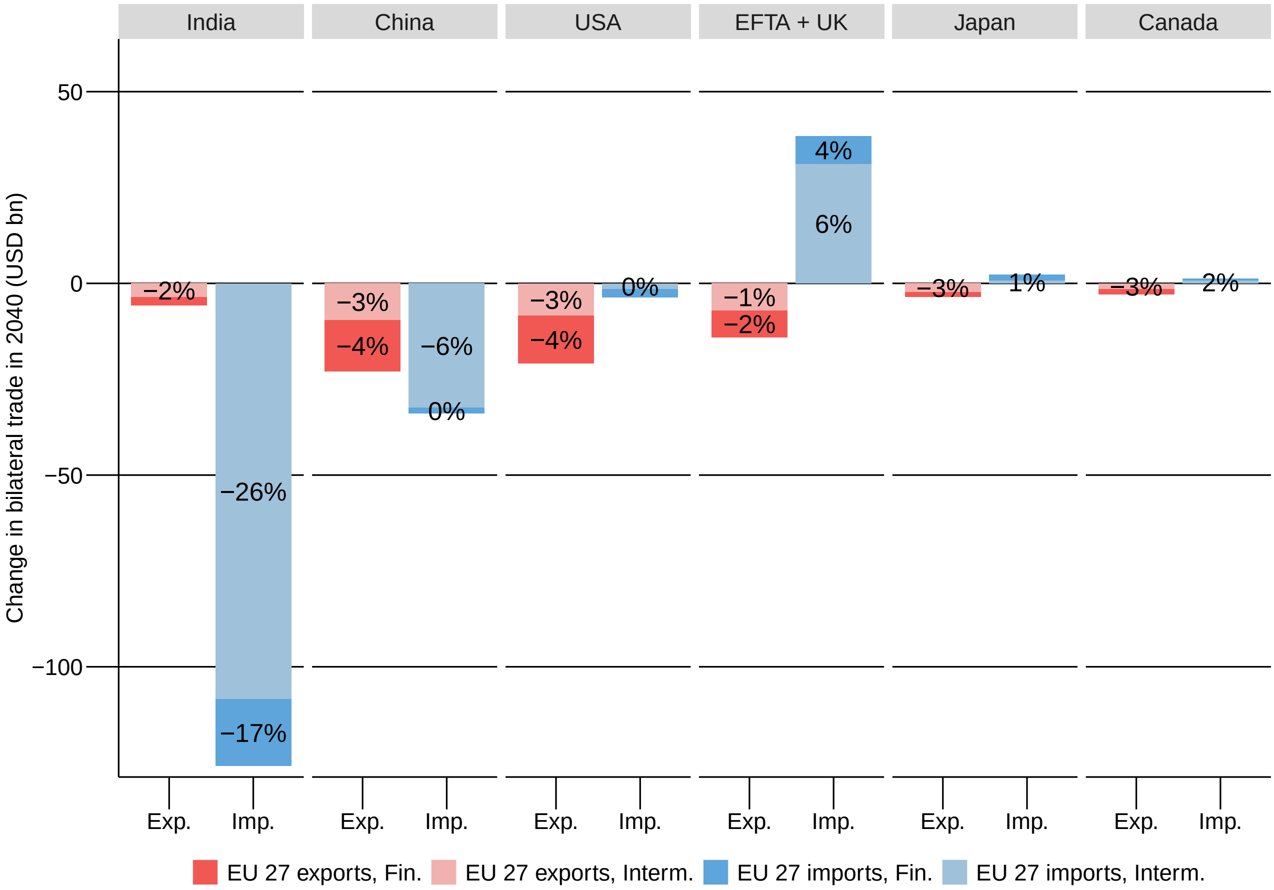
Table A4: Impact of the CBAM on European sectors – Scenario 3

	Imports		Exports	
	(USD bn.)	(%)	(USD bn.)	(%)
Sectors covered by the CBAM				
Chemistry	−100.2	−10.7	−138.9	−15.7
Electricity (incl. distribution)	−146.8	−68.8	9.4	61.0
Metal products	−55.0	−9.1	−59.3	−11.0
Other manuf. – energy intensive	−12.6	−6.2	−34.2	−12.2
Primary sectors				
Cattle and other animal productions	−0.3	−0.3	3.9	2.0
Crops	−0.5	−0.4	2.0	1.5
Forestry	−0.2	−3.1	0.3	2.2
Secondary sectors				
Beverages and tobacco	−0.5	−0.7	−0.3	−0.3
Electronics	−23.8	−2.6	−124.7	−9.5
Other food products	−1.8	−0.7	0.8	0.3
Other manufactured products	−13.5	−1.3	−95.9	−6.4
Textile	−8.0	−1.5	−35.5	−8.2
Vehicles	−17.9	−1.6	−42.8	−7.3
Tertiary sectors				
Air transp.	−1.1	−1.2	1.9	1.4
Oth. transp.	−3.3	−2.0	5.2	2.7
Other services	−4.2	−1.6	6.5	1.6
Services to businesses	−21.3	−2.0	27.9	2.2
Water transp.	−0.4	−0.7	0.9	1.2

Notes: Changes are in volume (price effects excluded), with respect to the reference scenario, in 2040. Sectors are ranked by decreasing relative change in their sectoral value added. The table does not report results for the sectors in which the absolute change in value added is smaller than USD 50 Mn.
Source: MIRAGE-VA, calculations by the authors.

A.4.2 Bilateral trade

Figure A4: Impact of the CBAM on EU27 bilateral trade (Scenario 2 *vs Scenario 1*, in 2040)



Source: simulations with MIRAGE-VA. Values are in constant USD of 2014. Trade is reported in volume, i.e. excluding price effects. Absolute and relative variations are expressed with respect to the Scenario 1.

A.4.3 Sectoral impacts on third countries

Table A5: Impact of the CBAM on Chinese sectors – Scenario 3

	Value added		Imports		Exports	
	(USD bn.)	(%)	(USD bn.)	(%)	(USD bn.)	(%)
Sectors covered by the CBAM						
Metal products	0.4	0.0	−4.4	−1.7	−11.1	−1.7
Chemistry	−0.4	−0.1	−0.0	−0.0	−8.1	−1.6
Primary sectors						
Coal	−0.2	−0.2	1.4	1.3	−0.0	−1.2
Cattle and other animal productions	−0.4	−0.1	1.6	1.1	−0.1	−0.9
Crops	−0.7	−0.1	1.9	0.3	−0.0	−0.4
Secondary sectors						
Electronics	3.1	0.6	−13.3	−3.0	3.8	1.4
Other manufactured products	2.8	0.3	−7.1	−1.1	12.2	1.0
Textile	0.8	0.2	−1.2	−0.9	3.1	0.5
Tertiary sectors						
Air transp.	−0.2	−0.3	0.3	0.8	−0.2	−1.0
Water transp.	−0.3	−0.3	0.0	0.7	−0.1	−1.2
Services to businesses	−2.1	−0.0	5.5	1.1	−2.2	−1.4

Notes: Changes are in volume (price effects excluded), with respect to the reference scenario, in 2040. Sectors appear by decreasing relative change in their sectoral value added. The table does not report results for the sectors in which the absolute change in value added is smaller than USD 50 Mn or the absolute value of the relative change is smaller than 0.2%.
Source: MIRAGE-VA, calculations by the authors.

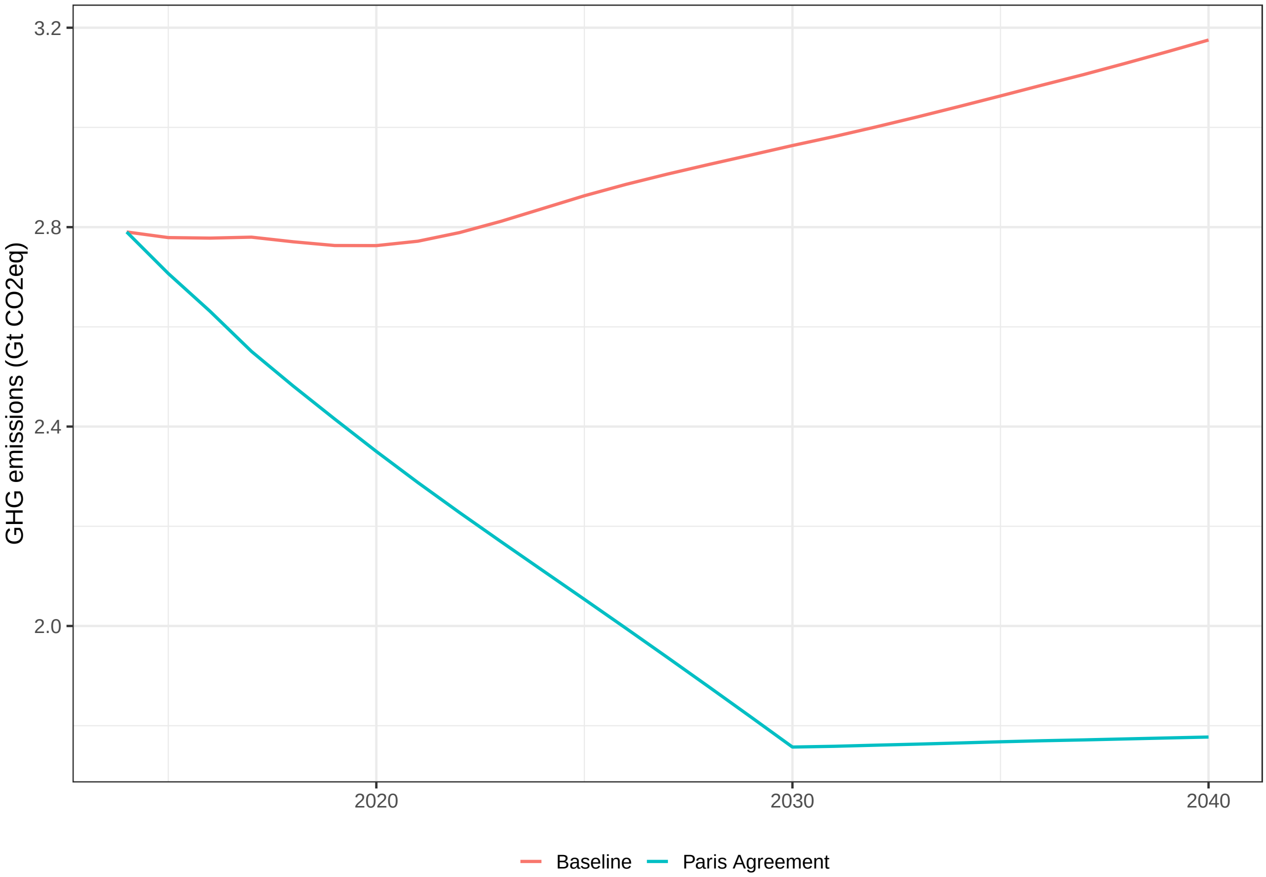
Table A6: Impact of the CBAM on US sectors – Scenario 3

	Value added		Imports		Exports	
	(USD bn.)	(%)	(USD bn.)	(%)	(USD bn.)	(%)
Sectors covered by the CBAM						
Chemistry	4.6	1.8	−7.9	−1.6	10.4	2.6
Metal products	3.2	1.3	−2.5	−1.1	6.3	3.2
Other manuf. – energy intensive	1.7	0.6	−1.6	−3.3	3.8	2.9
Primary sectors						
Coal	−0.2	−0.6	0.2	18.0	−0.2	−0.6
Oil	−0.6	−0.3	0.4	0.4	−0.2	−1.5
Gas	−6.0	−5.5	−0.8	−5.1	−22.6	−11.8
Secondary sectors						
Other manufactured products	3.4	0.5	−5.8	−0.8	6.8	1.6
Electronics	2.9	1.4	−7.6	−0.8	9.8	3.0
Vehicles	0.5	0.5	0.0	0.0	1.3	1.0
Textile	0.2	0.2	−0.2	−0.1	0.3	0.6
Tertiary sectors						
Air transp.	−0.3	−0.3	0.3	0.5	−0.3	−0.5
Oth. transp.	−0.4	−0.1	0.7	1.0	−0.7	−1.0
Services to businesses	−1.8	−0.0	3.1	0.7	−3.1	−1.1
Other services	−6.9	−0.1	0.3	0.2	−2.1	−0.8

Notes: Changes are in volume (price effects excluded), with respect to the reference scenario, in 2040. Sectors are ranked by decreasing relative change in their sectoral value added. The table does not report results for the sectors in which the absolute change in value added is smaller than USD 50 Mn or the absolute value of the relative change is smaller than 0.2%.
Source: MIRAGE-VA, calculations by the authors.

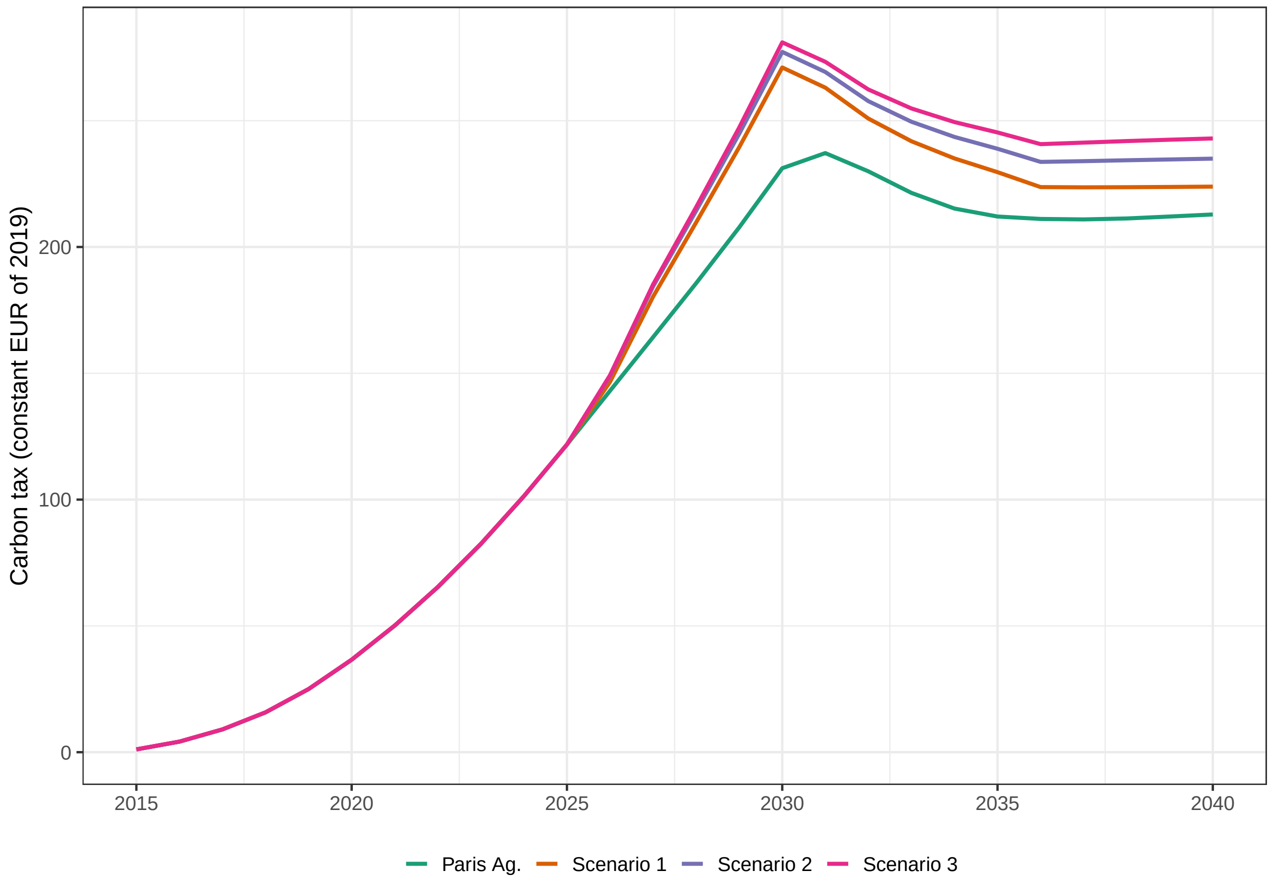
A.5 European Trading Scheme

Figure A5: Emissions of the EU 27 in MIRAGE-VA (Gt CO_2eq)



Source: MIRAGE-VA, calculations by the authors. GHG emissions of the EU27, excluding international bunkers.

Figure A6: Prices of the allowances on the European ETS market (EUR)



Source: MIRAGE-VA, calculations by the authors. Values are in constant EUR of 2019.