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

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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). 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. In addition, its design, as voted by the European Council on March 15, 2022, questions the compatibility of the CBAM with World Trade Organization (WTO) rules. The CBAM puts a price on carbon contained in imported products whose production-related emissions have not been taxed (or not at the same level as in the European Union) by the exporter country, in order to offset the difference in carbon prices at the border. This paper aims to quantify the economic and environmental impacts of different CBAM design choices with the aim of complying with WTO rules. Different from the previous literature, we evaluate the various options with a dynamic general equilibrium model featuring imperfect competition, global value chains, green-house gas emissions and endogenous price of emission quotas. We show that 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, 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.

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Introduction

Climate is a global public good that deserves global action. There is however a tension between ambitious commitments to reduce global Green-House 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. The proposed regulation on a Carbon Border Adjustment Mechanism (hereafter referred to as CBAM), included in the package of regulations announced in mid-July 2021, aimed precisely at avoiding such leakage.[2] 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

[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 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).

quotas and of the compensation for losses in competitiveness for exporters.[3] Offsetting differences in carbon price at the European border will indeed raise both the difficult question of its compatibility with the multilateral rules of international trade and the opposition of European businesses to the phasing out of free allowances on the Emissions Trading System (ETS) market: these are the main research questions addressed in this paper.

The CBAM indeed 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[4] that covers 40% of EU emissions generated by EU based firms of certain sectors during their production process. It presently sets a cap on these emissions so as to reduce them by 61% by 2030, with respect to 2005. Of course, efforts on other sectors are also set to reach the commitment taken by the EU in the Paris Agreement 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,[5] with a view to the presentation of the Commission's draft, which finally occurred in July 2021. Based on this first draft, the European Council reached an agreement on 15 March 2022, the text going now to the European Parliament.

The Commission's proposal foreshadowed a scheme combining 1) the purchase of allowances by importers on a specific market, price taker with respect to ETS; 2) a taxation base equal to the emissions of the exporter,[6] eventually 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;[7] 4) the phasing out of free allowances over a ten years period, progressively replaced by the CBAM; 5) the absorbtion

[3]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).

[4]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.

[5]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.

[6]"the carbon price of imports is based on actual emissions from third country producers rather than on a default value based on EU producers' averages"

[7]"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). The text additionally makes it clear that it has to be understood "net of export rebates in the exporter country".

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.[8] 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."[9]

The proposed compensation mechanism indeed 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 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.[10] 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

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

[9] "The following two issues, which are not covered by the CBAM Regulation, are of significance to the implementation of the CBAM: (a) The rate at which the obligation to surrender CBAM certificates becomes more extensive under Article 31 of the draft CBAM Regulation is determined by the rate at which free allowances are allocated to industry sectors covered by the CBAM, established by the EU Emissions Trading System Directive; (b) The issue of limiting potential carbon leakage from exports calls for appropriate solutions to ensure economic efficiency, environmental integrity and WTO compatibility. (*Regulation establishing a carbon border adjustment mechanism General approach, 12 March 2022, Ref. 6978/22*)"

[10] 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.

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. But 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,[11] 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,[12] 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 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 in-

[11]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 i.) the mechanism at the border taxes carbon at the exact same price as the domestic tax; ii.) the carbon tax is fully passed onto the consumer by producers and iii.) 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.

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

strument. Another issue is the reference chosen for offsetting emissions. As third country competitors will be charged on the basis of their own emissions this will penalise countries in the developing world with limited resources to combat climate change in absence of special and differential treatment. 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 at putting numbers on these issues. While the mechanisms underlying the impacts of an unilateral environmental policy are well known (Felder & Rutherford 1993), their relative magnitude, and therefore the size of the resulting leakages, remain empirical questions, depending on the characteristics of the policies in place, of the implementing countries and of the affected sectors. Our contribution to the literature is to assess the effectiveness of the various possible designs of the CBAM in meeting the environmental objectives and to quantify their economic impacts, with a focus on the questions listed above. Our modelling features a reference path for the world economy till 2040. It links trade and GHG emissions taking stock of Global Value Chains (GVCs), imperfect competition, substitution among energies and substitution among capital and energy. Nationally Determined Commitments (NDCs) of all countries are carefully examined. We also pay particular attention to the European ETS and to the free allowances. Such Dynamic Computable General Equilibrium modelling encompassing international trade and emissions is particularly adapted to address the economic impact of climate-change mitigation policies and the level of ambition required to reach the commitments. Calibrated multi-sectoral and global dynamic general equilibrium models allow to trace production displacements across sectors and regions and, as a consequence, account for carbon leakages. Relying on a model taking explicitly into account GVCs is also important when emissions related to intermediate consumptions have to be embarked. 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. We assume in the following that all ETS industries, in the broad sense, are covered by CBAM, which goes well beyond the initial stage of the proposed regulation restricted to cement, aluminium, fertilisers, electric energy production, iron and steel. This choice is consistent with the Commission's longer-term objective and 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.

First, we consider the trajectory of the world economy in terms of GDP[13] and the induced emis-

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

sions, in the absence of any abatement policy.

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) 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 four 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, allowances purchased at a carbon price equal to the ETS market price (minus any carbon price already paid in the exporter country). CBAM replaces the free allocation of allowances to European producers in ETS sectors exposed to international competition. This replacement is gradual in three of our scenarios, with CBAM being phased in as free allowances are phased out over a ten-year period. In contrast, CBAM is fully implemented in 2026 in the third scenario and free allowances are consequently phased out all at once in 2026. We consider different perimeters of emissions (direct emissions, versus direct and indirect energy-related ones) and different references for emissions (EU average versus exporter country average).

In all scenarios we apply the CBAM to all ETS sectors in order not to expose the EU to legal challenges at the WTO for "cherry-picking" excluded industries, i.e. industries that will continue to receive free allowances.[14] 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 recommendation.[15]. The revenues of the CBAM are not strictly earmarked: they are allocated to the European budget, as envisaged by the Commission.

In Scenario 1, the CBAM is designed to offset only the *direct* emissions of ETS sectors. Reference emissions are the European average. 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

[14]The Commission is less ambitious to begin with: "Whilst the ultimate objective of the CBAM is a broad product coverage, it would be prudent to start with a selected number of sectors with relatively homogeneous products where there is a risk of carbon leakage."

[15]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 development".

from EU exporters in the ETS sectors.[16] 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 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.

In Scenario 2, we add to Scenario 1 energy-related indirect emissions, using reference emissions from the EU here again.[17]

In Scenario 3, the CBAM is fully implemented in 2026 (with free allowances also abolished in 2026), using the reference European direct emissions as in Scenario 1.

In Scenario 4, we replicate Scenario 1 but using the reference emissions of the *exporter* country. The latter scenario is more ambitious in terms of offsetting emissions and incentivising 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.

To proceed, we use a dynamic, multi-sectoral and multi-regional model of the world economy, featuring a detailed representation of energy use. In particular, 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. GHG emissions due to both energy use (carbon dioxyde) and production processes (carbon dioxyde, methane, nitrous oxyde and fluorinated gases) are explicitly reported.[18] Climate policies are represented, based on 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. The model additionally embeds an improved representation of value chains that, coupled to the results on emissions, allows to discuss in details the impacts on GHG leakage through international trade and on GHG footprints.[19]

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

[16] Rebates were weakly supported by the European Parliament and would hardly be WTO consistent. Specifically, any tax rebate would provide a competitive advantage to European producers exporting to markets taxing carbon domestically without imposing a CBAM. Accordingly, we disregard the option of introducing rebates to exporters.

[17] The European commission suggests using the electricity mix of the exporter country, which may be difficult to implement and subject to contentious issues of energy subsidisation.

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

[19] The model also accounts for trade policies, based on highly disaggregated databases of the *ad valorem* equivalents of tariff and non tariff protection.

compensating carbon taxes at the border of Annex B countries (before the US opt out).[20] 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.[21] 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.[22] 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.[23] 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. 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 partners could take if considering the mechanism as not compliant with WTO rules.

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

[20] 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".

[21] 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.

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

[23] 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).

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 proposal of the Commission made in July 2021 is backed by an impact assessment report using the JRC-GEM-E3 model.

We contribute to this literature in four ways. First, we highlight policy options that sound to us like WTO-compatible. Second, we rely on a dynamic baseline of the world economy accounting for unconditional NDCs associated with the Paris agreement and for the effective implementation of a carbon price at the national level in third countries. Third, on the modelling side, we take stock of the intermediate versus final nature of traded goods, which helps tracking the consequences of various approaches to the CBAM along the value chains. Lastly, and 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. A consequence is the adjustment of this price to the introduction of the CBAM, with cascading consequences for ETS producers and their downstream clients.

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 sectoral 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.[24]

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.

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.

Trade is represented with two different Armington structures, one for final consumption and one for trade in intermediates. This double structure explicitly accounts for GVCs. In both structures, domestic and imported goods are imperfectly substitutable, as are imported goods from different origins.[25] 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

[24]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.

[25]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.

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.[26] 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 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). 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

[26]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.

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) (see details in Appendix A.1). 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 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.[27] 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".[28][29] Free allowances are preserved until 2040 in our baseline scenario and phased out when

[27]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, Liechestein and Iceland implement their commitments but in a parallel system, not connected to the EU ETS.

[28]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.

[29]Considering the sectoral 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 XXX for details on the representation of free allowances in the MIRAGE

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.[30]

For all other countries we consider all the *unconditional* commitments, and disregard conditional ones, as reported in the National Determined Contribution interim registry of the United Nations Framework Convention on Climate Change (UNFCC) at the COP26.[31] 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,[32] 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.[33]

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

model.

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

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

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

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

meet this target.[34] 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.[35]

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

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.

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

[34] 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.

[35] The calculation of effective carbon prices raises methodological issues. OCDE (2021) is a first attempt.

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 this second step we also update the tariff protection to its level of 2014[36] and represent – in a stylized way – the most recently signed or negotiated trade agreements: the Comprehensive and Progressive Agreement for Trans-Pacific Partnership (CPTPP), the EU-Japan Economic Partnership Agreement, the Comprehensive Economic and Trade Agreement between the EU and Canada and Brexit.[37] For all the new trade agreements, we remove all the tariffs but leave the NTMs unchanged. 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.[38] 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, updating trade protection and 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

[36]We do not consider changes in the MFN rates following 2014. In particular, the decreases in MFN tariffs implemented by China in 2018 and 2019 are neither taken into account in the baseline nor in the policy scenarios.

[37]We represent a soft Brexit by leaving the tariffs applied by the UK and the EU unchanged, while increasing their bilateral NTMs to halve the preferential access of the UK to the EU market, and reciprocally.

[38]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.

simultaneous introduction of CBAM and phase-out of free allowances, as detailed in the next section.

1.5 Scenarios

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.[39] 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 articulate the ETS market with a compensation at the border that should remain WTO-compatible. The practical implementation issues concern i) the maintenance or termination of the free allocation of allowances to the industries of the ETS; 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? The Commission is more affirmative than the Parliament on that front. But consistent with the Parliament, this principle of substitution being affirmed, the proposed implementation of the CBAM is progressive, over ten years, while free allowances would be progressively phased out in parallel. We adopt this approach in three of our scenarios. However, WTO compatibility of such approach is an open issue and this approach may evolve after consultations with main trading partners. Therefore, in Scenario 3 we explore the consequences of a one-off CBAM with free allowances being withdrawn simultaneously.

What scope? The European Parliament 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.[40] The pro-

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

[40] "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 (...)".

posal 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".[41] 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.

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 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.[42] 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. 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

[41] 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.

[42] 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.

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 and the Commission favor the purchase of emission allowances by European importers (without excluding the principle of a tax, but which would require a unanimous vote in the Council, as it is a fiscal measure). 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.[43] If the price is fixed, then the quantities of allowances on the second market adjust accordingly.[44]

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.[45] 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.

What restitution? Rebating to exporters the cost of the permits they had to acquire on the ETS market is an option. 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.[46] However, rebating has an undesirable consequence: European

[43] Garicano (2021) details the choices of the Parliament and explains the envisaged gradual phasing-out of free allowances.

[44] 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".

[45] 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.

[46] 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

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. Note that even if reduced, the incentive provided by a rebate is larger than the one provided by fully free allowances. The wording of the text adopted by the Parliament remains ambiguous but reflects limited support for the idea of a refund to European exporters that could be interpreted as an export subsidy for carbon products.[47] The Commission proposal carefully disregards export rebates to ensure WTO compatibility. In the absence of a refund to exporters, CBAM cannot therefore be considered equivalent to a consumption tax.

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 4 scenarios summarized in Table 1. In all scenarios the CBAM is applied on all sectors covered by the ETS.[48] 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. Whatever the scenario, there is no export rebate. The outcomes of these four scenarios will be compared to a baseline in which free allowances are maintained.

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 as a reference. This is the simplest approach to implement but also the one that potentially reduces leakages of the European policy the least.

In the second scenario, the CBAM also compensates the indirect emissions induced by the generation of electricity used in the production process. The reference for emissions related to electricity generation remains the EU, as in Scenario 1. Offsetting also the emissions induced by the production of the electricity used in the production process of the imported product is an additional step to further reduce leakage. This however adds complexity in terms of reporting, and we disregard this option. This indeed reduces the impact of this scenario.

While the CBAM is phased in progressively over a ten-year period in the two first scenarios, the

tax when selling to European consumers, while no producer (European or not) pays the tax when serving third-country consumers.

[47] 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; stresses that (..) any form of potential export support should be transparent, proportionate and not lead to any kind of competitive advantages for EU exporting industries in third countries”.

[48] 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.

Table 1: Scenarios

Scen.	Scope	Emissions	Tax base	SDT	End of free allow.
S1	All ETS sect.	Direct	EU	Yes	2035
S2	All ETS sect.	**Direct + indirect**	EU	Yes	2035
S3	All ETS sect.	Direct	EU	Yes	**2025**
S4	All ETS sect.	Direct	**Exporter**	Yes	2035

third scenario reproduces Scenario 1 but implements the CBAM fully in 2026 (and thus abolishing the free allowances in 2026 as well). The third scenario may ensure WTO compatibility better than the first, but at the cost of an abrupt end to free allowances in 2026 that may be disruptive for the sectors concerned.

The last scenario differs from the first in terms of reference emissions: we consider the emissions of 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. In this fourth scenario, CBAM is introduced (free allowances are phased-out) over a period of 10 years.

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

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 package, 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). 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. In our four 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 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 (carbon sinks 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 4 including the respective assumptions on the pace of free allowances phase-out.

The implementation of the European NDCs, without free allowances generates cumulated leakages amounting to 18.5 Gt of CO_2 eq. over the period 2021-2040. Free allowances reduce these leakages by a third. Substituting CBAM for free allowances, regardless of its design, further reduces leakage, by up to two-thirds in Scenario 4, compared to the situation without free allowances. Scenario 4 is more efficient than scenario 1, but the difference is of second order (1 Gt in cumulative terms over the period considered).

It is important to note that, even if the reduction in EU leakages is large in relative terms, it only has a limited impact on *global* emissions, which are those that are actually at stake to mitigate climate change. Global emissions would be reduced by -1% in the best case, in Scenario 4. Practically, in 20 years, the implementation of the CBAM would allow to reduce the leakages of the "Fit for 55" package by an amount equivalent to six months of emissions by China, or 2 years of emissions by the

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	18.5	62.1
Paris Ag., free allowances in EU ETS	12.4	41.4
Scenario 1	7.6	25.4
Scenario 2	7.5	25.0
Scenario 3	6.7	22.5
Scenario 4	6.6	22.1

Note: cumulated emissions over the period 2021-204.
Source: MIRAGE-VA, calculations by the authors.

EU, at their 2020 level. The small relative size in the reduction of global emissions achieved by the CBAM is related to the fact that the EU is presently responsible of 10% of the global emissions (and even less by 2040) only.

However, achieving this environmental goal has an economic cost, the complex mechanisms of which we now detail. Table 3 provides a summary of the main macroeconomic impacts of our four 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 capping their emissions according to those NDCs. Free allowances on the ETS market are maintained in this baseline. Therefore, the economic and environmental impacts of the modelled CBAM are the result of the substitution of CBAM for free allowances. The first column 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 as reference, and exempting LDCs in the name of SDT. The second column compensates also the indirect emissions linked to the generation of electricity used in the production process, relying again on average EU emissions for this additional tier. The third column implements the CBAM as a one-off, in 2026. The fourth column replicates the first, but using as a reference the average emission in the exporter country.[49] 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 free allowances and the CBAM is fully implemented, in our four scenarios. Therefore we expect differences in economic and environmental impacts to proceed mainly from the reference emissions used for compensation. The indirect emissions induced by the electricity mix in Scenario 2 should make the difference with Scenario 1, while the use of the direct emissions of the exporting country instead of the EU average emissions should make Scenario 4 more

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

Table 3: Impact of the CBAM in EU

	CBAM (1)	+ Indir.emiss. (2)	+ free all. end in 2026 (3)	+ ref. exp (4)
GDP	−1.4	−1.4	−1.5	−1.6
Exports				
Exports int. goods	−7.0	−7.6	−7.2	−9.5
Exports final goods	−2.7	−3.6	−2.5	−6.6
Imports				
Imports int. goods	−3.7	−4.8	−3.6	−8.6
Imports final goods	−2.4	−2.5	−2.6	−2.4
Carbon price ETS	10.8	11.6	10.2	15.4

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.

effective in terms of leakage reduction; differences between scenarios 1 and 3 are mainly expected to come from the differences in the dynamic path towards 2040.

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 4 imposes a much larger toll on European intermediate imports (−8.6%) than Scenario 1 (−3.7%). The reason is that we change emissions used as a reference for compensation. We will see below which exporters and sectors are most affected. In contrast, Scenario 3 is not more effective in reducing imports than Scenario 1: implementing CBAM in one go in 2026 makes no difference in 2040 as we have returned to a new equilibrium. The difference would instead be visible at an interim date: in 2032, for instance, intermediate imports would be down by −2.5% in scenario 1 and by −3.2% in Scenario 3.

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 10.8% 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. The logic is as follows. EU ETS producers benefit from the protection of CBAM in the European market. They therefore increase their production to meet the resulting increased 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. The price of allowances increases slightly more in the more protective Scenario 2 (11.6%). In Scenario 3 there is barely any difference with Scenario 1. More precisely, the price increases we observe in Table 3 results from two opposite effects: as detailed, on the one hand, the CBAM raises carbon prices on the ETS market. On the other hand, the removal of free allowances tend to *decrease* 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.

The induced increase in the price of electricity is an additional cost for European producers (and 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 resulting from the CBAM. The resulting increase in European production costs translates into a loss of competitiveness for European intermediate and final products on third-country markets. 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.[50] A more restrictive CBAM, using as a reference the exporter country emissions, will also 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. The loss of competitiveness when free allowances are substituted for CBAM, in the absence of rebates to exporters, therefore results in lower exports, which leads to additional leakage.

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 −2.7% to −6.6% below the baseline in our scenarios. But the drop in exports in Scenario 1 (resp. Scenario 4) reaches −32.1% (−35.3%) for the chemical industry, −30.6% (−32.1%) for metal products and −36.3% (−37.7%) for other energy intensive manufactured products. Downstream producers of final goods are also affected, although export declines of lower magnitude, but spread across several industries, and increasing with the stringency of border carbon adjustment, so that the overall impact of Scenario 4 on final goods exports to third countries peaks at −6.6 percent in Scenario

[50] 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.

4. These drops in exports will partially offset the reduction in leakages obtained on the import side as a result of the CBAM.

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 −1.4 to −1.6 percent drop in the EU 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. 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 4 imposes a higher toll on trade. In Scenario 4, the net negative impact on ETS sectors is simply alleviated as shown below. Another pace of introduction of the CBAM could bring another difference: a comparison of outcomes of Scenario 1 and 3 in 2032 shows that the one-off introduction of CBAM has more pronounced transitory effects on relative prices and trade, subsuming into respectively a −0.7% and −0.8% drop in the 2032 EU GDP, relative to the baseline, in scenarios 1 and 3.

The impact of changes in domestic demand (which is reduced by the higher price of carbon in domestic products, directly or indirectly through the price of intermediate consumption), combined with the change in exports (negatively affected by the higher cost of carbon intensive intermediate consumption and by the loss of free allowances in ETS sectors subject to leakages) and imports (negatively affected by the CBAM in ETS sectors, but positively affected by the loss of competitiveness of downstream sectors in the EU), subsumes in variations in the sectoral value added. The other mechanisms at play are energy substitution in the EU, both in industry and in the rest of the economy, and the "servicification" of the economy, which is the other side of the transition to a low-carbon economy. We expect an "electrification" of the economy and an increase in the value added of services.

All these impacts of the CBAM in our first scenario nicely show up in Figure 1, which shows the variation in 2040 (with respect to the baseline), of the value added of 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 (+37%, which corresponds to USD + 52 bn) because of higher demand and higher prices. The negative impact on downstream industries, intensive in intermediate products sourced from ETS sectors, such as vehicles (−2.6%, i.e. USD −4.8 bn), electronics (−1.4%, i.e. USD −1.9 bn), textile (−1.5%, i.e. USD −1.3 bn) or other manufactured products (−1.5%, i.e. USD −5.3 bn) 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 and are not subject to the CBAM, while EU competitors pay their intermediate consumption at a higher price because of CBAM. Rather unexpected is the deleterious impact of the CBAM on carbon intensive industries (metals: −11.0%, chemicals: −18.9%, other energy intensive industries: −7.7%). This large negative impact on upstream industries is the net of two opposing effects: on the positive side, the protection offered by CBAM on the European market (which is possibly smaller than the one by free allowances, depending on the design of CBAM) ; 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 (which CBAM replaces) 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. This is done in Figure 2 which compares the outcome of Scenario 4 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. 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 4 than in Scenario 1, sectors using ETS products as inputs are now more severely affected by CBAM in Scenario 4 as shown in the left part of Figure 2. For instance, compared to Scenario 1, the vehicle sector loses more than USD 10 billion in value added.

Figure A2 in the Appendix is constructed on the same principles as 1 and illustrates the impact of the CBAM when indirect emissions are added to direct ones. Differences with Scenario 1 are marginal because we use the EU average energy mix to produce electricity as a reference for the CBAM. We illustrate in Figure A3 in the Appendix the impact of a carbon offset similar to Scenario 1, but with the end of free allowances in 2026 and the implementation of a one-off carbon offset. As we observe the deviation from the baseline in 2040, the outcome of Scenario 3 is qualitatively to Scenario 1, but what matters is the transition between 2026 and 2040, and hence the cumulated impact of this scenario in terms of emissions.

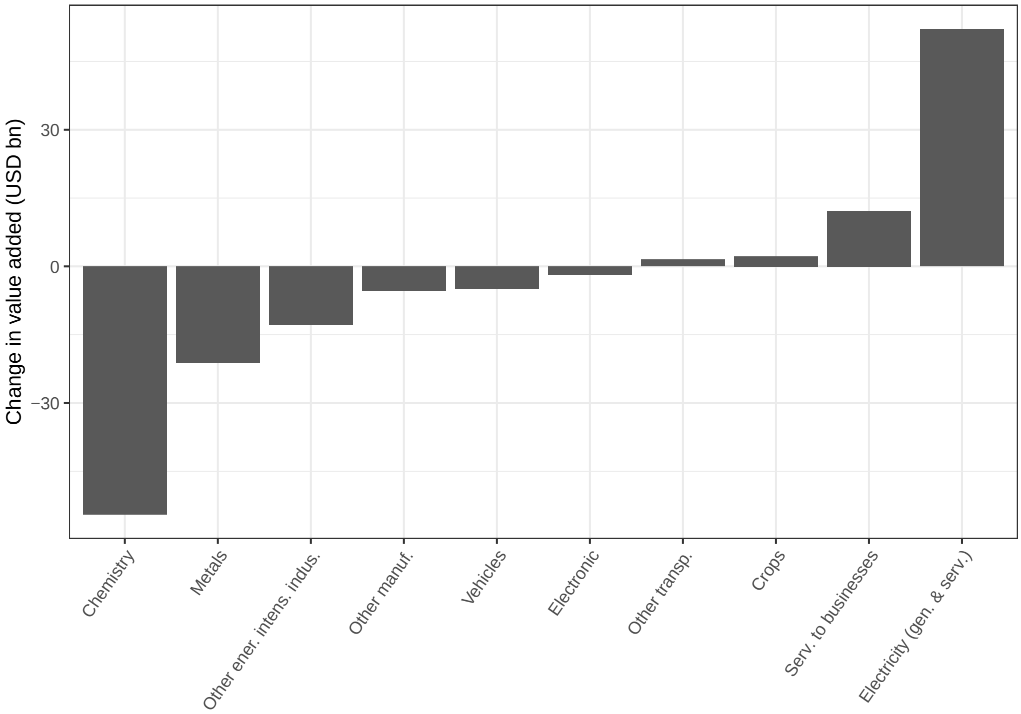
If we now turn to the possible impacts of the European CBAM on third countries, we first notice that the EU enjoys a positive terms of trade effect when introducing the CBAM. It varies between 0.7% in the first scenario and 0.9% in Scenario 4 where the emissions of the exporter country are chosen as 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 from the exporters (Balistreri, Kaffine & Yonezawa 2019). This may also pose difficulties for the acceptance of the CBAM by WTO members. Incidentally, the EU tariff revenues significantly increase when replacing free allowances by a CBAM:[51] from +25% in Scenarios 1 and 2 up to +51% in scenario 4, with respect to our reference scenario. The direct integration of such a large new revenue to the European budget, without a clear earmarking to environmental purposes, constitutes a second WTO-compatibility issue.

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 20 billion USD cut in exports towards the EU. However, EU exports to the USA are also down, by 9%, and exports of final goods also, with CBAM being ultimately the source of a bilateral trade imbalance *favourable* to the USA. A similar pattern is observed with China or Japan, although of a much smaller magnitude. India is negatively affected but the absolute amounts are limited. 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 4 to Scenario 1, Scenario 4 having potentially the largest impact on trade. Comparison with other scenarios is provided in the Appendix. The main finding is that India

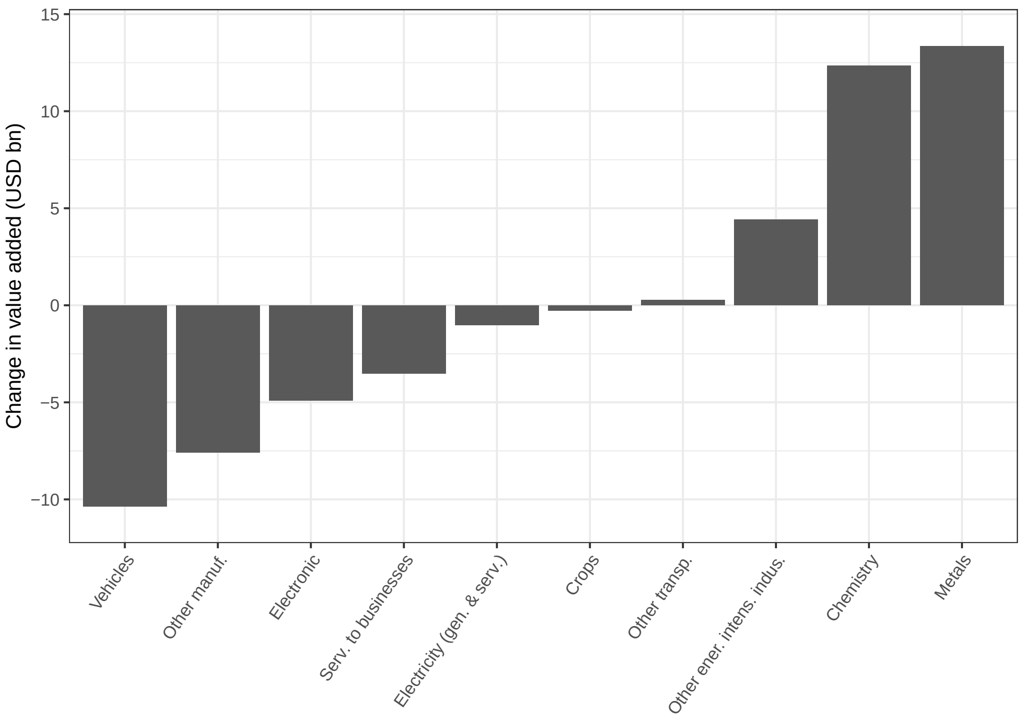
[51] The increase in tariff revenue detailed here is the result of general equilibrium effects. It arises from the border adjustment but also from the change in the European trade level and composition, both in terms of products and in terms of origins.

Figure 1: Impact of the CBAM on sectoral value added (*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.

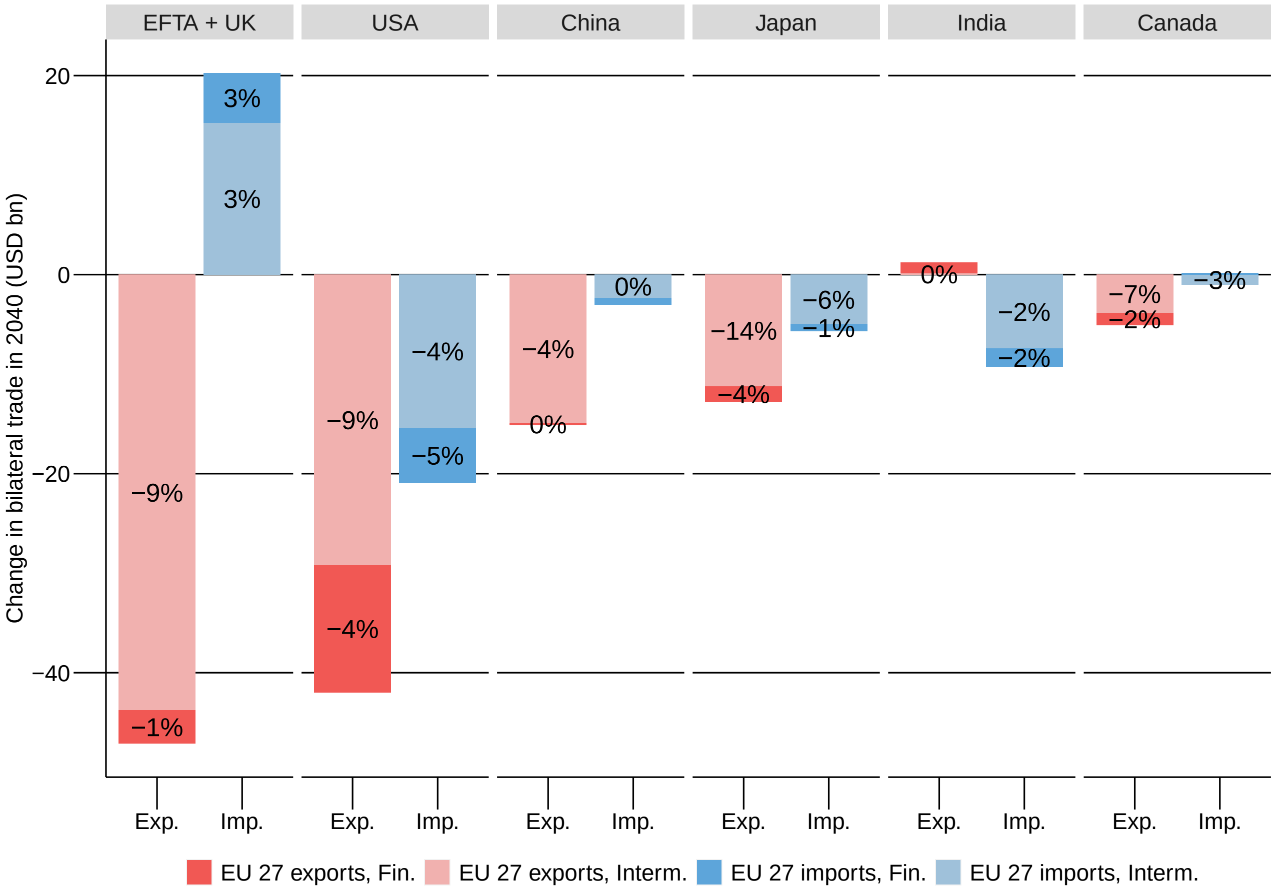
Figure 2: Impact of the CBAM *based on the emissions by the exporters* on sectoral value added (Scenario 4 *vs* Scenario 1, in 2040)



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.

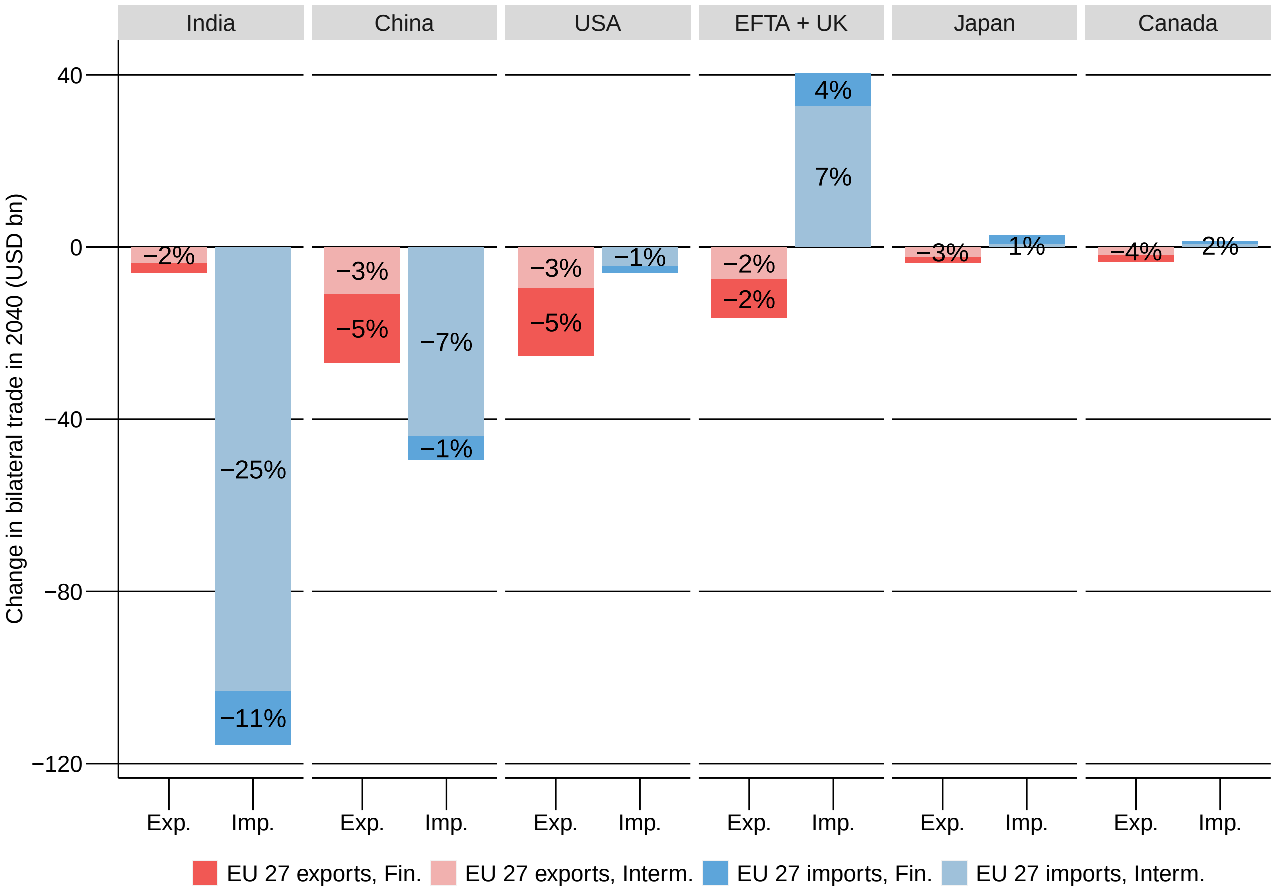
is deeply affected by the change in baseline emissions, with an additional 25% drop of its exports of intermediate products towards the EU, which amounts to some USD 100 billion. China is also affected, but the magnitude of the additional loss is half that simulated for India. It is interesting to note that Canada almost recovers its export losses, as using the baseline emissions as a reference is favourable, in relative terms, to this country committed to reducing its emissions.

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 4 *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

Taking stock of the move of the European Parliament, the Commission and the Council towards a compensation of carbon at the borders of the EU, this paper simulates the environmental and economic impact of different options of implementation of this mechanism. We explore the impacts on leakages, GDP, trade, sectoral value added. 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 implements free allowances to ETS sectors exposed to carbon leakage. The counterfactuals all consider a CBAM that replaces free allowances. They consist in i) a CBAM limited to direct emissions and based on EU reference emissions, gradually phased-in between 2026 and 2035; ii) augmented by indirect emissions in the electricity sector; iii) implemented in a one-go at the onset of the mechanism, in 2026; iv) or alternatively augmented by an alternative choice of reference emissions, namely the exporter country's emissions (and still gradually implemented). 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. 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 efficient 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: the price of ETS allowances increase, the cost of intermediate consumption of ETS products increases for downstream industries, and ETS producers are no longer protected by free allowances on their export markets.

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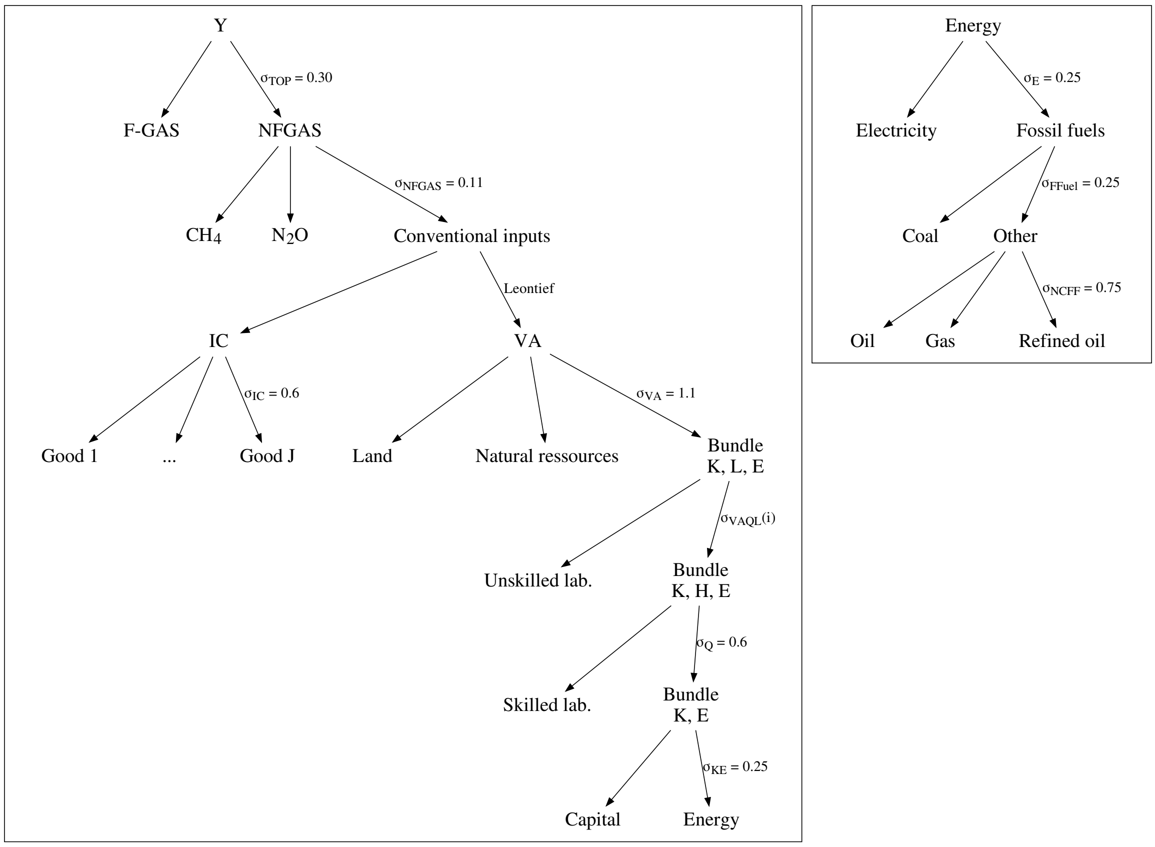
A Appendix

A.1 The production function in MIRAGE-VA

Figure A1 shows the 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.

Figure A1: Structure of the production function for manufacture sectors and services in MIRAGE-VA



A.2 Free allowances

In MIRAGE-e, the price of GHG emisions, 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
Clombia 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 are may be used in some figures and tables of the paper.

Table A2: Sectoral aggregation

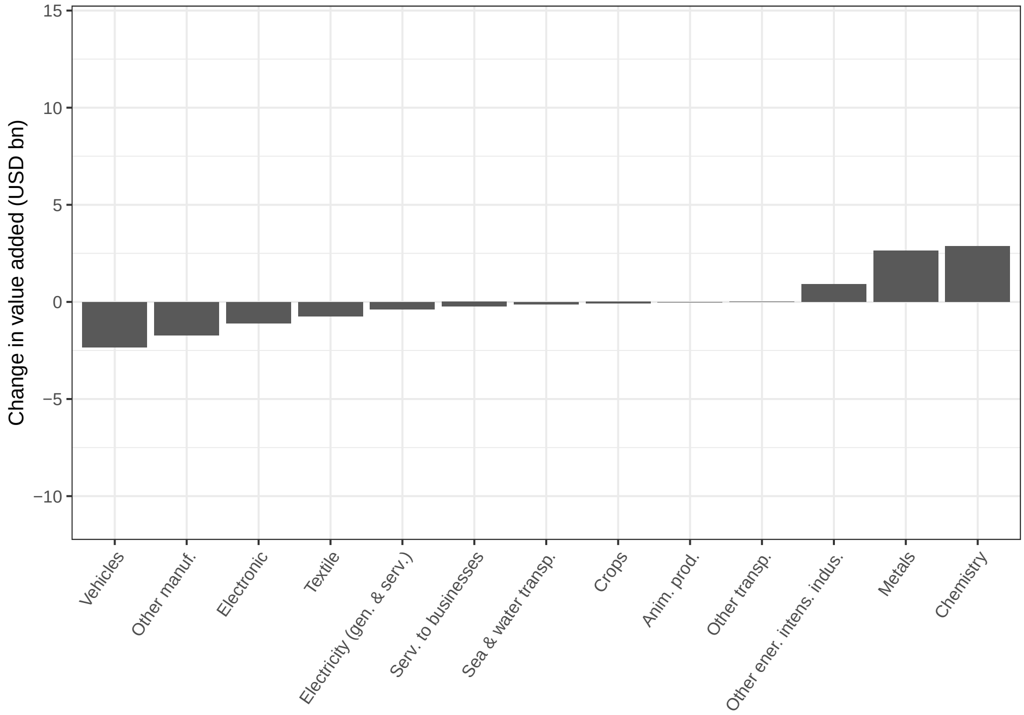
MIRAGE	Aggreg. code	GTAP sector
Air transp.	AirTransp	atp
Beverages and tobacco	BevTob	b_t
Business services	BusiServ	trd, cmn, ofi, ins, rsa, obs
Cattle and other animal productions	AnimProd	ctl, oap, rmk, wol, fsh, cmt, omt, mil
Chemistry	Chemistry	chm, bph, rpp
Coal	Coal	coa
Crops	Crops	pdr, wht,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

A.4 Additional results

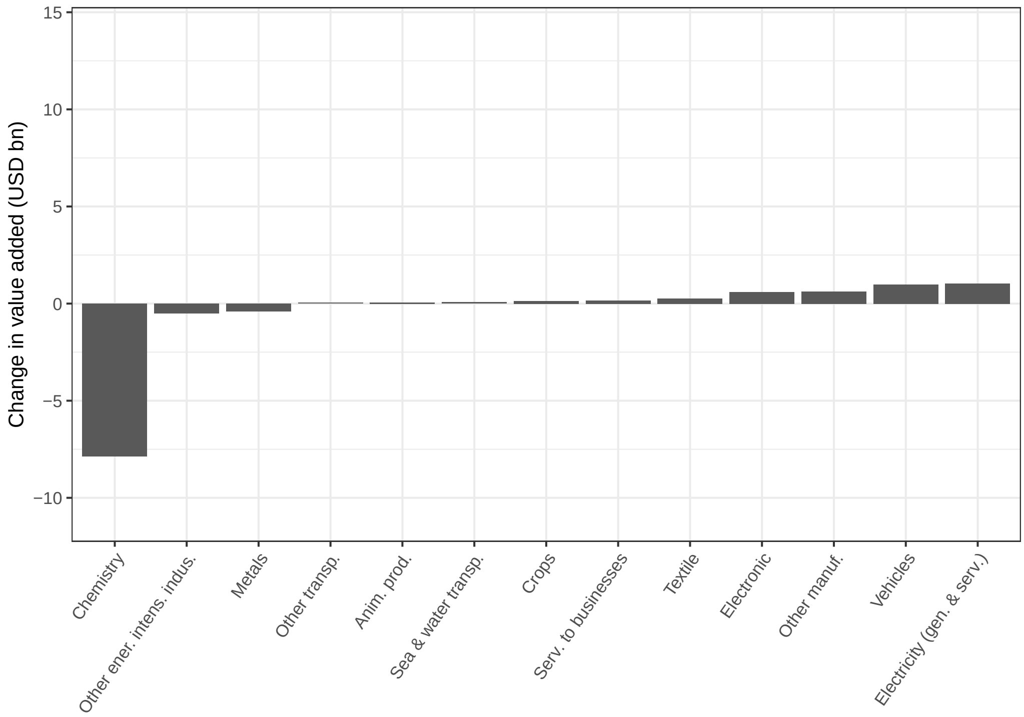
A.4.1 Sectoral value added

Figure A2: Impact of the CBAM *covering also indirect emissions* on sectoral value added (*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.

Figure A3: Impact of the CBAM *with free allowances ending in 2026* on sectoral value added (*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.

A.4.2 Sectoral impacts on trade and production costs

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

	Prod. price	Imports		Exports	
	(%)	(USD bn.)	(%)	(USD bn.)	(%)
Sectors covered by the CBAM					
Chemistry	3.3	−60.8	−5.1	−317.4	−26.9
Electricity (incl. distribution)	3.1	−169.3	−65.2	9.4	65.2
Metal products	3.2	−3.1	−0.5	−110.7	−21.5
Other manuf. energy intensive	6.1	−1.8	−0.9	−64.5	−23.0
Primary sectors					
Cattle and other animal productions	−1.2	−0.9	−0.7	5.5	2.9
Crops	−1.3	−1.3	−1.0	3.9	2.9
Forestry	−1.7	−0.2	−2.9	0.5	3.4
Other primary products	−0.4	−5.3	−9.0	4.7	3.4
Secondary sectors					
Electronics	0.3	−18.1	−1.9	−39.9	−3.0
Other food prodducts	−0.8	−4.8	−1.8	4.2	1.6
Other manufactured products	0.0	−17.3	−2.1	−17.7	−1.4
Textile	−0.1	−11.0	−2.1	−6.1	−1.4
Vehicles	0.1	−17.8	−1.5	−8.6	−1.6
Tertiary sectors					
Air transp.	−0.6	−2.0	−2.1	2.1	1.6
Business services	−1.6	−35.3	−3.3	52.3	3.9
Oth. transp.	−1.4	−5.9	−3.4	7.1	3.8
Other services	−1.4	−8.3	−3.1	16.5	3.8
Water transp.	−0.8	−0.7	−1.1	1.5	1.8

Notes: Except for production prices, changes are in volume (price effects excluded), with respect to the reference scenario, in 2040. Sectors appear are ranked by decreasing realtive 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.

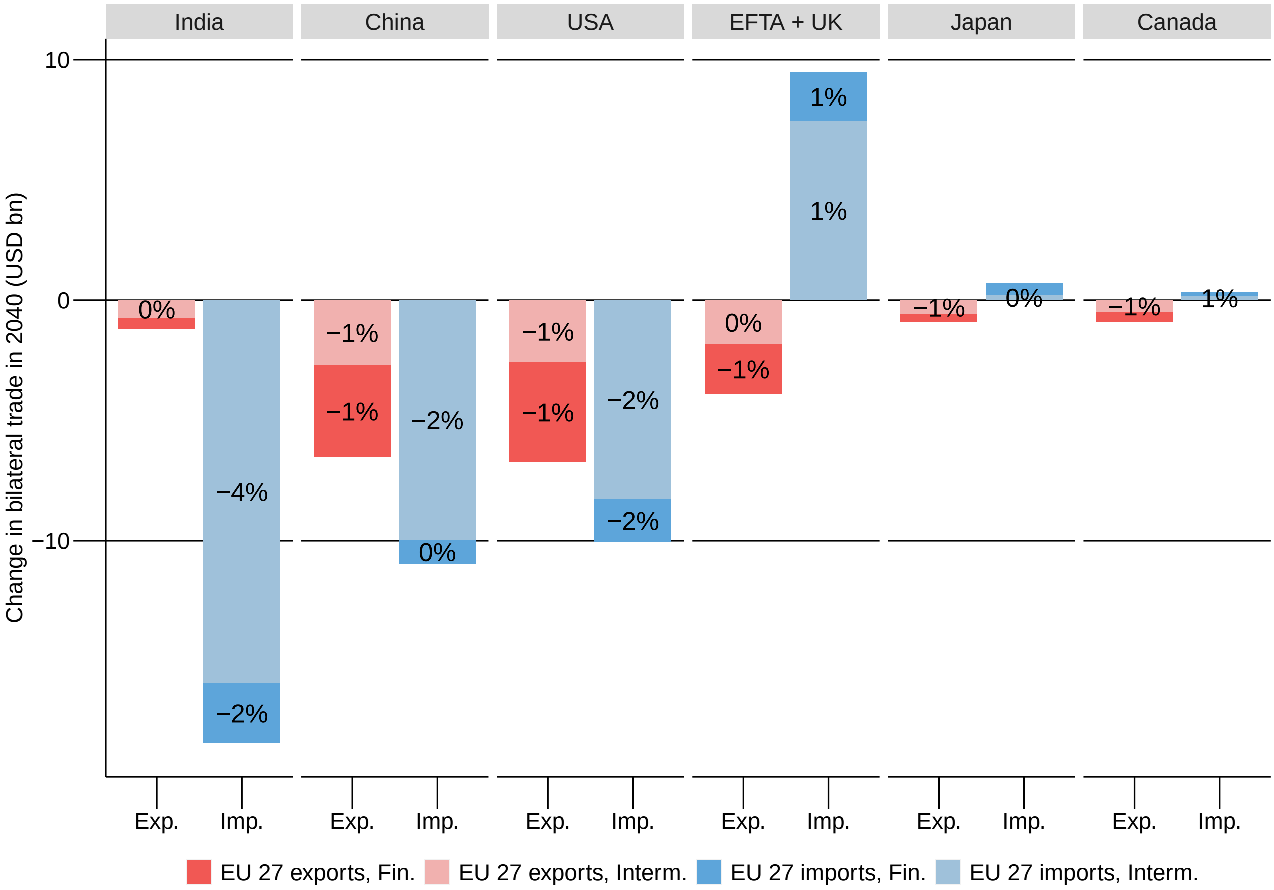
Table A4: Impact of the CBAM on European sectors – Scenario 4

	Prod. price	Imports		Exports	
	(%)	(USD bn.)	(%)	(USD bn.)	(%)
Sectors covered by the CBAM					
Chemistry	4.6	−120.9	−10.2	−280.0	−23.8
Electricity (incl. distribution)	4.7	−159.2	−61.3	8.2	56.6
Metal products	4.2	−65.8	−10.6	−74.4	−14.5
Other manuf. energy intensive	6.9	−16.1	−7.8	−57.5	−20.5
Primary sectors					
Cattle and other animal productions	−1.0	−0.7	−0.5	5.0	2.6
Crops	−1.2	−1.0	−0.8	3.4	2.5
Forestry	−1.7	−0.2	−3.2	0.4	3.2
Other primary products	−0.3	−3.3	−5.6	2.6	1.9
Secondary sectors					
Beverages and tobacco	−0.2	−1.0	−1.4	−0.1	−0.1
Electronics	0.9	−27.2	−2.9	−130.1	−9.8
Other food prodducts	−0.5	−3.8	−1.4	2.5	1.0
Other manufactured products	0.6	−14.8	−1.8	−60.8	−4.8
Textile	0.5	−11.3	−2.1	−27.5	−6.4
Vehicles	0.5	−21.7	−1.8	−35.8	−6.6
Tertiary sectors					
Air transp.	−0.7	−1.8	−1.8	2.4	1.8
Business services	−1.4	−31.7	−2.9	45.8	3.4
Oth. transp.	−1.4	−5.1	−2.9	6.9	3.7
Other services	−1.2	−6.9	−2.6	12.7	3.0
Water transp.	−0.8	−0.7	−1.1	1.3	1.6

Notes: Except for production prices, changes are in volume (price effects excluded), with respect to the reference scenario, in 2040. Sectors appear are ranked by decreasing realtive 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.

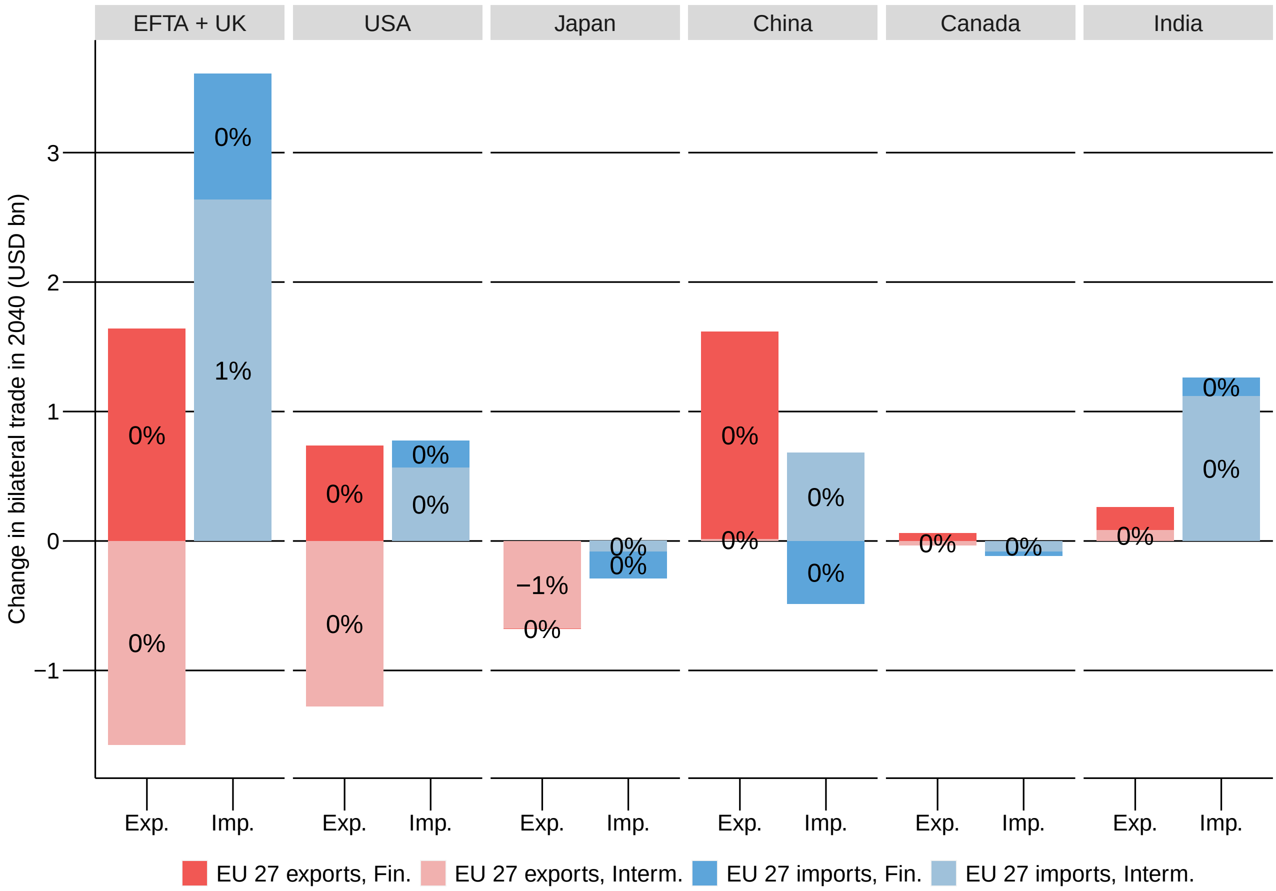
A.4.3 Bilateral trade

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.

Figure A5: 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.

A.4.4 Sectoral impacts on third countries

Table A5: Impact of the CBAM on Chinese sectors – Scenario 4

	Value added		Imports		Exports	
	(USD bn.)	(%)	(USD bn.)	(%)	(USD bn.)	(%)
Sectors covered by the CBAM						
Chemistry	2.4	0.3	−4.9	−1.3	3.8	0.4
Metal products	0.6	0.1	−6.5	−2.3	−12.2	−1.8
Other manuf. energy intensive	0.5	0.1	−3.6	−4.5	−2.4	−1.6
Electricity (incl. distribution)	0.2	0.0	−0.2	−3.3	−1.0	−27.7
Primary sectors						
Coal	−0.2	−0.1	1.7	1.4	−0.0	−0.4
Cattle and other animal productions	−0.4	−0.1	1.9	1.3	−0.1	−1.2
Crops	−0.6	−0.1	2.3	0.4	−0.0	−0.4
Secondary sectors						
Electronics	3.3	0.6	−12.9	−3.2	5.4	1.7
Other manufactured products	1.8	0.2	−3.8	−0.6	7.6	0.7
Textile	0.6	0.2	−0.8	−0.6	1.6	0.2
Vehicles	−0.7	−0.1	8.7	0.6	−4.3	−0.1
Tertiary sectors						
Other services	0.9	0.0	1.9	1.2	−2.3	−2.0
Air transp.	−0.2	−0.4	0.3	0.8	−0.3	−1.1
Water transp.	−0.4	−0.4	0.0	0.7	−0.1	−1.4
Business services	−2.6	−0.0	7.8	1.5	−3.3	−1.8

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 4

	Value added		Imports		Exports	
	(USD bn.)	(%)	(USD bn.)	(%)	(USD bn.)	(%)
Sectors covered by the CBAM						
Chemistry	9.6	2.3	−16.8	−2.9	18.1	3.5
Metal products	3.6	1.5	−4.1	−1.6	7.3	3.9
Other manuf. energy intensive	2.5	0.9	−2.8	−5.4	5.7	4.1
Electricity (incl. distribution)	−3.3	−1.3	−0.1	−6.5	−11.2	−26.4
Primary sectors						
Coal	−0.3	−0.7	0.2	18.7	−0.2	−0.5
Oil	−0.6	−0.2	0.3	0.3	−0.2	−1.2
Gas	−6.8	−5.8	−1.2	−6.7	−26.3	−12.4
Secondary sectors						
Electronics	2.6	1.3	−7.9	−0.7	9.3	2.9
Other manufactured products	1.8	0.4	−4.6	−0.6	4.0	1.2
Vehicles	0.4	0.4	−0.4	−0.0	0.9	0.8
Textile	0.2	0.2	−0.4	−0.1	0.3	0.5
Tertiary sectors						
Air transp.	−0.4	−0.4	0.4	0.6	−0.4	−0.7
Oth. transp.	−0.5	−0.1	0.9	1.2	−1.1	−1.4
Business services	−3.1	−0.0	5.2	1.0	−4.6	−1.6
Other services	−9.1	−0.1	0.9	0.7	−3.2	−1.1

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.