Analyzing CBAM's Effects on the Supply Chain: Green Growth or Green Inflation?*

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January 2025

Abstract

This study examines the economic implications of the Carbon Border Adjustment Mechanism (CBAM). As an implicit carbon tax at EU borders, the CBAM could be a powerful tool for achieving carbon neutrality by complementing the European Union Emissions Trading System (EU ETS). However, this instrument may generate supply chain distortions with economic consequences diverging widely across countries and sectors in terms of carbon costs and inflationary pressures. If the policy is yet to be implemented, many uncertainties remain regarding the right CBAM design, notably concerning product coverage and carbon intensity estimations. This paper addresses these challenges by developing an import-based price model based on Leontief's input-output framework. Several scenarios are tested to account for different CBAM designs and are evaluated regarding economic, social and environmental impacts. The key contribution of the study lies in accurately defining sectoral cost pass-through rates, which capture supply chain transmission effects that other models often overlook.

Keywords: Climate change, carbon pricing, decarbonization policy instrument, CBAM, carbon tax, emissions trading scheme, net-zero emissions, negative externality, input-output analysis, social welfare.

JEL Classification: Q5, H2, E3.

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*The authors are very grateful to ??? for their helpful comments. The opinions expressed in this research are those of the authors and are not meant to represent the opinions or official positions of Amundi Asset Management.

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1 Introduction

The creation of an instrument such as the Carbon Border Adjustment Mechanism (CBAM) echoes Europe's ambition to become a reference model for the environmental transition toward a carbon-neutral economy. Underpinned by the Green Deal, Europe intends to keep the promises made under the Paris Agreement, that is, reducing net greenhouse gas (GHG) emissions by at least 55% by 2030 compared to 1990 levels to keep global warming below 2°C. Drawing on years of experience in reform and economic planning through its environmental tariff mechanism, namely, the European Emission Trading Scheme (EU ETS), Europe will nonetheless face a number of obstacles, for which CBAM could well prove to be the solution.

The ambitions of the European Green Deal for the environmental transition call for a major deployment of public policies aimed at lowering emissions by cutting domestic energy consumption while maximizing its efficient use (European Commission, 2019). Achieving this goal will require an overhaul of the European carbon pricing system, notably by creating a new market for previously excluded sectors (*i.e.*, buildings and transport) and by adjusting the stringency of the EU ETS (Pietzcker *et al.*, 2021). This involves reinforcing the key principles of carbon pricing: expanding the emissions coverage while sustaining a high carbon price. A key step toward achieving the EU ETS stringency goal would be to reassess existing exemptions, particularly the persistent over-allocation of free allowances (Martin *et al.*, 2014; De Vivo and Marin, 2018; Grubb *et al.*, 2022).

In a global context where carbon pricing policies are yet to be the norm, deviant behaviors could undermine these efforts (Felder and Rutherford, 1993; Stiglitz *et al.*, 2017). Economists fear a rise in carbon leakage —the shift of production (and therefore emissions) to regions with less stringent environmental regulations— within a European economy already weakened by international competition as reckoned by Draghi (2024). While evidence of carbon leakage has been limited so far at the European level (Joltreau and Sommerfeld, 2019; Fontagné and Schubert, 2023), it could surge if regulatory constraints are tightened. In this light, border carbon pricing takes the place of free allowances by discouraging European companies from offshoring their production while maintaining decarbonization incentives. Fundamentally, any regulated product imported into Europe should be subject to carbon pricing under conditions equivalent to those applied to domestic production (European Commission, 2023). In addition, through the implementation of this instrument, Europe aims to narrow the gap in global carbon pricing, or "level the playing field" between EU industry and foreign producers.

Nevertheless, the CBAM directive may face several challenges. Historically, the primary challenge has been ensuring alignment with World Trade Organization (WTO) rules, which mandate non-discrimination and prohibit preferential treatment (Fontagné and Schubert, 2023). As a varying import tax according to foreign carbon pricing level, the regulation could be in contradiction with those principles (Horn and Mavroidis, 2011; Mehling *et al.*, 2019). The CBAM also raises questions regarding fairness for emerging countries and whether it effectively transfers a substantial share of the transition costs onto them (Cosbey, 2008; Holmes *et al.*, 2011). Imposing additional costs on imported goods would likely increase demand for domestic output and reduce import volumes. Developing countries with export-led growth patterns are likely to voice such concerns (Boute, 2024; Böhringer *et al.*, 2022) following reduced employment and significant income losses (Magacho *et al.*, 2024; Sun *et al.*, 2024). As reported by the European Commission (2023), further technical challenges may also affect policy effectiveness. For instance, the cascading effects of carbon pricing might extend to downstream sectors of CBAM-covered products, potentially shifting the risk of carbon leakage further along the supply chain. Moreover, CBAM compliance costs depend on certain carbon accounting conventions used to compute emission intensities (European Commission, 2021a). For some products in some regions, obtaining accurate and actual estimates is difficult, leading to reliance on default values. Methodological choices in these calculations can influence the instrument's effectiveness and subsequent costs (Rocchi *et al.*, 2018; Mehling and Ritz, 2020; Zhong and Pei, 2024). Finally, interdependencies within global value chains and pass-through mechanisms could support inflationary pressures.

This study seeks to clarify several of these questions by empirically looking at the global supply chain. We analyze the CBAM using input-output (IO) models, a framework introduced by Leontief (1936) to assess interlinkages between sectors based on their intermediate consumption and final demand. This approach provides a deep understanding of the supply chain and allows for an accurate evaluation of the economic impact of policy measures at both regional and sectoral levels. Drawing on an environmental extension of the Exiobase 3 tables (Stadler *et al.*, 2018), we recreate different scenarios under which CBAM could be implemented. These scenarios unveil different emission computation methodologies and the range of products subject to CBAM (initially iron, steel, aluminium, cement, and fertiliser), particularly focusing on downstream products. Although analyzing CBAM impact on countries with IO models is not new (Rocchi *et al.*, 2018; Schotten *et al.*, 2021; Magacho *et al.*, 2024), we offer a comprehensive methodology to capture the cascading effects of carbon border pricing by incorporating global value chain mechanisms along pass-through mechanisms. In addition, by including social account data, we also highlight the effects of CBAM on employment and income, both in European and non-European regions.

While CBAM-covered products account for roughly 1.24% of global GDP, with nearly half concentrated in China and Europe, preliminary results show a limited impact of CBAM on non-European countries, mainly because the covered goods amounted to €56 bn in 2022, representing just 2% of EU imports. Iron and steel dominate (65% of imports), followed by aluminum (28%), primarily exported by Russia, Africa, and Great Britain, which together account for 15% of combined flows. Although China is the largest producer (48% of CBAM total output) and the main carbon emitter (60% of CBAM global emissions), it ranks only fifth among exporters to Europe. Yet, along with India, China contributes nearly 45% of the total emissions embedded in EU imports, amounting to 107 MtCO_2e in 2022, which is almost 48% of Europe's direct domestic emissions of CBAM-covered production. This is partly due to higher carbon intensity, with iron and steel emitting twice and cement ten times more than in the EU. Breaking down the different emissions scopes, transport activities (upstream) and finished-goods manufacturing (downstream) exhibit the strongest links to these products. Nevertheless, upstream emissions are almost twice as high as downstream emissions.

This article is organized as follows. The second section examines the adoption of CBAM in Europe, emphasizing its various objectives and challenges. In the third section, we present the methodology used to adapt the price model initially proposed by Roncalli and Semet (2024) to incorporate CBAM analyses. The fourth section details our findings. We begin by describing the characteristics of products covered by CBAM, drawing on an analysis of trade flows, carbon emissions, value-added, competitiveness, and labor productivity. Then, we provide the economic and social impacts of the CBAM. We particularly focus on estimating the domestic effects regarding economic costs, inflationary pressure, competitive distortions, and labor disruptions. In the fifth section, we offer our conclusions and a set of policy recommendations.

2 Designing a carbon border adjustment mechanism

2.1 The CBAM in practice

2.1.1 Objectives of the trade regulation

The remedy for carbon leakage There are three possible approaches to addressing the risk of carbon leakage. Historically, the allocation of free allowances has helped offset the risks faced by certain sectors by exempting them from the compliance costs of the pricing system (Jakob, 2021). As climate commitments heterogeneity favors carbon leakage, aligning climate policies through international cooperation would reduce the likelihood of carbon leakage (Eyland and Zaccour, 2014). The idea is built around the concept of a "coalition of the willing" where participants commit to policies that reduce emissions in a more effective and efficient manner than if they were acting individually. This approach is based on the concept of climate clubs (Nordhaus, 2015). The members would implement a uniform carbon price to reach emissions targets, while non-members would face trade penalties or carbon tariffs when trading with club members. Furthermore, by participating in the club, members would enjoy benefits such as access to technology transfers, knowledge sharing, and potential financial support for their green transition (Nordhaus, 2020). In a non-cooperative global context, a final strategy is to reduce regulatory disparities by subjecting imports to the same environmental standards as domestic products through a carbon pricing mechanism at the borders (Markusen, 1975; Hoel, 1996). In light of the significant disparities in Nationally Determined Contributions (NDCs) and carbon pricing mechanisms across countries, the level-playing field argument[1] seems to prevail over the deadlock surrounding free allocations, thus supporting the adoption of the CBAM (Fontagné and Schubert, 2023).

Tightening the climate regulations gap Beyond addressing the risk of carbon leakage, the CBAM should also encourage the adoption of carbon pricing in foreign regions (Marcu *et al.*, 2020; Boute, 2024). Its goal is to ensure that both domestic production and imports are subject to equivalent carbon pricing. The relative price increase should be proportional to the carbon content of the imported product, but only if a comparable regulation has not already priced it. Therefore, imported products subject to an equivalent carbon price should not be affected by the CBAM. By design, the regulation indirectly intends to create incentives for third countries to adopt carbon pricing policies to mitigate emissions (Böhringer *et al.*, 2016; Parry *et al.*, 2021). Additionally, the EU's extensive experience in carbon accounting and clean-technology improvements could support the implementation of carbon pricing in third countries (Perdana and Vielle, 2022). Finally, the CBAM would ultimately result in a loss of revenue for exporting countries, creating incentives to repatriate fiscal revenues for their own economies (Keen *et al.*, 2022; Parry *et al.*, 2021). Thus, the regulation should be seen as part of a global climate effort rather than solely an EU initiative.

2.1.2 Designing an optimal carbon border adjustment mechanism

Scenarios proposal The design of the CBAM should be analyzed in a framework translating the evolving landscape of the EU ETS, notably in concordance with the "Fit for 55" package and the European Green Deal. In other words, the European pathway to reach carbon neutrality depends on external economic factors such as the energy and transport demand in line with population growth, economic and industrial activity dynamics, fuel

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[1] That is bringing uniform conditions and incentives for carbon emission reductions in third countries that should be equivalent to those of domestic producers (European Commission, 2021a).

prices, technology development, and market trends until 2050. Baseline economic scenarios[2] set the scene for the future of the EU ETS, regarding allowances allocation.

As outlined in this section, there is no one-size-fits-all in the CBAM design. Various design features, such as sectoral coverage, embedded emissions estimation, allowance allocation, and payment methods, shape policy outcomes. In many cases, opting for one alternative over another can lead to significant trade-offs that affect the regulation's overall efficiency. Therefore, the European Commission (2021a) proposed several options to gauge the policy's efficiency. Six policy options offer various approaches to five key design features: the depth of the value chain, product coverage, allowances allocation process, type of compliance payment, and embedded emissions assessment. Each option differs compared to the other regarding one or several characteristics. A summary of these options is given in Figure 1.

Option 3 appears as the default option since it shares all of its characteristics with at least one other option. In this framework, the CBAM takes the form of CBAM certificates that the importer must buy on a CBAM allowances market. If the surrendering mechanism is similar to the EU ETS, this market shouldn't be viewed as a cap-and-trade system since it has no cap on emissions and the price is fixed[3]. Options 1 and 6 differ in this perspective. In option 1, the CBAM would apply to CBAM imports through a carbon tax. In option 6, which differs in many aspects compared to other options by integrating both border carbon adjustment and domestic consumption taxation, the payment is an excise duty. Regarding the depth of the value chain, the default coverage includes basic materials and basic materials products (Options 1, 2, 3, and 4). Option 5 enlarges the coverage by also including finished products. By doing so, the option increases the scope of the value chain further down by considering semi- and finished products. Option 6 considers emissions from all consumed products, either coming from domestic production or not. As the CBAM is an alternative to free allowances allocation, most options (Options 1, 2, 3, and 5) are considering a full auctioning of allowances for CBAM sectors in the EU ETS. In option 4, the CBAM implementation is considered alongside a gradual phase-out of free allowances from 2025 to 2035. The CBAM would be introduced in 2025 with its size proportionally getting bigger as the free allowances allocation decreases gradually. The purpose of option 4 is to adjust the implementation of the CBAM by allowing time for CBAM sectors to adapt gradually. Conversely, in option 6, free allowances allocation continues. The different options are split regarding the methodology used to estimate embedded emissions in CBAM compliance.

The majority of options (Options 3, 4, and 5) assume actual carbon intensity to be used for computing the carbon costs of imports. In this case, the importer should report the accurate value of embedded emissions based on the carbon intensity estimation in third countries. Conversely, when the default method is preferred, as in the case of options 1 and 2, the value of the carbon intensity of imported products reflects the EU producers' averages. Compared to any other options, option 6, takes a more advanced approach, going beyond a pure carbon border adjustment mechanism. Imports of basic materials and products

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[2] The baseline scenario known as the EU reference scenario 2020 (Capros *et al.*, 2021), *REF*, sets the projection of macroeconomic aggregates to estimate future energy demand and subsequent GHG emissions pathway. The scenario assumes that ETS allowances allocation is given for free remaining for sectors at high risk of carbon leakage while achieving the reduction target of −40% GHG abatement. The second scenario, known as the *MIX* scenario, accounts for the rising EU climate ambitions and aligns with a gradual decrease of the EU ETS cap in the coming years to achieve the 55% emission reduction goal by 2030. Under this scenario, the free allowances allocation remains the main tool for dealing with the carbon leakage risk. A variant of this scenario assumes a full auctioning of allowances for CBAM sectors, which serves as a reference to test the CBAM counterfactual. The idea is to evaluate the CBAM impact on carbon leakage against other leakage protections.

[3] Setting an emissions cap would influence the EU's trade volumes, whereas allowing a dynamic price could shift carbon costs away from those established by the EU ETS (European Commission, 2023).

Figure 1: Summary of the options considered in the design of the CBAM

Option 1

- **Depth of the value chain**: Basic materials and basic material products
- **Coverage**: Imports only
- **Allocation in the EU ETS**: Full auctioning of CBAM sectors
- **Payment**: Tax on imports
- **Embedded emissions**: Default value

Option 2

- **Depth of the value chain**: Basic materials and basic material products
- **Coverage**: Imports only
- **Allocation in the EU ETS**: Full auctioning of CBAM sectors
- **Payment**: CBAM certificates
- **Embedded emissions**: Default value

Option 3

- **Depth of the value chain**: Basic materials and basic material products
- **Coverage**: Imports only
- **Allocation in the EU ETS**: Full auctioning of CBAM sectors
- **Payment**: CBAM certificates
- **Embedded emissions**: Actual carbon intensity

Option 4

- **Depth of the value chain**: Basic materials and basic material products
- **Coverage**: Imports only
- **Allocation in the EU ETS**: Gradual phase-out of free allowance
- **Payment**: CBAM certificates
- **Embedded emissions**: Actual carbon intensity

Option 5

- **Depth of the value chain**: Basic materials and finished products
- **Coverage**: Imports only
- **Allocation in the EU ETS**: Full auctioning of CBAM sectors
- **Payment**: CBAM certificates
- **Embedded emissions**: Actual carbon intensity

Option 6

- **Depth of the value chain**: Basic materials and final products
- **Coverage**: Domestic products, imports and exports
- **Allocation in the EU ETS**: Free allocation continued
- **Payment**: Excise duty
- **Embedded emissions**: Default value

Source: European Commission (2021a).

containing significant quantities of these materials would incur an excise duty. This aligns with the "destination principle" where goods are taxed where they are consumed, regardless of where they were produced. Thus, imports would face the same liability as EU-produced materials, based on the material's weight and not on its specific production emissions. The excise duty would only apply once the product is released for consumption within the EU. Therefore, this option requires a robust system for monitoring liability throughout the value chain.

Scope of emissions To mirror the EU ETS, emissions covered by the CBAM should follow the same ruling process. Thus, the policy mainly addresses carbon dioxide emissions. Additionally, when it is relevant, nitrous oxide (N_2O) and perfluorocarbons (PCFs) are also subject to the EU directive. These gases are emitted in the process of fertilizer making and aluminum smelting.

Regarding the scope of emission coverage, the CBAM should focus primarily on direct emissions (Scope 1), which gather emissions emitted during the production process over which the entity has direct control. As the EU ETS also integrates emissions from electricity use, indirect emissions (Scope 2) might also be relevant to account for in the CBAM coverage. At the current stage of development, the CBAM does not account for the product's entire carbon footprint[4], which includes emissions from every stage of its life cycle (Scope 3). This refers to upstream emissions, such as those from raw material extraction and production, as well as downstream emissions, such as transportation, retail, use phase, and eventual waste management.

Embedded emissions measurement The policy's effectiveness and associated compliance costs depend on how the carbon content of imported products is measured. While the EU has standardized its carbon accounting framework, which facilitates domestic carbon intensity estimations, assessing the carbon content of foreign products can be complex and costly (Parry *et al.*, 2021; Lin and Zhao, 2023; Magacho *et al.*, 2024). As one option, default emissions values could be applied to imported products under certain circumstances. For simplicity, this default value may correspond to average EU producer levels, ensuring that imports and EU-produced goods are compared on an equal footing (*e.g.*, in tCO_2e per tonne of material). In practice, however, this process can be more complex and may involve multiple stringency criteria, such as best-in-class estimates, the average carbon intensity of EU imports, or intensity deciles (Mehling and Ritz, 2020). This poses the question of fairness. Taking a value from developed countries would simplify data collection. However, it will mechanically inflate the carbon burden toward developing countries (Magacho *et al.*, 2024; Zhong and Pei, 2024), which might alter the abatement mechanism (Mehling and Ritz, 2020). In contrast, using emissions at the source can better align with global trade principles, yet may introduce difficulties in ensuring comparable production technology standards across the global supply chain (Rocchi *et al.*, 2018).

All in all, the regulation will likely opt to adopt default values initially to streamline the administrative process. If this method results in an overestimation of the carbon intensity of imported goods, importers will have the opportunity to provide evidence through current valuations. The policy's effectiveness will, therefore, depend on the complementarity of these two methodologies.

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[4] This might become an important drawback of the regulation in terms of carbon leakage (Parry *et al.*, 2021). We discuss further this point in section 2.1.3 on page 11.

Product coverage In terms of product coverage, the CBAM focuses[5] especially on basic materials and basic materials products. According to the definition of the European Commission (2021a), basic materials refer to derived materials from industrial processing of raw materials. They take the form of a substance or mixture of substances in a physical state. Conversely, basic materials products[6] are products composed of one single basic material, generally produced within the entity producing the basic material.

During the pilot phase of the CBAM, not all sectors within the carbon leakage list will be considered to fall under the directive. This exclusion is mainly due to some sectors' lack of product homogeneity[7], which creates significant uncertainties in measuring embedded emissions (European Commission, 2021a). This kind of products should not be considered in the pilot phase[8]. As such, the European Commission (2023, Annex I) assumes a shortlist of homogeneous products that will be primarily targeted with their respective gaz:

- **Cement** (CO_2): kaolinitic clays, cement clinkers, white and other Portland cement, aluminous cement, and other hydraulic cements.
- **Electricity** (CO_2): electrical energy.
- **Fertilizers** (CO_2 and N_2O): nitric acid, sulphonitric acids, anhydrous ammonia, potassium nitrates, and various mineral or chemical fertilizers.
- **Iron and Steel** (CO_2): products such as ferro-silicon, iron ores, steel concentrates, sheet piling, railway or tramway track materials, tubes, pipes, hollow profiles, structural parts, reservoirs, tanks, vats, drums, screws, bolts, nuts, rivets, washers, and other articles of iron or steel.
- **Aluminium** (CO_2 and PCFs): unwrought aluminium, aluminium powders and flakes, bars, rods, profiles, wires, sheets, plates, strips, tubes, pipes, foil, reservoirs, tanks, vats, containers, casks, drums, cans, boxes, and other aluminium articles.
- **Chemicals** (CO_2): hydrogen.

We note that the electricity sector stands out as an exception under the CBAM rules. Indeed, the EU's electrical production does not receive allowances for free and shouldn't be considered at risk of carbon leakage. However, as electricity is a major source of both direct and indirect emissions, the EU's ambitious climate plan could further widen the electricity cost gap between Member States and third countries. Before the complete unification of the electricity grid between countries, the CBAM should prevent incentives to buy electricity abroad and thus limit indirect carbon leakages.

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[5] Notice that an important feature is also related to practical feasibility (European Commission, 2021a). In other words, the material or product class should be clearly defined to ensure the feasibility of measuring embedded emissions and to minimize the administrative burden of the regulation.

[6] For example, focusing on fertilizer products, basic materials include ammonium nitrate, urea, and diammonium phosphate, each derived from nitrogen, phosphorus, or potassium. These basic materials are used to produce basic materials products such as NPK (nitrogen, phosphorus, potassium) fertilizers, which are applied directly for crop growth.

[7] For instance, refineries produce a wide range of heterogeneous products simultaneously, including gasoline, diesel, jet fuel, and petrochemicals. Each of these products has a distinct carbon intensity and production pathway, making it challenging to establish a single, standardized measure of embedded emissions across the sector.

[8] This mainly concerns coke, mineral products, crude petroleum, food and beverages, non-ferrous metals, some chemicals, mining, wood-based panels, textiles, and nuclear fuel processing (European Commission, 2021a).

How the CBAM operates According to the European Parliament (2023b), the CBAM is expected to function as a declarative system, requiring importers of specific products to report the quantity of goods crossing EU borders. Imports will be allowed only after submitting an official declaration. Each year, importers must provide the competent authority with emissions data totaling embedded emissions of imports from the previous year. This estimation should be based on actual values verified by an accredited third party or, if unavailable, estimated using default values. For every tonne of CO_2e emitted, importers need to purchase an equivalent number of CBAM certificates from a centralized platform. The price of the certificate will match the weekly price average of auctioned allowances in the EU ETS. In other words, the carbon price is exogenously set and does not result from a cap-and-trade resolution. Thus, the CBAM is at the crossroads between a carbon tax and an emission trading system.

2.1.3 Challenges in designing the right CBAM

Trade regulation barriers Since the beginning of discussions about adopting a CBAM regulation in Europe, one of the main obstacles has been ensuring its compliance with the General Agreement on Tariffs and Trade (GATT) of the World Trade Organization (WTO) rules and the United Nations Framework Convention on Climate Change (UNFCCC) principle of Common but Differentiated Responsibilities (Cameron and Baudry, 2023; Boute, 2024). The first drawback of the border tax mechanism is to align with the so-called non-discrimination principle. The principle stipulates that any import shouldn't be subject to internal taxes that would be in excess of those applied in the domestic country (World Trade Organization, 1947, Article III). In other words, trade regulation cannot be a discriminant measure, that is, favoring domestic markets over foreign markets. Under the most-favored-nation principle, a measure must not discriminate among imports from different WTO members (World Trade Organization, 1947, Article I). Yet, imposing higher compliance costs on carbon-intensive imports than on less carbon-intensive products could be seen as a form of discriminatory treatment (Mehling *et al.*, 2019). Some CBAM detractors are considering the proposal as taking the form of a trade sanction in view of unfair protection of domestic industries to the detriments of export countries (Cosbey, 2008; Holmes *et al.*, 2011). This side effect could start a trade war escalation ended up with seriously damaging consequences (Quick, 2021).

Nonetheless, it is possible to defend the CBAM project since Article XX allows exceptions for measures protecting human, animal, health, life, and the conservation of natural resources (World Trade Organization, 1947, Article XX). Still, the UNFCCC introduces another constraint, asserting that the CBAM applied without accounting for countries' different development levels would be discriminatory and misaligned with its principles. Indeed, the principle stipulates that an individual country's contribution to resolving the climate issue should be proportional to its historical liability and its current capacity. Thus, some exemptions would be required to limit the adverse effects on economic prospects in vulnerable countries (Cosbey *et al.*, 2021; Perdana and Vielle, 2022).

To overcome this regulation compliance, the CBAM might be designed in a specific manner. Several options have been analyzed to date, particularly regarding the treatment of imports and exports (OECD, 2020). The first approach follows the principle of imposing a carbon tax on imported products while exempting exported products from taxation (Monjon and Quirion, 2010). This is commonly referred to as a full carbon border adjustment and could be viewed as a consumption tax (Böhringer *et al.*, 2018). However, such a mechanism would limit flexibility in price setting and complicate the determination of the appropriate tax level (Monjon and Quirion, 2010). Additionally, the rebate on exports would be difficult to justify in terms of environmental benefits. The second option is to mirror the EU ETS for EU imports, requiring importing installations to surrender permits corresponding to the carbon intensity of imported products at a price similar to that in the EU ETS. In this case, imported products would receive the same regulatory treatment as domestic products, making it a potentially viable option (Pauwelyn and Kleimann, 2020).

The complexity of embedded emissions, upstream and downstream supply chain assessment Implementing the CBAM at the level of basic materials and their derived products targets relatively homogeneous imports and their carbon content while helping to minimize administrative complexity. However, limiting CBAM's scope to these products' emissions may generate adverse effects, notably regarding the upstream and the downstream of the supply chain (Böhringer *et al.*, 2022). For instance, non-EU industrials may be motivated to produce and export semi-finished products, which do not fall under the CBAM coverage, rather than providing basic materials products (Golombek *et al.*, 1995; Hoel, 1996). As a result, part of the domestic supply chain would be displaced abroad, impacting carbon leakage and the EU industry's competitiveness. Similarly, the downstream supply chain in the EU could become at risk of carbon leakage due to the increase in input costs (European Commission, 2021a). If the demand for impacted inputs is elastic, the downstream of the supply chain may benefit from importing these processed goods from third countries, transferring the carbon leakage risk further down in the supply chain.

Furthermore, excluding downstream emissions may hinder the trade partners from transitioning toward cleaner energy sources. Non-EU manufacturers might optimize their processes only for basic materials, disregarding emission efficiency in subsequent steps of domestic production. They can also adopt cleaner production techniques only for EU exports while maintaining their carbon-intensive production for the rest of their trades (European Commission, 2021a). This kind of indirect carbon leakage is known as the resource shuffling issue, which may limit the mitigation potential of CBAM regarding global emissions (Mehling and Ritz, 2023).

Including semi-finished goods in CBAM could mitigate these effects, but further feasibility assessment regarding administrative efforts is required. For instance, exporters can exploit this caveat by spreading production across the global supply chain, making the embedded emissions computation task impossible. In addition, highly processed products generally involve a mixture of materials coming from various producers and production pathways of the global supply chain. The effect is exacerbated for steel and aluminium products, which serve as an input in several transformed products (*e.g.*, cars, machinery, or electronics equipment), making the initial use of the basic material largely diluted in the production process. By keeping these steps offshore, countries avoid the CBAM's cost while still accessing the EU market.

The European Commission (2023) reviewed two main critical points to tackle downstream emissions. First, it is important to define the optimal step level, or the n-tiers, of downstream production related to the making of subsequent products requiring CBAM-covered products as inputs. This would fall mostly on semi-finished products. Second, the carbon price level would also be critical. If the relative cost of carbon on imports is low, the impact would be diluted at each subsequent step of the downstream supply chain and does not appear at high risk of carbon leakage. Conversely, with relatively high carbon prices, customers may see their value-added impacted by this additional cost and should be considered.

Estimating the right pricing process of covered emissions To motivate the adoption of carbon pricing mechanisms and clean technology adoption in third countries, the compliance costs of exported products should be credited in accordance with the existing carbon pricing mechanisms. In the case of an existing pricing mechanism, the declarant may be able to claim a rebate on the compliance cost paid. This would enforce the equalization of carbon pricing across regions while rewarding exporters who already operate under such mechanisms. For practicability purposes, only market-based instruments (*i.e.*, carbon tax and emissions trading systems) would be considered effective in pricing emissions while the carbon price should have been effectively paid[9] (European Parliament, 2023b). This raised criticism, as focusing solely on market-based instruments could disadvantage countries that do not adhere to the same regulatory standards as the EU (Boute, 2024). In other words, exporting countries that rely on alternative regulatory approaches, such as command-and-control policies, would be excluded. (Boute, 2024) suggests that the CBAM, by requiring third countries to adopt market-based instruments that may not effectively achieve efficient mitigation, could undermine the overall effectiveness of the policy.

However, from the regulator's perspective, this choice is clearly justified by the need to simplify the carbon accounting system (European Parliament, 2023b). It is already challenging to compare market-based instruments due to differences in emission scopes, sector coverage, pricing mechanisms, exemptions, and offsets (Dao *et al.*, 2024). Expanding the scope of regulatory instruments to non-market-based instruments would substantially increase both the administrative burden and the uncertainty in emissions estimates (Marcu *et al.*, 2020).

2.2 Literature review on the CBAM induced costs

Since the beginning of the CBAM talks in Europe, the literature has exhaustively taken possession of the subject. At least four main literature reviews have been made on the subject (Branger and Quirion, 2014; Cosbey *et al.*, 2019; Böhringer *et al.*, 2022; Zhong and Pei, 2024), compelling more than 100 published articles. If most articles in late 2010 were focused more on administrative feasibility and trade regulation barriers, more recent articles have deep-dived into the quantitative assessment of the economic, social, and environmental impacts of the policy (Zhong and Pei, 2024). These quantitative studies are generally using either computable general equilibrium (CGE) or input-output (IO) models (Rocchi *et al.*, 2018; Schotten *et al.*, 2021; Magacho *et al.*, 2024).

2.2.1 The impact on carbon leakage and competitiveness

As a tool to prevent carbon leakage, the CBAM has predominantly been studied in its capacity to effectively reduce this risk. However, it is challenging to verify carbon leakage mechanisms *ex-post*, advocating for very few empirical evidence of the phenomenon (Joltreau and Sommerfeld, 2019; Fontagné and Schubert, 2023). This lack of evidence in empirical studies is partially resulting from the use of a weak historical data coverage in the case of the EU ETS. Studies are mainly concentrating on the first two trading phases during which a very low level of policy stringency (*i.e.*, free allowances allocation domination, low carbon price, high carbon offsets) was recorded (Branger et al., 2016; Verde, 2020; Felbermayr *et al.*, 2024). Dechezleprêtre and Sato (2017) reviewed the literature on the impact of environmental policies and competitiveness. They found that the impact of environmental policies has a negative impact but is relatively small compared to the volume of trade flows. Similarly, Venmans *et al.* (2020) reviewed the empirical literature and found that the

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[9] The mechanism should account for emissions generated during the production of exported products, whether from embedded carbon content or combustion, without factoring in free allowance allocation. Particular attention may also be given to any form of fossil subsidies.

impact was not statistically significant and of feeble magnitude. In contrast, some articles found a shift in embodied carbon emissions in developed countries (Peters and Hertwich, 2008b). For instance, Aichele and Felbermayr (2015) found that commitments made under the Kyoto Protocol have increased embodied carbon imports by around 8%, resulting in a 3% increase in import emission intensity. Yet, Nielsen *et al.* (2021) find the opposite, suggesting that commitments do not lead mechanically to carbon outsourcing. In fact, Ferguson and Sanctuary (2019) stipulated that carbon-intensive producers' substitution from domestic to foreign inputs is rather difficult in the short run. Consequently, the effects of climate policy leakage would be rather low in the short run.

Regarding the CBAM potential in limiting carbon leakage, most studies used *ex-ante* assessment through CGE models. Some studies estimate that the carbon leakage risk will be effectively tackled by the initiative (Böhringer *et al.*, 2012; Burniaux *et al.*, 2013; Branger and Quirion, 2014) and that most of the competitive loss would be restored (Kuik and Hofkes, 2010). The variation of relative prices induced by the CBAM might trigger two direct effects. First, as a response to the relative price increase of imported goods, domestic industries might benefit by producing locally. However, this would ultimately increase downstream producers' intermediary input costs, which in turn might be less competitive than similar imported products. The intensity of these two direct effects depends on the carbon content of the product, the price elasticity of demand, and the trade intensity (Bassi and Yudken, 2011). On the other hand, indirect effects are any behavior change that emerged as a solution to CBAM implementation, such as resource shuffling, bilateral trade restructuring, or climate initiatives[10], for instance.

In contrast, Zhong and Pei (2024) suggests that the quantitative results of carbon leakage limit induced by the CBAM are not unanimous across studies. Most of the reviewed literature found no or relatively small effect (from 2% to 12% with CBAM). Using empirical data for the year 2004, Jakob *et al.* (2013) estimates that a full[11] European CBAM on Chinese products would increase carbon leakage. The mechanism is that there is a shift in China's production from relatively low carbon-intensive products to more carbon-intensive products that are not exported. Perdana and Vielle (2022) investigated the repercussions of the EU regulation on least developed countries. The results indicate that the EU CBAM lowers carbon leakage from 17% to 12.6% by 2040, representing a reduction of nearly one-third. Sun *et al.* (2024) estimates that the carbon leakage risk would be reduced by the CBAM would be no greater than 20%. They advocate that the competitiveness losses cannot be compensated by the CBAM due to a too small carbon tariff and a low level of price elasticities for intermediate inputs in the EU. Peterson and Schleich (2007) also find no carbon leakage reduction when imposing carbon border adjustment. Overall, these results conclude on the incapacity of such a mechanism to deter indirect carbon leakage (Cameron and Baudry, 2023).

2.2.2 The impact on trade flows, production prices, and GDP

As a carbon pricing mechanism, the CBAM would likely increase the production costs of targeted sectors. This compliance cost would primarily impact the domestic economy. Taking a large scope of product coverage (*e.g.*, ferrous and non-ferrous metals, oil, paper), Pyrka *et al.* (2020) estimated the CBAM costs in European economies. The total cost

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[10] The regulation can also improve the competitive situation since regulations could incentive domestic producers to adopt climate-friendly technologies that would not be found in the absence of the policy (Porter, 1991). Furthermore, environmental improvement can leak to third countries, reducing emissions elsewhere. This phenomenon can be viewed as a positive carbon leakage, operating through the innovation channel (Cameron and Baudry, 2023).

[11] Full means taxing imports and subsidizing exports.

of import would increase by 1.6% in 2030, which might deter around −0.5% of European imports but widely diverging across Member States. In response, EU export prices would increase by 0.2% while export volumes would decrease by −0.7%. Nonetheless, the impact on GDP is close to zero. Using a static trade patterns framework, Korpar *et al.* (2023) also found very small estimates. The CBAM would decrease EU exports by only −0.03%, while the EU region will slightly gain from the measure (+0.02%) at the expense of third countries with a subtle decline of −0.01% of GDP. Similar results are advocated by Sun *et al.* (2024), which stated that these negligible direct effects are due to (*i*) a very limited product coverage, (*ii*) a low carbon price, and (*iii*) a relatively low level of extra-EU trade on the product covered. By considering effects induced by free allowances phasing out, Bellora and Fontagné (2022) found a −1.2% drop in EU GDP, which is mainly attributable to downstream sectors using CBAM-covered products as intermediary inputs. They shed light on two opposite effects at play, namely a decrease in imports from CBAM sectors and an increase in downstream imports due to competitiveness losses. Also considering a broad range of product coverage from Exiobase data, Kuusi *et al.* (2020) estimated that the CBAM would amount to 4.8% of extra-EU trade, which is −0.7% of total GDP for a €25 carbon price. For a €50 carbon price, Schotten *et al.* (2021) estimated that the CBAM would increase production cost by only 0.2% while not affecting EU's competitiveness. Regions in Central and Eastern Europe are the most impacted, with the energy sector bearing the brunt of the costs. In these areas, carbon intensity exceeds that of Western Europe, largely due to a heavier reliance on coal. Using WIOD tables, Rocchi *et al.* (2018) compared the economic impact of implementing a CBA by considering tariffs based on embodied emissions or avoided emissions. Findings suggest that the implementation of a CBA based on avoided emissions at the EU borders would mechanically impact non-metallic minerals, chemicals, and coke production but would lessen the economic impact in third countries.

By imposing an additional cost on imported goods, domestic alternatives become more competitive, likely increasing demand for domestic output and reducing import volumes, or redirecting imports from economies with lower carbon intensities. Developing countries with export-led growth strategies with more carbon-intensive production technologies than the average are likely to voice such concerns. This demand shift may represent the third countries' exposure to CBAM, translating into a substantial income shortfall (Böhringer *et al.*, 2022; Sun *et al.*, 2024; Magacho *et al.*, 2024). According to Magacho *et al.* (2024), many developing countries face impacts on over 2% of their exports and 1% of their production. In particular, Eastern European nations, along with Mozambique, Zimbabwe, and Cameroon, are among those most exposed. Turkey is particularly exposed to this regulation. Acar *et al.* (2022) estimated that the cost of the measure would amount to over 3% of GDP by 2030. In terms of trade exposure, Chepeliev (2021) found that Ukraine will be the most impacted country, followed closely by the other European trade partners, with chemical products, iron and steel being the most impacted products. According to Sun *et al.* (2024), India, Russia, Ukraine, South Africa, and Saudi Arabia will be the main losers, with their exports and GDP slightly declining. Perdana and Vielle (2022) found that the measure will be particularly harmful to least developed countries (LDCs). Welfare losses attributable to export reduction can be partially offset by making exemptions but become detrimental in terms of carbon leakage. They conclude that the optimal scenario involves redistributing CBAM revenues to LDCs to support clean, efficient energy usage. Similar impacts have been found in Morocco (Morchid *et al.*, 2024), South Korea (Lee and Yoo, 2022), and Russia (Votinov *et al.*, 2021). As a consequence, Fouré *et al.* (2016) warned that CBAM would involve trade retaliations, notably from China, India, and the USA, and, in exchange, introduce prohibitive duties. Though these effects would be rather small, Overland and Sabyrbekov (2022) determined a list of countries that might be particularly reluctant to the CBAM implementation based on a CBAM opposition index. On the other hand, some economies might benefit from such a policy by increasing their export volumes given the shift in demand. For instance, Great Britain and Switzerland might enjoy an increase in CBAM product exports (Sun *et al.*, 2024; Korpar *et al.*, 2023).

2.2.3 The impact on welfare and employment

Competitiveness is not the only criterion for assessing the validity of the CBAM. The regulation also poses challenges regarding social efficiency and fairness. Employment might be particularly important to safeguard as a way to make public acceptability viable (Bayer and Schaffer, 2024). The European Commission (2021a) supports that the aggregate impact on employment is close to zero but oscillates geographically between -0.48% and $+2.59\%$. Yet, few studies have investigated the employment impact of the CBAM measure. Perdana and Vielle (2025) recently evaluated labor effects in energy-intensive sectors by using a general equilibrium model based on regional data. While the Fit for 55 package was initially set to destroy around 675 000 jobs by 2030, CBAM could lower these job losses by 300 000. They add that the impact might be geographically varying, with German regions being the most impacted. Losses in exports would hit value-added, employment, and wage share in third countries. According to Magacho *et al.* (2024), Eastern Europe and several African countries rank among the top ten most vulnerable in terms of labor exposure, where potential production declines could jeopardize over 0.5% of both the wage bill and overall employment. Finally, Böhringer *et al.* (2018) stipulated that the CBAM would benefit, for the most part, the implementing region and can exacerbate pre-existing income inequality.

3 Reading the CBAM from an MRIO perspective

The multi-regional input-output (MRIO) model is particularly suited for this research since it allows us to have a representative picture of trade interlinkages at the sector, product, and country levels. The environmental extension of MRIO is straightforward and allows many applications to evaluate climate policy implications (Perese, 2010; Mardones and Muñoz, 2018; Kay and Jolley, 2023; Roncalli and Semet, 2024), notably regarding the cascading price impact on the global supply chain. In this part, we present the basics of input-output analysis and provide some descriptive results on the CBAM-covered products.

3.1 An overview of MRIO models

3.1.1 The demand-pull quantity model

The input-output modeling is a national accounting tool summarizing the macroeconomic structure of an economy (Leontief, 1936, 1941). The framework summarizes the production dependencies, expressed in monetary units, to meet the demand within a single economy (IO) or multi-regional economy (MRIO). Following the mathematical notation of Miller and Blair (2009), the n different sector-products[12] in m different regions, sell and purchase to each other through $Z_{i,j}^{r,s}$, representing the transaction matrix from sector i in region r to sector j in region s. In rows, the matrix accounts for the magnitude and source of the sector i's output in region r, while reading in columns, the flows represent the sources and magnitudes of sector j's input in region s.

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[12] As the input-output framework is generally associated with sectors production and interlinkages, we use the words sector-products, sectors, and products interchangeably.

As a national accounting framework, the table must be balanced between supply and demand. Supply is the sector's production or output x_i^r, while demand is represented by intermediate consumption of inputs $Z_{i,j}^{r,s}$ plus final demand $Y_i^{r,s}$. Compared to a single-economy input-output table where demand is composed of external sales (*e.g.*, households, governments, foreign trades, and investment), the final demand in a multi-regional framework is composed of external sales from domestic and foreign regions. The balance between supply and demand can be represented by this standard equation:

$$x_i^r = \sum_{s=1}^{m} \sum_{j=1}^{n} Z_{i,j}^{r,s} + \sum_{s=1}^{m} Y_i^{r,s}$$

where $z_i^r = \sum_{s=1}^{m} \sum_{j=1}^{n} Z_{i,j}^{r,s}$ depicts the total intermediary demand to sector i's output in region r. In the multi-regional input-output case, the Z matrix is a block matrix of size $mn \times mn$ composed of m^2 sub-matrices of size $n \times n$. The block matrix representation in MRIO models is provided in Appendix A.2 on page 75. Compared to the single economy IO model, the MRIO model differentiates the source of final demand in matrix Y of size $mn \times m$. As stated before, part of the final demand in the single-economy IO representation was devoted to exports to third countries. Direct exports from sector i in region r to region s can be retrieved by summing intermediate trade flows for input use in foreign regions and trade to satisfy foreign final demand such that:

$$\boldsymbol{\mathcal{X}}_i^{r \to s} = \sum_{j=1}^{n} Z_{i,j}^{r,s} + Y_i^{r,s} \quad \text{for } s \neq r$$

where $\boldsymbol{\mathcal{X}}_i^{r \to s}$ represents direct bilateral exports of sector i's output in region r to region s. For direct import of intermediate inputs of sector i in region r from region s:

$$\boldsymbol{\mathcal{M}}_i^{r \leftarrow s} = \sum_{j=1}^{n} Z_{j,i}^{s,r} \quad \text{for } s \neq r$$

Assuming that final demand can be aggregated at the sector-product level for each region r, we get $y_i^r = \sum_{s=1}^{m} Y_i^{r,s}$, or in matrix form: $y = Y\mathbb{1}_m$, such that $y = \left(y_1^1, \ldots, y_n^m\right)$ represents the column vector of total final demand.

Intermediate trade flows are commonly expressed as a ratio between $Z_{i,j}^{r,s}$ and x_j^s through $A_{i,j}^{r,s} = Z_{i,j}^{r,s}/x_j^s$. Matrix A represents the technical coefficients and is expressed as $A = \left(A_{i,j}^{r,s}\right) = Z \operatorname{diag}(x)^{-1}$ where $Z \equiv A \operatorname{diag}(x) = A \odot x^\top$. It follows that:

$$x = Ax + y$$

where $x = \left(x_1^1, \ldots, x_n^m\right)$. Based on the main hypothesis of the Leontief model, namely, final demand is exogenous, technical coefficients are fixed, and the output level is endogenous, the following equation characterizes the basic relationship of the demand-pull quantity model:

$$x = \left(I_{mn} - A\right)^{-1} y \tag{1}$$

where I_{mn} is the identity matrix of size $mn \times mn$. $\boldsymbol{\mathcal{L}} = (I - A)^{-1}$ is known as the Leontief inverse or the total requirement matrix and defines the amount of total output from sector i in region r that is required by sector j in region s to meet its final demand. Thus, matrix A is central in any input-output analysis requiring many properties check as illustrated in Appendix A.1 on page 73. This set of equations composes the demand-pull quantity model of Leontief (1936), which stipulates a clear dependence between output and final demand levels through fixed inter-sectoral dependency relationships.

3.1.2 The cost-push price model

The cost-push price model introduces an additional layer to the previous input-output framework. Sometimes referred to as the "*payment sectors*" (Miller and Blair, 2009), the formation of total output is related to the use of primary production factors such as labor, capital, or primary energy, for instance. Let c be the number of primary inputs, and $V = \left(V^s_{k,j}\right)$ the value added matrix where the element of $V^s_{k,j}$ represents the amount of input k required to produce the output of sector j in region s. Thus, the j^{th} column sum, composed of intermediary and primary inputs (*i.e.*, total inputs), is equal to the total output of sector j^{th}:

$$x^s_j = \sum_{r=1}^{m}\sum_{i=1}^{n} Z^{r,s}_{i,j} + \sum_{k=1}^{c} V^s_{k,j}$$

Summing across the c primary inputs gives the amount of total value-added from sector j in region s:

$$\upsilon^s_j = \sum_{k=1}^{c} V^s_{k,j} = x^s_j - \sum_{r=1}^{m}\sum_{i=1}^{n} Z^{r,s}_{i,j}$$

We denote υ the column vector of total value-added $\upsilon = \left(\upsilon^1_1, \dots, \upsilon^m_n\right) = V^\top \mathbb{1}_c$. As in the quantity model, the interdependence between primary inputs and outputs can be expressed as a ratio of technical coefficients such that $B^s_{k,j} = V^s_{k,j}/x^s_j$ or $B = \left(B^s_{k,j}\right) \equiv V \operatorname{diag}\left(x^\top\right)^{-1}$.

Following Johnson and Noguera (2012), we define the total value-added ratio, or the ratio of GDP to gross output, as follows:

$$\begin{aligned}
\upsilon^s_j &= x^s_j - \sum_{r=1}^{m}\sum_{i=1}^{n} Z^{r,s}_{i,j} \\
\frac{\upsilon^s_j}{x^s_j} &= \frac{x^s_j}{x^s_j} - \sum_{r=1}^{m}\sum_{i=1}^{n} \frac{Z^{r,s}_{i,j}}{x^s_j} \\
\frac{\upsilon^s_j}{x^s_j} &= 1 - \sum_{r=1}^{m}\sum_{i=1}^{n} A^{r,s}_{i,j}
\end{aligned}$$

Denoting this ratio by $\boldsymbol{\mathcal{VI}}j^s = \upsilon j^s/x^s_j$, it represents either the sector's value-added intensity or the primary input share of total output. This ratio is particularly useful for estimating value-added decomposition. For direct value-added exported from region r:

$$\upsilon^r_{\boldsymbol{\mathcal{X}}} = \sum_{s=1}^{m}\sum_{i=1}^{n} \boldsymbol{\mathcal{VI}}^r_i \boldsymbol{\mathcal{X}}^{r\to s}_i \text{ for } s \neq r$$

For the domestic value-added contribution:

$$\upsilon^r_d = \sum_{i=1}^{n} \upsilon^r_i - \upsilon^r_{\boldsymbol{\mathcal{X}}}$$

Let $p = \left(p^1_1, \dots, p^m_n\right)$ and $\psi = (\psi_1, \dots, \psi_c)$ be the vector of sector prices and primary inputs respectively. Then, we can specify the balance between sectors input and outputs such that:

$$p^s_j x^s_j = \sum_{r=1}^{m}\sum_{i=1}^{n} Z^{r,s}_{i,j} p^r_i + \sum_{k=1}^{c} V^s_{k,j}\psi_k \tag{2}$$

Following Desnos *et al.* (2023), we can deduce that:

$$
\begin{aligned}
p_j^s &= \sum_{r=1}^{m}\sum_{i=1}^{n}\frac{Z_{i,j}^{r,s}}{x_j^s}p_i^r + \sum_{k=1}^{c}\frac{V_{k,j}^s}{x_j^s}\psi_k \\
&= \sum_{r=1}^{m}\sum_{i=1}^{n}A_{i,j}^{r,s}p_i^r + \sum_{k=1}^{c}B_{k,j}^s\psi_k
\end{aligned}
$$

This can be translated into matrix form:

$$
\begin{aligned}
p^\top &= p^\top A + B^\top \psi \\
p^\top \left(I_{mn} - A\right) &= B^\top \psi \\
p^\top &= B^\top \psi \left(I_{mn} - A\right)^{-1}
\end{aligned}
$$

Knowing that $\upsilon = B^\top \psi$, and favoring the column vector writing, we get:

$$
p = \left(I_{mn} - A^\top\right)^{-1} \upsilon \tag{3}
$$

with $\left(I - A^\top\right)^{-1}$ being the dual inverse matrix noted $\tilde{\boldsymbol{\mathcal{L}}}$. The $\tilde{\boldsymbol{\mathcal{L}}}$ matrix represents the effect of primary input cost passed through to the intermediary prices of inputs composing output prices. Then, for any change in the value-added of sector j in region s, its output price variation is defined by:

$$
\Delta p = \left(I_{mn} - A^\top\right)^{-1} \Delta \upsilon \tag{4}
$$

In contrast to the demand-pull model, quantities are fixed, and prices can vary.

3.1.3 Environmental extension of the input-output model

Leontief (1970) introduced key methodological principles for adapting the basic input-output framework to environmental matters. In most applications, as well as in this study, input-output models in monetary terms are augmented with environmental accounts to support national carbon accounting (Perese, 2010; Desnos *et al.*, 2023; Roncalli and Semet, 2024). The central idea is to connect carbon emissions embedded in production to the carbon footprint of final demand. This is achieved through two approaches: the output-based approach, focusing on downstream analysis, and the input-based approach, emphasizing upstream analysis.

The output-based approach In order to specify a robust and comprehensive carbon accounting framework, the development of an accurate estimation of indirect emissions is required. Let's assume that only one pollutant[13] is considered here, the GHG emissions. Let e_j^s be the direct emission level of sector j in region s expressed in tCO_2e. The direct carbon intensity is defined as the amount of CO_2e emitted per monetary unit of output:

$$
d_j^s = \frac{e_j^s}{x_j^s}
$$

In matrix form $d = e \operatorname{diag}(x)^{-1}$. The total emissions level summarizes the direct and indirect emissions coming from the whole supply chain to produce one monetary unit of the

---

[13] For a generalization of more than one pollutants, see Miller and Blair (2009) and Desnos *et al.* (2023).

j^{th} output in region s. In the case of the multi-regional input-output model, the analysis can be conducted at the country level while differentiating carbon liability between agents. We have:

$$\mathbb{E} = \operatorname{diag}(d)\left(I_{mn} - A\right)^{-1} Y$$

where matrix $\mathbb{E}$, of size $mn \times m$, is the global emission matrix specifying the total emissions generated by each sector i in region r to satisfy final demand in region s. This matrix admits several accounting frameworks for cost-sharing decomposition (Jiborn et al., 2020). Read in column, the matrix sums up the consumption-based emissions (CBA):

$$\mathbb{E}^{s}_{\text{CBA}} = \sum_{r=1}^{m}\sum_{i=1}^{n} \mathbb{E}^{r,s}_{i}$$

Consumption-based emissions include all emissions associated with goods consumed in region s, regardless of where they are produced. In contrast, production-based emissions account for all emissions generated within region r, regardless of where the resulting goods are consumed. Read in rows, the matrix sums up the production-based carbon emissions (PBA):

$$\mathbb{E}^{r}_{\text{PBA}} = \sum_{s=1}^{m}\sum_{i=1}^{n} \mathbb{E}^{r,s}_{i}$$

The elements at the cross-road between PBA and CBA represent the "*domestic-domestic*" emissions (Darwili and Schröder, 2023), and represents the domestic emissions embodied in domestic final demand:

$$\mathbb{E}^{r}_{d} = \sum_{s=1}^{m}\sum_{i=1}^{n} \mathbb{E}^{r,s}_{i} \quad \text{for } s = r$$

Furthermore, it is also possible to get details on emissions embodied in trade flows. As a result, we get export- and import-based estimates of emissions given the source of production and destination of consumption. We have respectively:

$$\mathbb{E}^{r}_{\mathcal{X}} = \sum_{s=1}^{m}\sum_{i=1}^{n} \mathbb{E}^{r,s}_{i} \quad \forall s \neq r$$

$$\mathbb{E}^{s}_{\mathcal{M}} = \sum_{r=1}^{m}\sum_{i=1}^{n} \mathbb{E}^{r,s}_{i} \quad \forall r \neq s$$

Then, we can obtain the balance of emissions embodied in trade, which is the net difference between exports and imports of embodied emissions in trade:

$$\mathbb{E}^{s}_{net} = \mathbb{E}^{r}_{\mathcal{X}} - \mathbb{E}^{s}_{\mathcal{M}} \quad \text{for } r = s$$

This measure helps to distinguish countries being net importers or net exporters of GHG emissions.

Illustration Let's consider an example. In Table 1, we present a simplified two regions $(\mathcal{A}, \mathcal{B})$ input-output table. Each economy is composed of two sectors (S_1 and S_2). Values of $Z^{r,s}_{i,j}$, $Y^{r,s}_{j}$, x^{r}_{j} are expressed in € mn. The direct carbon emissions E are expressed in ktCO$_2$e, while the direct carbon intensities D are in tCO$_2$e/€ mn. For instance, the intermediary consumption $Z^{1,2}_{1,2}$ is equal to €800 mn, the final demand y^{B}_{4} is equal to \$3 bn, the output x_4 is equal to €12.5 bn, the carbon emissions level $E_{1,2}$ is equal to 20 000 tCO$_2$e and the direct carbon intensity $D_{1,4}$ is equal to 10 tCO$_2$e/€ mn.

Table 1: A tow regions, two sectors input-output table (Example #1)

		Region $\mathcal{A}$		Region $\mathcal{B}$		$y^{\mathcal{A}}$	$y^{\mathcal{B}}$	x
		S_1	S_2	S_1	S_2			
Region $\mathcal{A}$	S_1	500	800	1 600	1 250	400	450	5 000
	S_2	500	400	1 600	625	475	400	4 000
Region $\mathcal{B}$	S_1	250	800	2 400	1 250	1 250	2 050	8 000
	S_2	100	200	800	4 375	4 025	3 000	12 500
	E	500	200	200	125			
	D	0.10	0.05	0.03	0.01			

Let's first compute the matrix of technical coefficient:

$$A = Z \operatorname{diag}(x)^{-1} = \begin{pmatrix} 0.10 & 0.20 & 0.20 & 0.10 \\ 0.10 & 0.10 & 0.20 & 0.05 \\ 0.05 & 0.20 & 0.30 & 0.10 \\ 0.02 & 0.05 & 0.10 & 0.35 \end{pmatrix}$$

The global emissions matrix for the two regions, two sectors economy is defined by:

$$\begin{aligned} \mathbb{E} &= \operatorname{diag}(D)\,(I_4 - A)^{-1}\, Y \\ &= \begin{pmatrix} 0.10 & 0.00 & 0.00 & 0.00 \\ 0.00 & 0.05 & 0.00 & 0.00 \\ 0.00 & 0.00 & 0.02 & 0.00 \\ 0.00 & 0.00 & 0.00 & 0.01 \end{pmatrix} \begin{pmatrix} 1.1881 & 0.3894 & 0.4919 & 0.2884 \\ 0.1678 & 1.2552 & 0.4336 & 0.1891 \\ 0.1430 & 0.4110 & 1.6303 & 0.3044 \\ 0.0715 & 0.1718 & 0.2993 & 1.6087 \end{pmatrix} \begin{pmatrix} 400 & 450 \\ 475 & 400 \\ 1\,250 & 2\,050 \\ 4\,025 & 3\,000 \end{pmatrix} \\ &= \begin{pmatrix} 243.59 & 256.40 \\ 98.31 & 101.68 \\ 87.89 & 112.10 \\ 69.59 & 55.40 \end{pmatrix} \end{aligned}$$

From the global emissions matrix, we can compute the different carbon accounts. In Table 2, we summarize the results for both regions. We take the perspective of Region $\mathcal{A}$:

$$\begin{aligned} \mathbb{E}^{\mathcal{A}}_{\mathrm{CBA}} &= 243.55 + 98.32 + 87.89 + 69.59 = 499.39 \\ \mathbb{E}^{\mathcal{A}}_{\mathrm{PBA}} &= 243.59 + 256.40 + 98.32 + 101.68 = 700 \\ \mathbb{E}^{\mathcal{A}}_{\mathcal{X}} &= 256.40 + 101.68 = 358.08 \\ \mathbb{E}^{\mathcal{A}}_{\mathcal{M}} &= 87.89 + 69.59 = 157.48 \\ \mathbb{E}^{\mathcal{A}}_{\mathrm{d}} &= 243.59 + 98.32 = 341.91 \\ \mathbb{E}^{\mathcal{A}}_{\mathrm{net}} &= 358.08 - 157.48 = 200.60 \end{aligned}$$

Table 2: Summary of carbon emissions accounting (Example #1)

	$\mathbb{E}_d$	$\mathbb{E}_{\mathrm{CBA}}$	$\mathbb{E}_{\mathrm{PBA}}$	$\mathbb{E}_{\mathcal{X}}$	$\mathbb{E}_{\mathcal{M}}$	$\mathbb{E}_{\mathrm{net}}$
Region $\mathcal{A}$	341.9	499.4	700.0	358.1	157.5	200.6
Region $\mathcal{B}$	167.5	525.6	325.0	157.5	358.1	−200.6
Total	509.4	1025.0	1025.0	515.6	515.6	0.0

Transforming the row vector D into a column vector noted $\boldsymbol{\mathcal{CI}}_{\text{direct}}$, we deduce the total upstream carbon intensity of production:

$$\boldsymbol{\mathcal{CI}}^{\text{up}}_{\text{total}} = \left(I_{mn} - A^{\top}\right)^{-1} \boldsymbol{\mathcal{CI}}_{\text{direct}} \tag{5}$$

From this equation, we can retrieve the indirect upstream carbon intensity of the production:

$$\begin{aligned} \boldsymbol{\mathcal{CI}}^{\text{up}}_{indirect} &= \boldsymbol{\mathcal{CI}}^{\text{up}}_{\text{total}} - \boldsymbol{\mathcal{CI}}_{\text{direct}} \\ &= \left(\left(I_{mn} - A^{\top}\right)^{-1} - I_{mn}\right) \boldsymbol{\mathcal{CI}}_{\text{direct}} \end{aligned} \tag{6}$$

In the same manner, let's consider $\boldsymbol{\mathcal{CE}}_{\text{direct}}$ be the transpose of the row vector E. The previous mathematical expressions can be extended to account for absolute upstream emissions by simply multiplying by total output:

$$\begin{aligned} \boldsymbol{\mathcal{CE}}^{\text{up}}_{\text{total}} &= \boldsymbol{\mathcal{CI}}^{\text{up}}_{\text{total}} \odot \frac{\boldsymbol{\mathcal{CE}}_{\text{direct}}}{\boldsymbol{\mathcal{CI}}_{\text{direct}}} \\ &= x \odot \ \boldsymbol{\mathcal{CI}}^{\text{up}}_{total} \end{aligned}$$

Similarly, for the estimation of indirect upstream emissions in absolute terms, we have:

$$\begin{aligned} \boldsymbol{\mathcal{CE}}^{\text{up}}_{\text{indirect}} &= \boldsymbol{\mathcal{CE}}^{\text{up}}_{\text{total}} - \boldsymbol{\mathcal{CE}}_{\text{direct}} \\ &= \left(\boldsymbol{\mathcal{CI}}^{\text{up}}_{\text{total}} - \boldsymbol{\mathcal{CI}}_{\text{direct}}\right) \odot \ \frac{\boldsymbol{\mathcal{CE}}_{\text{direct}}}{\boldsymbol{\mathcal{CI}}_{\text{direct}}} \end{aligned}$$

The input-based approach The previous methodology informs on the output-based analysis of emissions. That is the induced emissions impact for producing one monetary unit of output in a given sector. However, we can arguably estimate the decomposition of the produced output in terms of input requirements (Desnos *et al.*, 2023). In this case, we are looking at the production stages based on backward sectoral linkages by moving down (*i.e.*, downstream) on the global supply chain rather than moving up (*i.e.*, upstream).

The basic idea is to look at the global supply chain in reverse by defining the technical coefficients for one monetary unit of input:

$$\breve{A}^{r,s}_{i,j} = \frac{Z^{r,s}_{i,j}}{x^{r}_{i}}$$

where $\breve{A} = \left(\breve{A}^{r,s}_{i,j}\right) = \operatorname{diag}\left(x^{\top}\right)^{-1} Z$ refers now to the proportion of one monetary unit produced by sector i in region r used by sector j in region s. In this sense, the model might be interpreted as a "*supply-driven*". From this reordered matrix, we pursue the same methodology as before to catch the carbon intensity of downstream production:

$$\boldsymbol{\mathcal{CI}}^{\text{down}}_{\text{total}} = \left(I_{mn} - \breve{A}\right)^{-1} \boldsymbol{\mathcal{CI}}_{direct}$$

This specification is particularly interesting to navigate in the different layers of the supply chain since we can decompose the previous equation as the sum of the carbon intensities of the k-tier of the production:

$$\boldsymbol{\mathcal{CI}}^{\text{down}}_{\text{total}} = \boldsymbol{\mathcal{CI}}_{\text{direct}} + \breve{A}\boldsymbol{\mathcal{CI}}_{\text{direct}} + \breve{A}^{2}\boldsymbol{\mathcal{CI}}_{\text{direct}} + \ldots + \breve{A}^{k}\boldsymbol{\mathcal{CI}}_{\text{direct}} + \ldots$$

Similarly, for indirect downstream carbon intensities, we have:

$$\boldsymbol{\mathcal{CI}}_{\text{indirect}}^{\text{down}} = \left(\left(I_{mn} - \breve{A} \right)^{-1} - I_{mn} \right) \boldsymbol{\mathcal{CI}}_{direct}$$

The estimation of absolute carbon emissions follows the same principles as stated for the upstream analysis.

3.2 Descriptive analysis of CBAM-covered products' profile

In what follows, we propose a descriptive analysis of the CBAM-covered product profile. The analysis is performed on products' global production, trade patterns, emissions, and labor characteristics.

3.2.1 Production analysis

Let's begin this analysis of CBAM-covered products by looking at global production. For each CBAM product, we present in Figure 5 the biggest producers in terms of total output. The correspondence between country ISO codes and country names is available in Table 17 on page 77. China (CHN) dominates global production, particularly in iron, steel, and aluminium, contributing 50% of the total global output in these sectors. Cumulatively, China holds nearly 48% of the global production of CBAM-covered products, which is four times the combined amount of the United States (USA), Germany (DEU), and Russia (RUS). The USA ranks second, closely trailing China in cement production, but accounts for only 7% of global output across these products. Other key regions consistently appearing across all four product categories include India (IND), which is a major producer of fertilizers, as well as Russia (RUS), the Middle East (WME), Germany (DEU), and Japan (JPN).

3.2.2 Trade analysis

At the region level In Figure 3, we illustrate total European imports of CBAM-covered products from non-EU regions. Overall, these imports amount to €56.77 bn, representing about two percent of total EU imports. Iron and steel imports drive the majority of these transactions, representing more than 65% of the total, followed by aluminium (28%). Cement and fertilizers constitute approximately 2% and 5% of CBAM imports, respectively.

Russia (RUS) is the largest exporter of CBAM-covered products to the EU, accounting for nearly 15% of total CBAM imports. The EU is heavily reliant on Russian iron and steel production. Russia is also providing more than 25% of total fertiliser European imports. Meanwhile, EU imports of CBAM-covered products only account for 1.8% of Russia's total exports. The African region[14] ranks second, with the majority of its exports coming from iron and steel production, accounting for approximately 15% of total EU iron and steel imports. In third place, we retrieve Great Britain (GBR), exporting for €6.1 bn of CBAM-covered products to the EU. Together, these three exporters supply almost 37% of total EU CBAM imports. China (CHN) ranks fifth on the list, with CBAM exports representing less than 0.2% of its total exports. India (IND) and the United States (USA) do not contribute significantly to CBAM exports, ranked eighth and tenth, respectively.

Regarding exports of CBAM-covered products from the EU to third countries, we illustrate trade relationships in Figure 4. Total CBAM-covered exports amount to €74.51 bn, making 2.33% of total EU exports. We notice that the CBAM product export patterns

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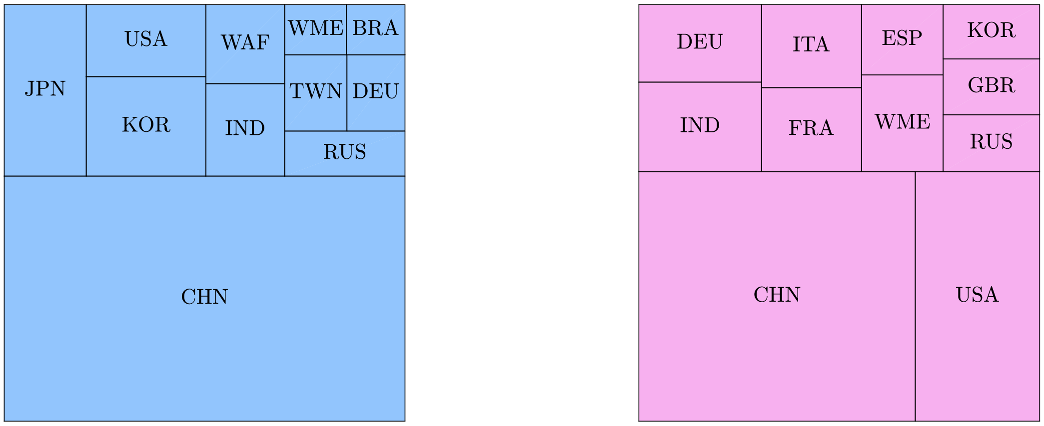
[14] The rest of the world Africa (WAF).

Figure 2: Top global producers of CBAM-covered products in 2022

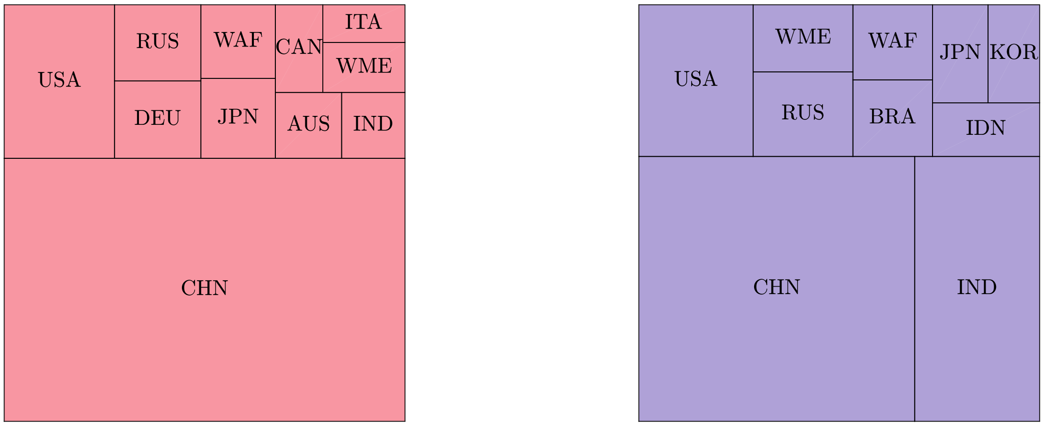
(a) Iron & steel

(b) Cement



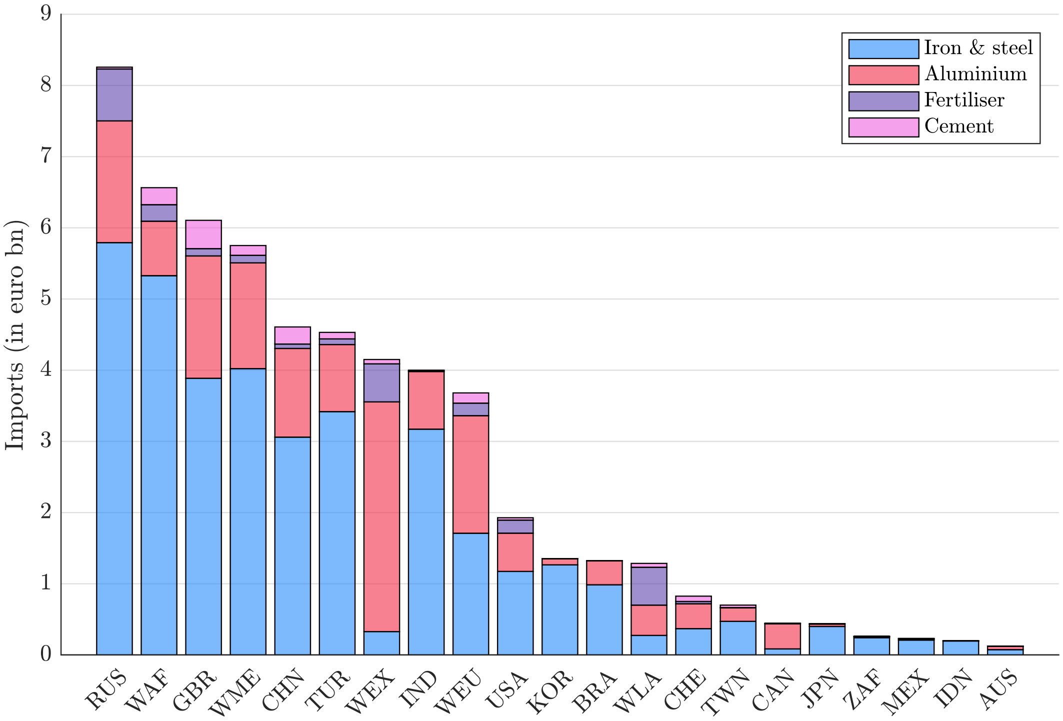
(c) Aluminium

(d) Fertiliser



Source: Exiobase 2022 & Author's calculations.

Figure 3: European imports of CBAM-covered products from third countries (in €bn)



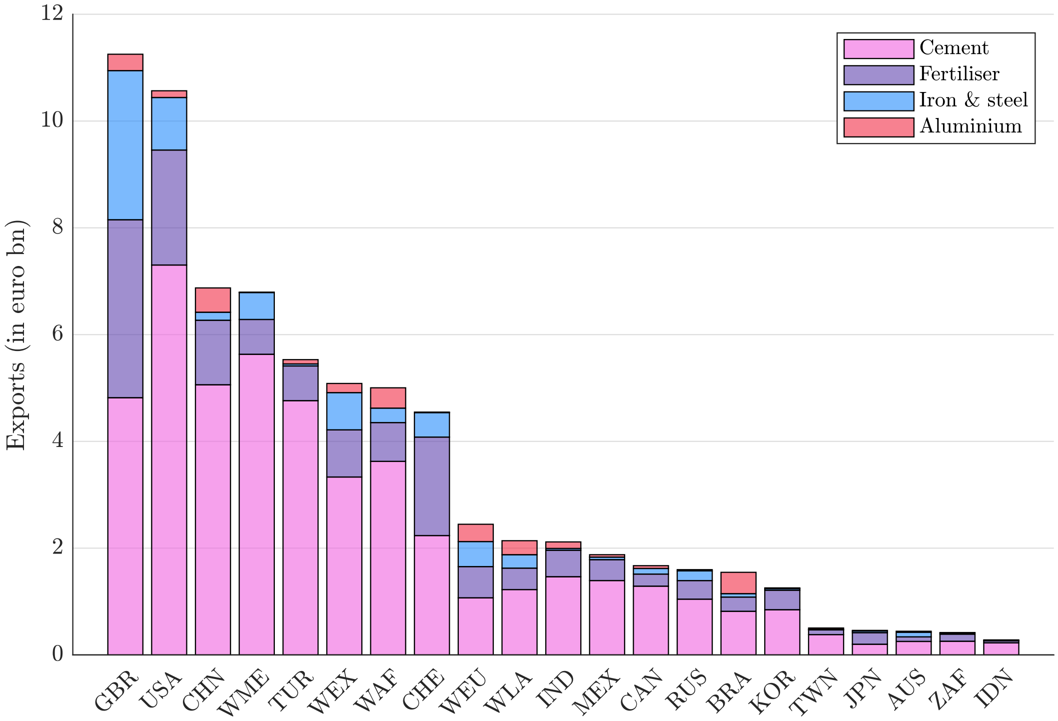
Source: Exiobase 2022 & Author's calculations.

are diverging in terms of product ranking and bilateral trade relationships. Cement and fertiliser products are the two main exported CBAM-covered products, accounting for 65% and 21% of total CBAM exports, respectively. Bilateral exports between the EU and third regions are particularly pronounced with Great Britain (GBR) and the USA. Both regions account for approximately 17% of the total EU's cement exports. These exports only represent 0.07% and 0.27% of the total imports of these countries, respectively. China is ranked third but relatively far behind the USA, accounting for a mere 10% of total CBAM exports.

As a whole, it seems that the EU appears to be a net exporter of CBAM-covered products. In more detail, we observe that the EU is a net exporter of fertiliser and cement products but rather a net importer of iron, steel, and aluminium. If those estimates on trade relationships with respect to third countries are informative for the cost impact of the measure, we highlight a high density of CBAM-covered trade within EU borders. We illustrate this in Figures 19 and 20 on page 82. Total exports of CBAM-covered products within EU borders represent €9.9bn, mainly driven by aluminium and fertiliser. Total imports amount to €2.5 bn and are led by aluminium, iron, and steel. In both cases, Germany is the biggest trade partner, accounting for 22% of total exports and more than 30% of total imports.

At the product level Trade relationships of CBAM-covered products should also be viewed at the product level. As basic materials, these products are related to upstream production to estimate indirect emissions (*i.e.*, Scope 3 upstream), but especially to downstream production (*i.e.*, Scope 3 downstream). Trade patterns of these upstream and downstream products are thus critical in evaluating the regulation's impact on the global supply chain.

Figure 4: European exports of CBAM-covered products to third countries (in €bn)



Source: Exiobase 2022 & Author's calculations.

Analyzing the CBAM at the product level helps assess which European producers will be directly impacted by the policy. It is often, albeit somewhat clumsily, assumed that the primary importers of CBAM-covered products are also producers of those products. As illustrated in Figure 5, in reality, the aggregated imports of these products also stem from industries that transform these basic materials into finished and semi-finished products. The primary importer is the metal products manufacturing sector, accounting for almost €12 bn —nearly 20% of total CBAM imports— and distributed among iron, steel, and aluminum. It imports almost as much aluminum as the aluminum sector itself, which is ranked fourth. The second sector-product on the list is the iron and steel industry, which imports nearly €9 bn of iron and steel, accounting for almost 25% of total iron and steel imports from third regions. In third place is the machinery and equipment production, which is also particularly exposed to the importation of iron and steel. In the ninth position, we observe imports of CBAM-covered products that directly satisfy the final demand, amounting to 2.5% of the total imports.

Since the technical coefficient matrix can be represented as a network, where coefficients define the connections between product edges, trade dependencies shape the density of the supply chain. To illustrate the upstream structure of the CBAM product network, we provide the corresponding graph in Figure 6. The graph only includes first-tier products in Europe[15], meaning that only products having a direct contribution to CBAM intermediary use within the European region are presented. Furthermore, to reduce the density of the graph and increase readiness, we filtered the original links, originally composed of 198 nodes and more

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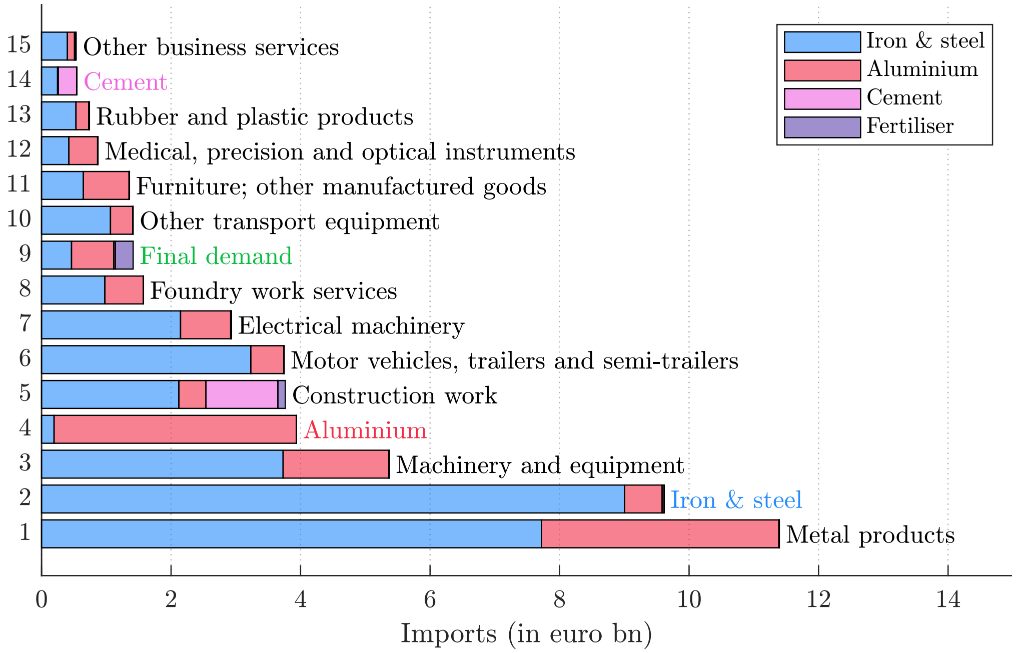
[15] It means that this production network disregards the region's origin.

Figure 5: Top 15 largest importing sectors of CBAM products from third countries (in €bn)



Source: Exiobase 2022 & Author's calculations.

than 700 edges, to only 21 nodes (10%) for 42 edges (6%). Thus, the links presented in the figure are the most substantial ones regarding CBAM production. Technical coefficients determine flow sizes, while flow colors are assigned based on the biggest contribution among CBAM-covered products.

In this simplified network representation, cement and aluminium products share the greatest degrees of edges since they are connected with eleven products. In contrast, fertiliser production is less intensively reliant on third products, with only nine connections. Five products are connected with all CBAM-covered products and are, thus, particularly central in the upstream of CBAM production: *other business activities*, *land transport services*, *wholesale trade*, *gaseous fuel serivces*, and *financial services*. In addition to being more interconnected with CBAM-covered products, they are also having the biggest individual technical coefficients. This indicates that most of the intermediary inputs used for CBAM production are services, especially transport services. Nonetheless, we retrieve some important goods dependent on each specific CBAM product. For instance, aluminum production requires *secondary raw materials*, *chemicals*, *metal products*, and *other non-ferrous metal products*, while cement production requires mainly *stone, sand and clay*. We also notice a complete absence of sectors linked to power generation. Only two energy sources are required for the production of fertilizers and iron and steel, namely crude oil extraction and gaseous fuels.

Turning to the downstream network of CBAM production in Figure 7, we apply the same filtering process[16]. In total, we keep 27 nodes (14%) and 37 edges (5%). As we could have anticipated, the trade patterns in the downstream supply chain are distinct from those in the upstream one. First, sectors inclined to use CBAM-covered products as intermediary inputs are goods rather than services. Second, apart from the strong link between *construction work*

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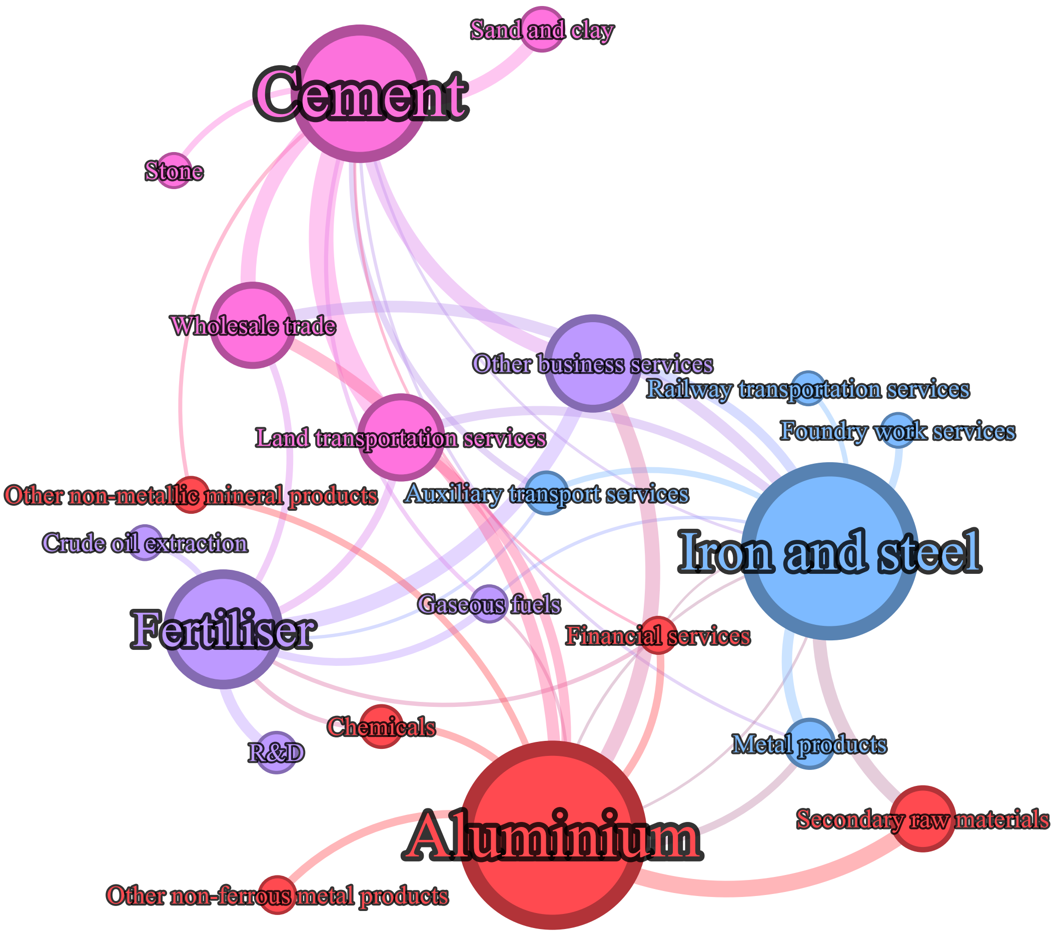
[16] Notice that instead of using A matrix, we use $\breve{A}$ matrix for the downstream analysis of the supply chain.

Figure 6: First-tier upstream production network of CBAM-covered products in Europe

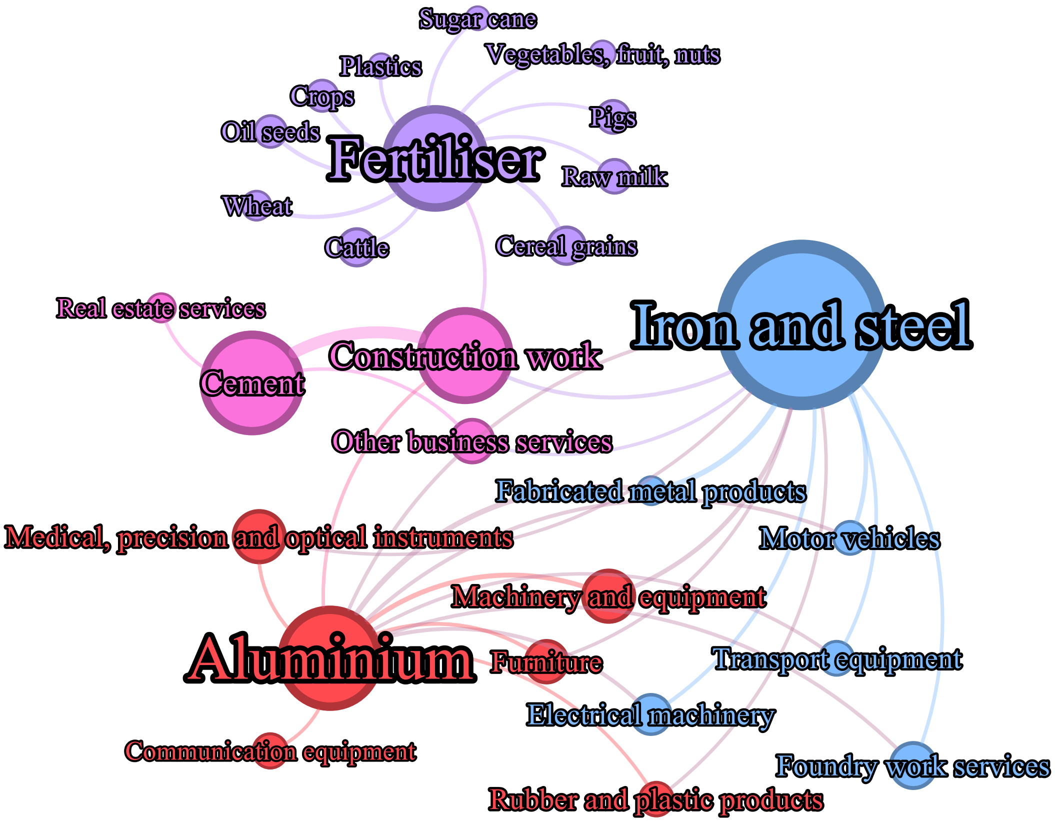


Source: Exiobase 2022 & Author's calculations.

and cement production, it is challenging to gauge highly influential trade dependencies. While the number of nodes retained increased, the bilateral relationships seem smaller. Notice that iron, steel, and aluminum production both supply eight common products.

Construction work plays a pivotal role downstream in the CBAM production network, as it relies on all CBAM-covered products as intermediary inputs. Moreover, it represents the strongest linkage in the network concerning cement production. Then we retrieve finished products such as *fabricated metal products*, *motor vehicles*, and *electrical machinery*. These products rely especially on iron, steel, and aluminium production. For fertiliser, except for the supply of plastics, all products are part of the agricultural sector. In total, fertilizer, iron, and steel production supply eleven products, but the edges of iron and steel tend to be relatively more important. Aluminium production supplies twelve industries, whereas cement production serves only three, albeit showing higher weights. This set of products composes the sub-set of products covered by the CBAM policy in our third scenario.

Figure 7: First-tier downstream production network of CBAM-covered products in Europe



Source: Exiobase 2022 & Author's calculations.

3.2.3 Carbon emissions analysis

Absolute emissions The breakdown of total carbon emissions from CBAM-covered products is presented in Table 3. Based on the upstream and downstream carbon accounting principles, we distinguish between indirect and total emissions using these two approaches. Again, China largely dominates the carbon emissions landscape of CBAM-covered products, with roughly 3.1GtCO$_2$e directly emitted in 2022, accounting for almost 60% of total CBAM-covered product emissions. These products' emissions represent around 27% of China's carbon footprint, mostly driven by iron, steel, and aluminium production. Europe arrived third, with around 220 MtCO$_2$e emissions in 2022, a mere 4% of the total.

On average, the indirect emissions of CBAM-covered products are twice as high as direct emissions, though this pattern holds for only half of the regions analyzed. East Asian countries, such as Taiwan, Japan, and South Korea, are particularly affected by indirect emissions, especially upstream ones, where indirect emissions exceed direct emissions by more than a factor of five. When distinguishing between upstream and downstream indirect emissions, upstream emissions overwhelmingly dominate. On average, upstream emissions are twice as high as downstream emissions, with India exhibiting an even stronger effect, surpassing a ratio of three. Conversely, Russia stands as an exception, with a more balanced ratio of two between indirect upstream and downstream emissions.

In Figure 8, we present the matrix of bilateral flows of carbon emissions from all CBAM-

Table 3: Upstream and downstream carbon emissions (in $MtCO_2e$) of CBAM products

Region	$\mathcal{CE}_{\text{direct}}$	$\mathcal{CE}^{\text{up}}_{\text{indirect}}$	$\mathcal{CE}^{\text{down}}_{\text{indirect}}$	$\mathcal{CE}^{\text{up}}_{\text{total}}$	$\mathcal{CE}^{\text{down}}_{\text{total}}$
Australia	12.25	29.77	17.96	42.01	30.21
Brazil	96.91	44.50	30.78	141.41	127.69
Canada	24.06	24.22	15.17	48.28	39.24
China	3 164.32	2 915.18	1 704.52	6 079.50	4 868.84
Europe	220.00	229.96	162.23	449.96	382.22
India	466.00	255.12	81.21	721.12	547.22
Indonesia	54.42	20.46	9.36	74.88	63.79
Japan	89.79	328.07	181.88	417.86	271.67
Mexico	42.04	14.74	12.21	56.78	54.25
Russia	118.31	51.23	100.70	169.53	219.00
South Africa	17.08	36.84	19.37	53.92	36.45
South Korea	64.60	243.91	92.97	308.50	157.57
Switzerland	3.54	1.14	1.06	4.69	4.60
Taiwan	12.29	80.55	28.39	92.84	40.68
Turkey	70.56	25.47	15.40	96.03	85.96
Great Britain	13.08	18.31	8.23	31.39	21.30
United States	131.50	159.80	91.15	291.29	222.64
World (Africa)	216.60	119.75	69.02	336.35	285.61
World (Europe)	66.39	31.99	17.93	98.38	84.32
World (Latin America)	61.75	30.95	17.15	92.70	78.90
World (Middle East)	137.26	70.86	39.34	208.12	176.59
World (Rest of the world)	74.61	31.04	14.39	105.65	88.99

Source: Exiobase 2022 & Author's calculations.

covered products. In rows, we have the aggregated flows of emissions exported ($\mathbb{E}_{\mathcal{X}}$), while columns depict the aggregated flows of imported emissions ($\mathbb{E}_{\mathcal{M}}$). Largest values are scaled at the column level, meaning that the biggest node values are emphasized for each region as an importer. Total embedded emissions in trade from CBAM-covered products amount to 966.75 $MtCO_2e$ in 2022. In the European region (EEU), bilateral emission flows with third countries are particularly significant, with imports amounting to 107 $MtCO_2e$. These emissions represent 48% of what is directly emitted domestically[17]. Overall, the sources of EU imported emissions correspond to previously observed direct trade patterns. Nonetheless, in this analysis, China (CHN) and India (IND) emerge as the largest contributors to EU-imported emissions, jointly accounting for 45% of the total. The computation of import- and export-based emissions is based on the Leontief demand-driven approach, which accounts for all upstream emissions required to meet final demand, moving beyond direct export estimates. Russia (RUS) and the African region (WAF), the two largest exporters of CBAM-covered products, follow closely, each contributing approximately 10 $MtCO_2e$ to EU imports.

On the export side, CBAM-covered exports amount to 61 $MtCO_2e$ in Europe, making it a net importer of CBAM-related emissions. Embedded emissions in exports represent less than 30% of CBAM-covered direct emissions. The EU region maintains the same list of trading partners as previously observed, with the USA, China, and Great Britain (GBR) accounting for approximately 45% of total exports. It is important to note that China

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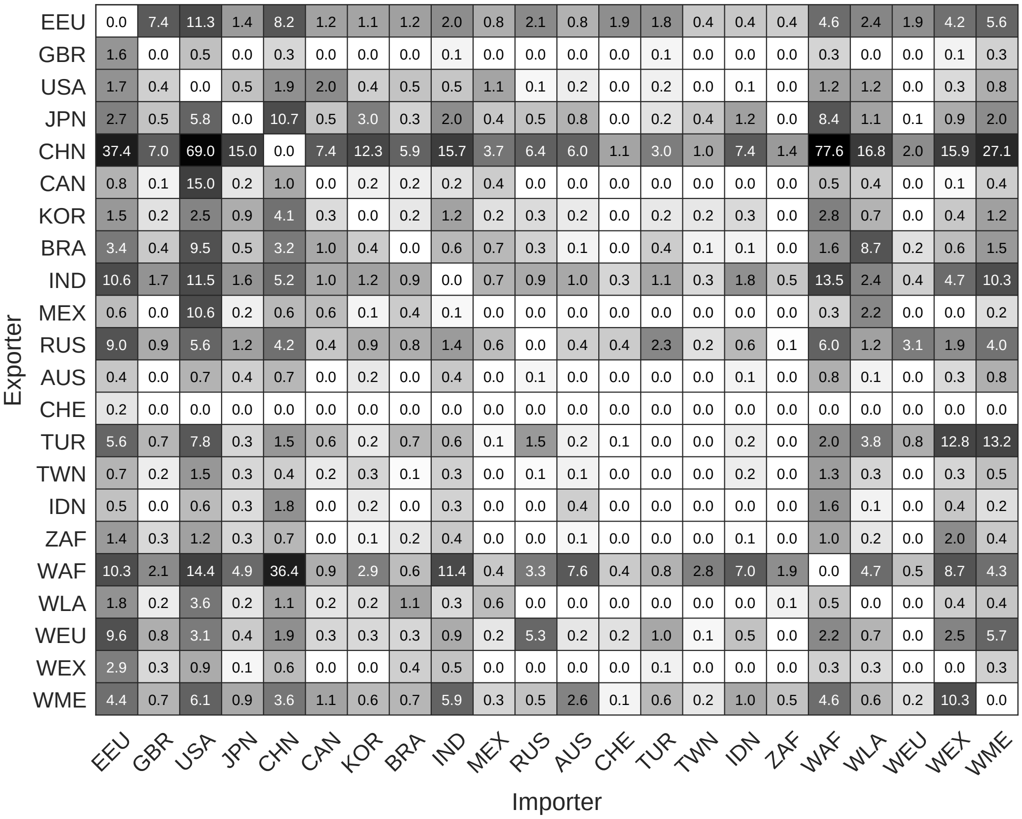
[17] When compared with domestic emissions emitted to satisfy domestic demand ($\mathbb{E}_d$), this figure would represent approximately 67%.

Figure 8: Bilateral flows of carbon emissions (in $MtCO_2e$) from CBAM products trade



	EEU	GBR	USA	JPN	CHN	CAN	KOR	BRA	IND	MEX	RUS	AUS	CHE	TUR	TWN	IDN	ZAF	WAF	WLA	WEU	WEX	WME
EEU	0.0	7.4	11.3	1.4	8.2	1.2	1.1	1.2	2.0	0.8	2.1	0.8	1.9	1.8	0.4	0.4	0.4	4.6	2.4	1.9	4.2	5.6
GBR	1.6	0.0	0.5	0.0	0.3	0.0	0.0	0.0	0.1	0.0	0.0	0.0	0.0	0.1	0.0	0.0	0.0	0.3	0.0	0.0	0.1	0.3
USA	1.7	0.4	0.0	0.5	1.9	2.0	0.4	0.5	0.5	1.1	0.1	0.2	0.0	0.2	0.0	0.1	0.0	1.2	1.2	0.0	0.3	0.8
JPN	2.7	0.5	5.8	0.0	10.7	0.5	3.0	0.3	2.0	0.4	0.5	0.8	0.0	0.2	0.4	1.2	0.0	8.4	1.1	0.1	0.9	2.0
CHN	37.4	7.0	69.0	15.0	0.0	7.4	12.3	5.9	15.7	3.7	6.4	6.0	1.1	3.0	1.0	7.4	1.4	77.6	16.8	2.0	15.9	27.1
CAN	0.8	0.1	15.0	0.2	1.0	0.0	0.2	0.2	0.2	0.4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.5	0.4	0.0	0.1	0.4
KOR	1.5	0.2	2.5	0.9	4.1	0.3	0.0	0.2	1.2	0.2	0.3	0.2	0.0	0.2	0.2	0.3	0.0	2.8	0.7	0.0	0.4	1.2
BRA	3.4	0.4	9.5	0.5	3.2	1.0	0.4	0.0	0.6	0.7	0.3	0.1	0.0	0.4	0.1	0.1	0.0	1.6	8.7	0.2	0.6	1.5
IND	10.6	1.7	11.5	1.6	5.2	1.0	1.2	0.9	0.0	0.7	0.9	1.0	0.3	1.1	0.3	1.8	0.5	13.5	2.4	0.4	4.7	10.3
MEX	0.6	0.0	10.6	0.2	0.6	0.6	0.1	0.4	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.3	2.2	0.0	0.0	0.2
RUS	9.0	0.9	5.6	1.2	4.2	0.4	0.9	0.8	1.4	0.6	0.0	0.4	0.4	2.3	0.2	0.6	0.1	6.0	1.2	3.1	1.9	4.0
AUS	0.4	0.0	0.7	0.4	0.7	0.0	0.2	0.0	0.4	0.0	0.1	0.0	0.0	0.0	0.0	0.1	0.0	0.8	0.1	0.0	0.3	0.8
CHE	0.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
TUR	5.6	0.7	7.8	0.3	1.5	0.6	0.2	0.7	0.6	0.1	1.5	0.2	0.1	0.0	0.0	0.2	0.0	2.0	3.8	0.8	12.8	13.2
TWN	0.7	0.2	1.5	0.3	0.4	0.2	0.3	0.1	0.3	0.0	0.1	0.1	0.0	0.0	0.0	0.2	0.0	1.3	0.3	0.0	0.3	0.5
IDN	0.5	0.0	0.6	0.3	1.8	0.0	0.2	0.0	0.3	0.0	0.0	0.4	0.0	0.0	0.0	0.0	0.0	1.6	0.1	0.0	0.4	0.2
ZAF	1.4	0.3	1.2	0.3	0.7	0.0	0.1	0.2	0.4	0.0	0.0	0.1	0.0	0.0	0.0	0.1	0.0	1.0	0.2	0.0	2.0	0.4
WAF	10.3	2.1	14.4	4.9	36.4	0.9	2.9	0.6	11.4	0.4	3.3	7.6	0.4	0.8	2.8	7.0	1.9	0.0	4.7	0.5	8.7	4.3
WLA	1.8	0.2	3.6	0.2	1.1	0.2	0.2	1.1	0.3	0.6	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.5	0.0	0.0	0.4	0.4
WEU	9.6	0.8	3.1	0.4	1.9	0.3	0.3	0.3	0.9	0.2	5.3	0.2	0.2	1.0	0.1	0.5	0.0	2.2	0.7	0.0	2.5	5.7
WEX	2.9	0.3	0.9	0.1	0.6	0.0	0.0	0.4	0.5	0.0	0.0	0.0	0.0	0.1	0.0	0.0	0.0	0.3	0.3	0.0	0.0	0.3
WME	4.4	0.7	6.1	0.9	3.6	1.1	0.6	0.7	5.9	0.3	0.5	2.6	0.1	0.6	0.2	1.0	0.5	4.6	0.6	0.2	10.3	0.0

Source: Exiobase 2022 & Author's calculations.

(CHN) is, for many regions, the greatest exporter[18] of CBAM-covered products' emissions, cumulating more than 339 $MtCO_2e$. These embedded emissions are particularly pointing toward the African region and the USA, with more than 77.6 and 69 $MtCO_2e$, respectively. Notice that the USA absorbs, in total, 180 $MtCO_2e$ from third regions, making it the biggest importer of CBAM-related emissions.

Carbon intensities In Table 4, we present direct ($\mathcal{CI}_{\text{direct}}$) and total ($\mathcal{CI}_{\text{total}}$) carbon intensities of CBAM-covered products. The table highlights significant disparities in carbon intensities across regions and CBAM-covered products, underscoring the varying environmental efficiency of production processes (Verdolini *et al.*, 2012).

Table 4: Direct and total carbon intensities (in $kgCO_2e$/€) of CBAM products

	Aluminium		Cement		Fertiliser		Iron & steel	
Region	$\mathcal{CI}_{\text{direct}}$	$\mathcal{CI}_{\text{total}}$	$\mathcal{CI}_{\text{direct}}$	$\mathcal{CI}_{\text{total}}$	$\mathcal{CI}_{\text{direct}}$	$\mathcal{CI}_{\text{total}}$	$\mathcal{CI}_{\text{direct}}$	$\mathcal{CI}_{\text{total}}$
Australia	0.39	1.70	0.73	1.67	0.18	0.44	0.14	0.59
Brazil	1.61	3.29	7.26	7.77	0.06	0.52	1.10	1.73
Canada	0.20	0.96	5.31	5.78	0.24	0.51	0.50	1.05
China	0.17	2.43	11.70	13.45	0.29	1.20	0.75	2.01
Europe	0.26	0.82	0.91	1.37	0.50	0.89	0.28	0.79
India	0.39	1.82	7.95	9.46	0.38	1.26	2.13	3.64
Indonesia	0.13	1.23	9.25	10.98	0.14	0.40	0.26	1.08
Japan	0.01	0.62	8.75	9.60	0.15	0.67	0.25	1.74
Mexico	2.41	2.83	6.40	7.72	0.82	1.08	0.26	0.61
Russia	1.00	1.14	3.06	3.78	0.55	0.93	0.65	1.08
South Africa	5.01	7.59	3.69	5.26	0.27	6.62	0.50	1.34
South Korea	0.04	1.72	2.72	3.73	0.11	0.75	0.16	1.35
Switzerland	0.01	0.19	0.88	1.11	0.27	0.35	0.07	0.19
Taiwan	0.03	0.65	3.84	5.46	0.33	1.16	0.06	1.08
Turkey	0.35	2.24	26.24	27.63	6.33	6.53	0.39	1.22
Great Britain	0.05	0.66	0.75	1.30	0.37	0.90	0.26	0.83
United States	0.07	0.71	1.45	2.03	0.27	1.05	0.10	0.64
World (Africa)	0.40	1.55	13.99	14.95	1.19	1.67	0.36	1.28
World (America)	0.11	0.84	3.92	4.67	1.62	2.07	0.25	0.92
World (Europe)	0.49	2.74	8.41	10.32	0.68	1.80	2.77	4.06
World (Middle East)	0.50	1.71	5.87	6.58	0.90	1.46	0.24	1.07
World (ROW)	0.28	1.11	7.55	8.24	0.77	1.09	0.10	0.99
Average	0.63	1.75	6.39	7.40	0.75	1.52	0.53	1.33
Median	0.27	1.39	5.59	6.18	0.35	1.06	0.26	1.08

Source: Exiobase 2022 & Author's calculations.

Across CBAM products, two distinct groups of regions emerge. On one side, the European region, Switzerland, Great Britain, the United States, and Canada consistently exhibit below-average total carbon intensities. On the other side, China, India, Turkey, Brazil, and the rest of the world's European region systematically show above-average carbon intensities. This group includes some of the largest exporters of CBAM-covered products to EU, reinforcing concerns over potential carbon leakage. For example, China's total carbon intensity for iron and steel is more than twice that of the EU. In fertilizer production, India emits 1.4 times more carbon dioxide equivalent per euro of output than the EU. Russia, while demonstrating relatively moderate carbon intensities for aluminium, cement, and fertilizers, still falls short of European standards. Russia's cement production generates nearly three

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[18] These results also reveal that a critical portion of China's emissions remains within its domestic economy. Its domestic-domestic emissions amount to 2 825 $MtCO_2e$, or almost 60% of total downstream emissions.

times more emissions per euro compared to the EU. The African region exhibits particularly high carbon intensities in cement and fertilizer production but shows more promising estimates for aluminium, iron, and steel production.

Cement production is by far the most carbon-intensive activity among CBAM-covered products, with an average direct carbon intensity of 6.4 $kgCO_2e$ per euro of output. The European region[19] appears to have a real advantage regarding cement production since its total carbon intensity is one of the lowest (1.37 $kgCO_2e$/€). In contrast, Turkey, China, the African region, and Indonesia have cement production that is particularly highly carbon intensive since they emit more than 10 $kgCO_2e$/€ of output. This implies that cement production in these regions emits ten times more carbon than within European borders. On the other hand, cement has the lowest indirect carbon intensity among CBAM-covered products, averaging 0.3 $kgCO_2e$/€. In aluminium production, significant discrepancies exist between direct and total carbon intensity estimates. The median total carbon intensity is five times higher than the direct one, indicating that a substantial share of emissions originates upstream, particularly from third-product inputs and electricity consumption. This effect is especially pronounced in Japan, South Korea, China, Switzerland, and Taiwan. Iron and steel production is much less carbon-intensive by contrast, with an average direct carbon intensity of 0.26 $kgCO_2e$ per euro of output. Notice that the gap between the average and the median is also relatively small, meaning that the majority of regions have low-carbon intensities.

3.2.4 Value added and labor analysis

Domestic value added of CBAM-covered products In Figure 9, we provide the value-added to output ratio, or value-added intensity ($\boldsymbol{\mathcal{VI}}$) of CBAM products. It measures the proportion of total output that is attributed to value-added, reflecting the economic contribution of CBAM-covered products beyond intermediate consumption. Higher values indicate a greater contribution of primary inputs in the total output production, while lower estimates might suggest a relatively stronger dependence on intermediary inputs. Thus, these estimates can serve as fair proxies for estimating if those products are especially important for the domestic economy.

Taking a domestic viewpoint first, we observe two groups of countries depending on their value-added intensities. Regions with above-average value-added ratios include Russia (RUS), Switzerland (CHE), Mexico (MEX), the Middle East (WME), and the rest of the world (WEX). In these regions, CBAM-covered production carries a relatively greater economic weight than other regions. Regardless of their carbon intensity, these regions would particularly feel the economic and social consequences of the CBAM impacts since a large part of their CBAM-covered production is value-oriented. On the other hand, Taiwan (TWN), South Korea (KOR), Japan (JPN), the United States (USA), Great Britain (GBR), and the European rest of the world region (WEU) have below-average figures. This indicates that CBAM production in these regions tends to generate less value-added and potentially more dependent on intermediary inputs. Compared to the previous group, this list comprises a higher proportion of developed countries.

Overall, the average value-added intensity is 0.34, remaining stable across CBAM-covered products. The median is slightly greater for cement and fertiliser products. The latter is particularly marked by a large dispersion of estimates with a standard deviation of 0.22, notably due to two extreme regions' ratios, namely Taiwan (TWN), and Mexico (MEX).

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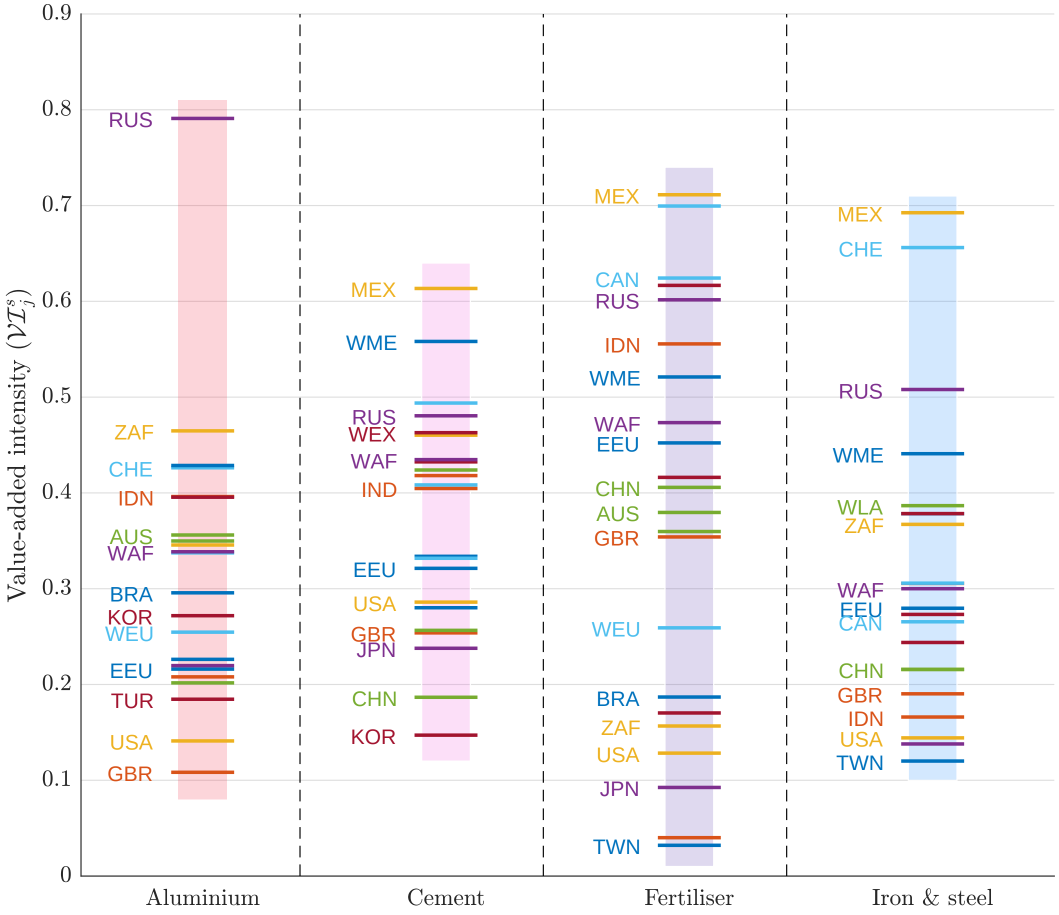
[19] In Table 20 on pages 80, we provide direct and total carbon intensities detail for European countries. Aluminium production is particularly carbon efficient since the median estimate of total carbon intensity is below 0.6$kgCO_2e$ per euro of output.

For each product, the European region (EEU) has a value-added intensity slightly below the average, except for fertilizers, where the ratio approaches 0.5.

Figure 9: Range of value-added intensity ($\boldsymbol{\mathcal{VI}}_j^s$) from CBAM production



Source: Exiobase 2022 & Author's calculations.

Value added content of trade The value-added analysis can be further refined to capture the value-added content of trade, reflecting the contribution of primary input factors embedded in the exchange of intermediate and final products (Johnson and Noguera, 2012). This enables value-added contribution and decomposition analysis, providing insights into the dependence of domestic production on trade. In Table 5, we provide the value-added decomposition of CBAM-covered products. υ denotes the total value added generated by CBAM-covered products, υ_d and $\upsilon_{\boldsymbol{\mathcal{X}}}$ represent the CBAM's value-added destined for domestic and foreign production, respectively. $\upsilon_{\boldsymbol{\mathcal{X}}}^{\text{EU}}$ represents the CBAM's value-added embodied in European final demand, representing the embodied value-added subject to the CBAM regulation. The table also provides these metrics in relative terms. In this case, υ expresses the share of CBAM-covered products' value-added within the total value-added of each region, while other metrics express the shares with respect to total CBAM's value-added.

We highlight four regions that seem particularly reliant on CBAM production in terms of value-added, namely Russia (4.27%), South Korea (3.08%), China (2.93%), and Taiwan (2.04%). Except for China, the CBAM-covered products' value-added generation from these regions is embedded in export rather than for domestic consumption. However, their value-added amounts covered by the CBAM regulation are not among the highest. The European rest-of-the-world region is particularly exposed, with approximately 20% of its CBAM value-added contribution embedded into EU exports. Great Britain (17.74%), Turkey (16.86%), and Switzerland (15.53%) are also value-depend on EU exports. Another region can be added to this list, namely, South Africa, which is dependent on CBAM's value-added generation and reliant on European exports at 11.79%. Those regions would be particularly at risk of increasing costs from the CBAM. In aggregated terms, around 4% of global CBAM value-added generation is embedded in exports toward the European region.

Table 5: CBAM value-added contribution and decomposition

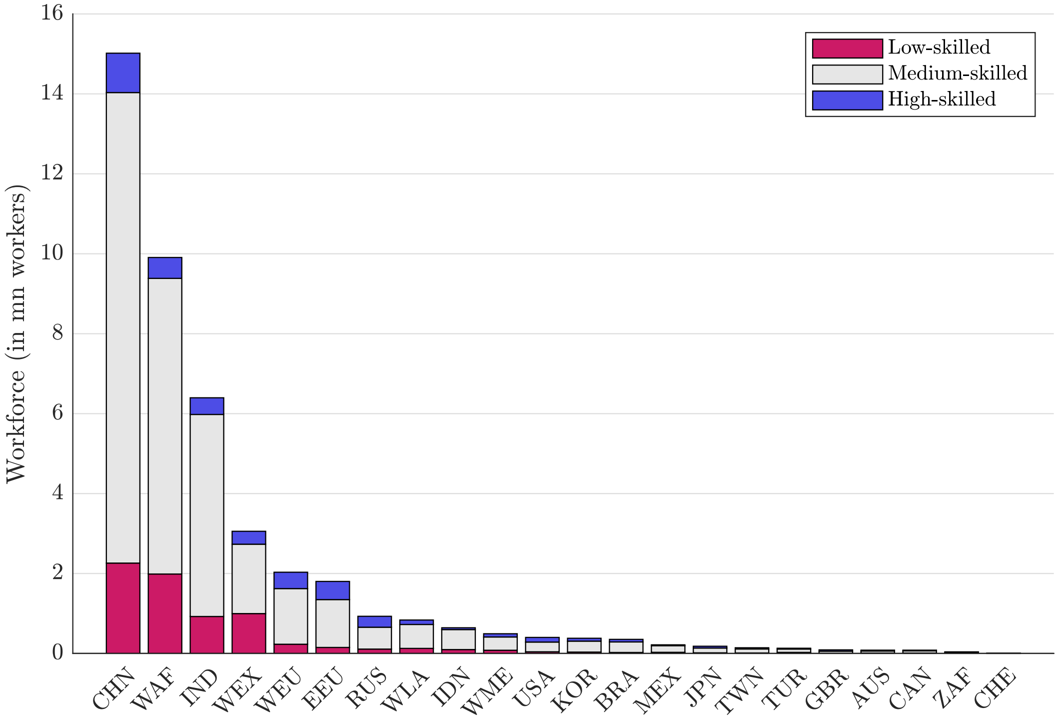
	υ	υ_d	$\upsilon_{\boldsymbol{x}}$	$\upsilon_{\boldsymbol{x}}^{\text{EU}}$	υ	υ_d	$\upsilon_{\boldsymbol{x}}$	$\upsilon_{\boldsymbol{x}}^{\text{EU}}$
Region		(in € bn)				(in %)		
Europe	132.32	83.16	49.16	–	0.88	62.85	37.15	–
Great Britain	6.30	3.31	2.99	1.12	0.24	52.52	47.48	17.74
United States	49.75	38.17	11.58	1.55	0.25	76.72	23.28	3.11
Japan	34.55	14.32	20.23	1.24	0.75	41.44	58.56	3.59
China	444.93	344.48	100.45	10.80	2.93	77.42	22.58	2.43
Canada	13.62	1.85	11.78	0.62	0.83	13.57	86.43	4.52
South Korea	48.98	24.13	24.84	1.85	3.08	49.28	50.72	3.77
Brazil	21.38	11.49	9.89	1.01	1.21	53.76	46.24	4.72
India	48.40	38.08	10.32	1.55	1.52	78.68	21.32	3.19
Mexico	19.07	6.49	12.58	0.61	1.61	34.01	65.99	3.19
Russia	68.49	33.55	34.95	6.85	4.25	48.98	51.02	10.00
Australia	9.83	4.11	5.72	0.45	0.74	41.78	58.22	4.54
Switzerland	2.64	1.62	1.02	0.41	0.39	61.41	38.59	15.53
Turkey	7.55	1.31	6.24	1.27	1.02	17.35	82.65	16.86
Taiwan	10.64	3.31	7.33	0.76	2.04	31.12	68.88	7.18
Indonesia	7.87	4.72	3.15	0.22	0.68	59.97	40.03	2.77
South Africa	5.85	2.29	3.56	0.69	1.79	39.16	60.84	11.79
World (Africa)	41.87	9.90	31.98	3.47	1.07	23.63	76.37	8.28
World (Latin America)	17.51	11.66	5.85	0.71	0.78	66.57	33.43	4.07
World (Europe)	6.09	1.67	4.43	1.20	1.63	27.35	72.65	19.75
World (ROW)	16.45	11.05	5.40	2.07	0.94	67.16	32.84	12.59
World (Middle East)	40.27	15.08	25.20	3.22	1.23	37.44	62.56	8.00
Total	1 054.39	665.73	388.66	41.66	1.24	63.14	36.86	3.95

Source: Exiobase 2022 & Author's calculations.

Overall, we notice that CBAM-covered products are essential in the global supply chain, amounting to approximately 1.24% of global GDP. More than 50% of CBAM products' value-added generated is concentrated in China and Europe. In aggregate terms, the value-added generated is directed to satisfy domestic demand. Some regions, such as Canada and Turkey, stand out as exceptions, with more than 80% of their value-added embedded in exports.

Workforce analysis One of the conditions for making the energy transition acceptable is the assumption of efficient economic gains, particularly in terms of job creation (Tvinnereim and Ivarsflaten, 2016; Dechezleprêtre and Sato, 2017). However, carbon-intensive industries are likely to decrease labor demand once stringent regulations are implemented (Walker, 2013). Meanwhile, this side effect could be potentially overturned by the job creation opportunity led by renewable and clean technology deployment (Montt *et al.*, 2018; Pai *et al.*, 2021; Sasse and Trutnevyte, 2023). It is highly likely that the impact on employment might vary greatly from one nation to another (McDowall *et al.*, 2023), not only by sector of activity but also by the level of qualification of the workforce (Xie *et al.*, 2023). Regarding this last argument, we provide in Figure 10, the workforce decomposition of CBAM production by employees' skills (*e.g.*, low-, medium-, and high-skilled labor). Estimates have been aggregated for each CBAM product and expressed in million workers at the regional level. We observe that the workforce is concentrated in a bunch of regions, namely, China (CHN), Africa (WAF), India (IND), and Europe (EEU). These regions accumulate more than 80% of the total CBAM-covered workforce globally. The African region (WAF), South Africa (ZAF), Turkey (TUR), and the rest of the world (WEX) show the biggest shares of low-skilled employees, amounting to more than 20% of the total workforce. Conversely, Great Britain (GBR), Russia (RUS), and Australia (AUS) record the greatest share of high-skilled workers, approximating 30% of the total workforce.

Figure 10: Workforce decomposition of CBAM products by skill (in mn workers)



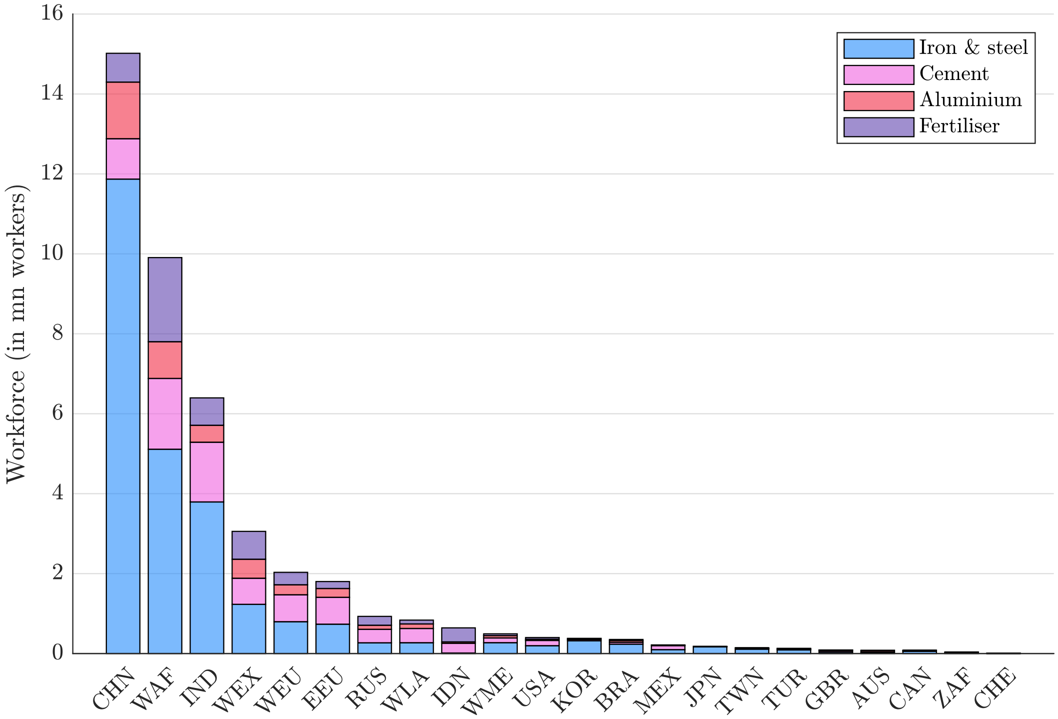
Source: Exiobase 2022 & Author's calculations.

When we detail workforce composition in CBAM-covered sectors (see Figure 11), we observe that the vast majority of the 42 million employed workforce come from the iron and steel industry. In total, it generates employment for more than 25 million workers globally, which represents nearly 60% of the total workforce of CBAM-covered products. This trend is largely driven by the three most populous regions, namely China (CHN), Africa (WAF), and India (IND), cumulating almost 70% of the total workforce used in CBAM sectors.

With some exceptions, this pattern holds across other regions. For instance, in Indonesia

(IDN), labor demand is primarily driven by the fertilizer and cement industries. In Switzerland (CHE), more than 80% of CBAM-related employment is concentrated in the cement sector. The cement industry ranks second in overall employment, providing over 7 million jobs, or nearly 18% of the total CBAM workforce. The aluminium industry, by contrast, is not a major global employer, with only 4 million workers. Australia (AUS) is the only country where a significant share of the CBAM-covered workforce is employed in the aluminium sector.

Figure 11: Total workforce by CBAM product (in mn workers)



Source: Exiobase 2022 & Author's calculations.

When we cross workforce qualifications and CBAM-covered sectors (see Table 6), we observe that the lion's share of employment is detained by medium-skilled workers, reaching almost 75% of total. While low-skilled workers represent 16% of the total workforce, that is, nearly 7 million jobs, high-skilled workers represent less than 10% of the total workforce. The fertiliser industry is the main hub for lower-skilled jobs, which might be driven by Indonesia. By contrast, the cement industry gathers the biggest share of high-skilled workers, with almost 12% of the industry's workforce.

Table 6: Aggregate workforce occupation (in % of total) by skills in CBAM sectors

Skills	Aluminium	Cement	Fertiliser	Iron & steel	Total
High-skilled	10.51	11.89	7.07	9.03	9.43
Medium-skilled	72.44	70.71	72.01	75.63	73.97
Low-skilled	17.04	17.40	20.92	15.35	16.60

Source: Exiobase 2022 & Author's calculations.

Labor productivity and competitiveness Our analysis thus far indicates that some regions play a larger role than others in the production and trade of CBAM-covered products. As a result, differences in labor allocation across regions and industries may reflect underlying comparative advantages. Ideally, each region specializes in CBAM products based on its relative productivity and competitiveness. From this perspective, assessing these performance values through a workforce-focused lens may provide valuable insights. In Table 11, we present the labor productivity $\mathcal{LP}$, expressed in value-added generated per hour worked, and competitiveness $\mathcal{LC}$, expressed in value-added generated per monetary unit of labor cost for each CBAM-covered product. First, we notice some extreme values of labor productivity[20] and competitiveness. As a rule of thumb, we consider that labor competitiveness cannot exceed €10 worth of value-added per hour worked.

Without providing a detailed list of the best and worst regions in terms of labor productivity and competitiveness, we can see recurring patterns across products. In terms of labor productivity, Switzerland, France, and Norway consistently rank among the top three most productive regions across all CBAM-covered products. Switzerland is showing high labor productivity regarding aluminium and cement, France for fertiliser and iron and steel, and Norway for cement, and iron and steel production. As a general rule, regions with high productivity ratios are predominantly high-income countries in Europe. Among the least productive regions, we retrieve the rest-of-the-world regions regarding Europe, with the lowest productivity figures across all CBAM-covered products. The African region also has the lowest productivity ratios regarding aluminium, cement, and iron and steel production. India is also recurring in the list as the least productive for aluminium, cement, and fertiliser production. Overall, aluminium production records the greatest labor productivity with €15.27 worth of value-added per hour worked. In contrast, the fertiliser production is the lowest one, with around €6.15 of value-added per hour worked.

Regarding labor cost competitiveness, we get a different sample of regions ranking across products, although it is difficult to emphasize recurring regions. Indonesia appears to be one of the most competitive regions for aluminium and cement production after omitting extreme values. China and Taiwan are particularly highly competitive in aluminium and iron and steel production, respectively. On the other hand, Denmark, Russia, Turkey, and Croatia are among the least productive regions across CBAM-covered products. Denmark consistently ranks among the least competitive in labor productivity for aluminium, cement, and iron and steel production, generating less than €1.5 of value-added per unit of labor cost. Overall, aluminium production is the most labor-competitive sector, whereas cement production is the least competitive.

The aggregated European region generally exceeds the global average in labor productivity across all CBAM-covered products but consistently lags in terms of labor cost competitiveness. In comparison to its main trading partners, we observe several key patterns. The EU is both less competitive and less productive than China and is less competitive than the African region in cement production. In iron and steel production, the EU lags in competitiveness compared to Russia, China, India, the USA, and the African region. However, it generally demonstrates higher productivity than most of its trading partners, with the exception of Russia and the USA. In fertilizer production, the EU tends to be more competitive than its counterparts, whereas the opposite holds for aluminium production. Once again, in both sectors, the EU exhibits higher productivity than its main trading partners, except for Russia and the USA.

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[20] Japan regarding aluminum, South Africa regarding cement, and Switzerland regarding iron and steel.

Table 7: Labor productivity ($\mathcal{LP}$) and competitiveness ($\mathcal{LC}$) of CBAM products

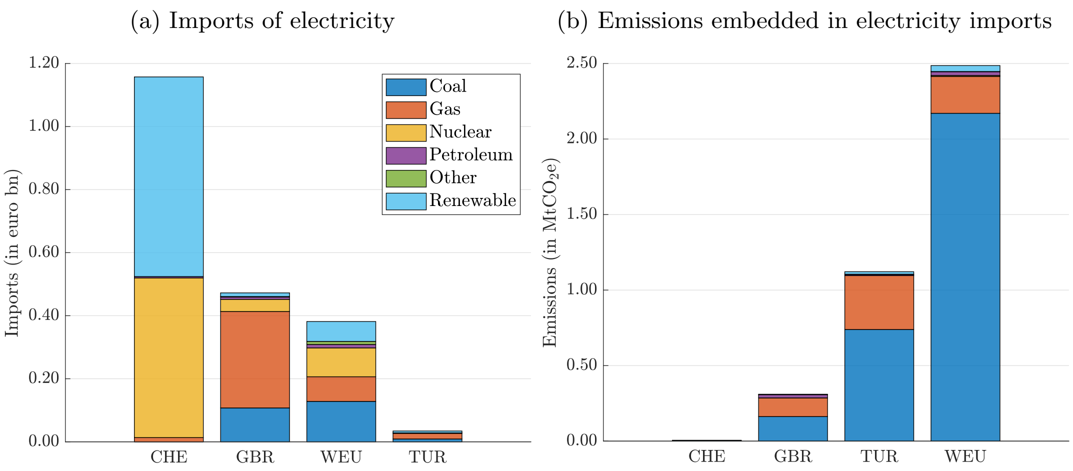
	Aluminium		Cement		Fertiliser		Iron & steel	
Region	$\mathcal{LP}$	$\mathcal{LC}$	$\mathcal{LP}$	$\mathcal{LC}$	$\mathcal{LP}$	$\mathcal{LC}$	$\mathcal{LP}$	$\mathcal{LC}$
Australia	71.10	3.40	74.30	1.72	37.57	1.58	58.71	1.73
Austria	65.64	2.31	51.71	1.57	317.37	9.87	97.49	2.62
Belgium	116.20	1.57	83.14	1.61	191.74	1.62	147.96	1.51
Brazil	19.18	2.24	13.69	3.12	18.62	1.94	31.54	3.82
Bulgaria	13.00	31.74	11.17	2.97	3.95	9.86	18.73	17.22
Canada	109.41	2.57	75.10	2.57	372.11	2.81	58.67	1.62
China	17.29	5.66	12.50	25.27	18.05	4.05	10.83	2.37
Croatia	40.04	1.20	19.30	1.49	9.08	2.46	36.98	1.32
Cyprus	–	1.88	31.40	1.49	3.69	1.81	26.39	1.60
Czech Republic	28.10	2.00	18.47	1.89	28.76	2.11	33.76	2.08
Denmark	82.46	1.25	89.85	1.41	5.34	1.39	143.42	1.38
Estonia	199.03	1.08	25.53	1.56	38.39	2.98	88.19	1.45
Europe	40.84	1.89	35.43	1.73	12.68	2.65	46.26	2.12
Finland	268.37	1.26	91.78	1.44	38.28	3.39	127.12	1.83
France	120.68	1.98	100.10	1.52	382.74	1.83	150.66	2.48
Germany	89.42	1.81	68.85	1.87	153.49	3.29	99.29	1.95
Greece	43.00	2.42	26.01	1.93	4.97	1.73	58.59	2.72
Hungary	42.30	1.77	23.17	2.12	3.22	3.19	23.85	1.78
India	2.41	2.81	2.99	1.96	0.87	1.74	3.61	2.39
Indonesia	5.27	9.28	4.17	3.25	4.16	1.93	54.49	13.76
Ireland	56.54	1.39	73.10	1.24	88.03	6.31	52.11	1.59
Italy	26.31	1.95	32.93	1.76	4.45	1.88	25.54	2.14
Japan	1 163.91	2.96	106.85	3.46	49.09	1.71	81.46	3.06
Latvia	13.87	3.47	12.90	2.51	10.17	2.01	21.38	4.97
Lithuania	13.00	1.92	9.19	5.64	44.02	86.07	24.69	3.37
Luxembourg	161.79	2.24	131.45	1.36	138.52	3.90	146.84	2.30
Malta	8.21	3.76	–	–	9.36	1.29	3.48	0.25
Mexico	48.17	90.30	11.30	28.12	42.14	89.99	58.42	84.73
Netherlands	53.59	1.66	107.47	1.72	20.50	3.32	75.35	1.82
Norway	159.29	1.98	162.16	1.38	35.54	1.89	220.31	1.95
Poland	13.16	3.06	14.69	3.20	10.38	3.42	12.77	2.81
Portugal	7.78	2.11	15.63	1.88	20.93	1.51	9.55	2.22
Romania	23.71	4.77	7.36	1.97	3.84	1.22	42.04	5.92
Russia	72.35	4.88	9.44	1.42	12.34	1.33	77.33	3.77
Slovakia	13.81	2.80	12.88	2.40	0.50	5.61	27.41	3.18
Slovenia	39.58	1.46	20.82	1.56	38.32	1.63	48.25	1.46
South Africa	44.86	91.40	1 190.36	157.54	11.34	3.32	141.29	25.98
South Korea	48.59	4.04	23.97	2.23	46.45	1.99	55.34	3.31
Spain	41.67	1.68	15.17	1.44	4.62	2.28	47.97	2.04
Sweden	84.84	1.66	96.03	1.83	60.84	2.12	133.73	1.84
Switzerland	641.51	1.75	157.25	1.65	165.03	1.85	1 097.75	2.22
Taiwan	29.21	2.04	23.95	2.44	8.03	20.05	35.61	6.11
Turkey	16.89	1.45	18.86	1.46	14.07	1.09	24.33	1.21
Great Britain	23.59	1.29	47.25	1.34	15.25	2.87	27.97	1.44
United States	130.22	3.19	84.60	1.76	55.85	2.02	55.28	2.26
World (Africa)	2.46	2.71	1.43	1.89	0.86	2.39	2.31	2.55
World (Europe)	1.78	2.32	0.97	1.64	0.77	2.02	2.11	2.87
World (Latin America)	9.64	3.81	6.53	2.19	6.43	2.81	13.26	4.24
World (Middle East)	29.91	3.30	34.03	2.17	35.62	3.99	26.14	2.45
World (ROW)	2.40	3.40	2.77	2.06	1.29	2.00	2.84	3.50
Total	15.27	3.28	11.26	2.13	6.15	2.73	11.84	2.53

Source: Exiobase 2022 & Author's calculations.

3.2.5 Electricity production

As far as electricity generation is concerned by the CBAM regulation, we should consider the width of the EU's electricity imports from third countries and their subsequent emissions. In Figure 12a, we present the major exporting regions of electricity to Europe. The list includes only four regions, namely Switzerland (CHE), Great Britain (GBR), the rest of the world European region (WEU), and Turkey (TUR), for a total trade amount of € 2 bn. Switzerland is dominating the other by exporting €1.2 bn worth of electricity, which represents almost 60% of total European electricity imports. Swiss electricity exports are principally coming from renewable and nuclear sources. In the second position, we retrieve the Great Britain, which principally exports electricity generated by gas and coal sources, similar to Turkey but in relatively less volume. The European rest-of-the-world region seems to export a balanced mix of electricity composed of coal, gas, nuclear, and renewable sources. Notice that trade is rather bilateral and promiscuous. For instance, Switzerland exports to Italy, the Great Britain to Norther Ireland, and Turkey to Greece.

Figure 12: European imports of Electricity from third regions


(a) Imports of electricity

(b) Emissions embedded in electricity imports

Source: Exiobase 2022 & author's calculations

If trade amounts seem rather small, embedded emissions tend to be significant (see Figure 12b). Indeed, the total embedded emissions amount to nearly 4 MtCO$_2$e, which represents approximately 2 kgCO$_2$e per euro of imported electricity. Coal overwhelmingly dominates the total impact, accounting for 80% of the total contribution.

4 Estimating CBAM impact on the global supply through MRIO modeling

In what follows, we provide a general overview of the methodology[21] used to frame the policy assessment using input-output modeling at the multi-regional level. As a carbon border mechanism, the carbon tax methodology should be refined to ensure an accurate estimation of compliance costs levied on imports.

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[21] This study is part of a research project following on from the work of Adenot *et al.* (2022), Desnos *et al.* (2023), and Roncalli and Semet (2024). This section takes up some of the points already mentioned in these studies.

4.1 Carbon pricing method

The previous methodology provides a comprehensive framework to set the stage for a carbon accounting framework using any input-output data. One peculiar application of the Leontief model is the simulation of carbon pricing cascading effects on the supply chain (Schotten *et al.*, 2021; Adenot *et al.*, 2022; Desnos *et al.*, 2023; Roncalli and Semet, 2024). Interlinkages between sectors, products, and regions enable the study of the carbon cost diffusion among actors (*i.e.*, suppliers, customers, and final consumers).

4.1.1 The carbon tax impact on value-added

In this study, we consider the value-added approach, in which the carbon tax affects the income of the producer. Let's consider a nominal carbon price τ (expressed in €/tCO$_2$e). The absolute amount of carbon tax paid by producer j in region s is defined by:

$$T^s_{\text{direct},j} = \tau_j \, \boldsymbol{\mathcal{CE}}^s_{\text{direct},j} \tag{7}$$

where $\boldsymbol{\mathcal{CE}}^s_{\text{direct},j}$ is the absolute amount of direct emissions generated by sector j in region s. The carbon tax rate can be defined as:

$$t^s_{\text{direct},j} = \frac{T^s_{\text{direct},j}}{x^s_j} = \frac{\tau_j \, \boldsymbol{\mathcal{CE}}^s_{\text{direct},j}}{x^s_j} = \tau_j \, \boldsymbol{\mathcal{CI}}^s_{\text{direct},j} \tag{8}$$

Thus, the direct cost for producer j in region s can be rewrite in matrix form as $T_{\text{direct}} = x \odot t_{\text{direct}}$ where $t_{\text{direct}} = (t^1_{\text{direct},1}, \ldots, t^m_{\text{direct},n})$ is the vector of direct tax rates. The value-added approach suggests that the total amount of carbon tax comes as an additional cost for producer j. Remaining equation (2), we can assess the tax impact as:

$$p^s_j x^s_j = \sum_{r=1}^{m} \sum_{i=1}^{n} Z^{r,s}_{i,j} p_i + \sum_{k=1}^{c} V^s_{k,j} \psi^s_k + T^s_{\text{direct},j}$$

From the cost-push price model, we retrieve:

$$p^s_j = \sum_{r=1}^{m} \sum_{i=1}^{n} A^{r,s}_{i,j} p^r_i + \sum_{k=1}^{c} B^s_{k,j} \psi^s_k + t^s_{\text{direct},j} = \sum_{r=1}^{m} \sum_{i=1}^{n} A^{r,s}_{i,j} p^r_i + v^s_j + t^s_{\text{direct},j}$$

or in matrix form $p = \left(I_{mn} - A^\top\right)^{-1} (v + t_{\text{direct}})$. Isolating the effect of the carbon tax only such that $\Delta v = t_{\text{direct}}$, the output price variation is equal to:

$$\Delta p = \left(I_{mn} - A^\top\right)^{-1} t_{\text{direct}} \tag{9}$$

The total tax cost can be deduced from the previous equation by generalizing it to the total output of the economy. We have:

$$T_{\text{total}} = x \odot \Delta p = x \odot \left(I_{mn} - A^\top\right)^{-1} t_{\text{direct}}$$

4.1.2 A simplified cap-and-trade system

Compared with the price instrument, the cap-and-trade system adjusts the quantity of carbon emitted over a given period of time, leaving the carbon price endogenously determined by the match between supply and demand on the carbon market. In practice, an ETS generally covers direct emissions at the installation level. For the purpose of this study, we present a simplified cap-and-trade system without endogenous price formation[22].

Let's denote the cap $\boldsymbol{\mathcal{C}}$ on emissions (expressed in tCO_2) for industries covered by the ETS. The amount of quotas $\boldsymbol{\mathcal{Q}}_j^s$ that a sector j in region s should surrender is equal to:

$$\boldsymbol{\mathcal{Q}}_j^s = \max\left[\left(1-\xi_j^s\right)\ \boldsymbol{\mathcal{CE}}_{\text{direct},j}^s\ ;\ 0\right]$$

where ξ_j^s is the share of allowances given for free to sector j in region s. This specification allows the sector to receive more allowances than its level of direct emissions. However, the emissions cap should be binding total emissions such that:

$$\boldsymbol{\mathcal{C}} \geq \underbrace{\sum_{s=1}^{m}\sum_{j=1}^{n}\left(1-\xi_j^s\right)\boldsymbol{\mathcal{CE}}_{\text{direct},j}^s}_{\text{total purchased allowances}} + \underbrace{\sum_{s=1}^{m}\sum_{j=1}^{n}\xi_j^s\boldsymbol{\mathcal{CE}}_{\text{direct},j}^s}_{\text{total free allowances}}$$

$$\boldsymbol{\mathcal{C}} \geq \sum_{s=1}^{m}\sum_{j=1}^{n}\boldsymbol{\mathcal{CE}}_{\text{direct},j}^s$$

For a carbon price τ, the direct ETS cost for sector j in region s is defined as:

$$Q_{\text{direct},j}^s = \tau_j\ \boldsymbol{\mathcal{Q}}_j^s$$

and similarly:

$$q_{\text{direct},j}^s = \frac{\tau_j\ \boldsymbol{\mathcal{Q}}_j^s}{x_j^s}$$

In matrix form, we have $Q_{\text{direct}} = x \odot\ q_{\text{direct}}$ where $q_{\text{direct}} = \left(q_{\text{direct},1}^1, \ldots, q_{\text{direct},n}^m\right)$ is the vector of direct ETS cost rates. Still, the direct ETS costs come as an additional cost for the producer j in region s:

$$p_j^s = \sum_{r=1}^{m}\sum_{i=1}^{n} A_{i,j}^{r,s} p_i^r + v_j^s + q_{\text{direct},j}^s$$

Thus, the output price variation is equal to:

$$\Delta p = \left(I_{mn} - A^\top\right)^{-1} q_{\text{direct}} \tag{10}$$

The total tax cost can be deduced from the previous equation by generalizing it to the total output of the economy:

$$Q_{\text{total}} = x \odot \Delta p = x \odot \left(I_{mn} - A^\top\right)^{-1} q_{\text{direct}}$$

Illustration Let's consider a variant of Example #1 in which the carbon pricing instrument is an ETS. If we assume that the free allocation allowances are distributed such that

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[22] Closing the model by endogenously determining the permit price would suggest knowing the marginal abatement cost (MAC) of every sector in each region.

$\xi_1 = 0.1$, $\xi_2 = 0.6$, $\xi_3 = 0.8$, and $\xi_4 = 0.2$. The amount of quotas surrendered is equal to:

$$\boldsymbol{\mathcal{Q}} = (\mathbb{1}_4 - \xi) \odot \boldsymbol{\mathcal{CE}}_{\text{direct}} = \begin{pmatrix} 450\,000 \\ 80\,000 \\ 40\,000 \\ 100\,000 \end{pmatrix}$$

If we assume a homogeneous carbon price for the emissions permits of $\tau = €100/\text{tCO}_2$, the direct ETS cost rate would be:

$$q_{\text{direct}} = \tau \odot (\mathbb{1}_4 - \xi) \odot \boldsymbol{\mathcal{CI}}_{\text{direct}} = \begin{pmatrix} 0.0180 \\ 0.0020 \\ 0.1250 \\ 0.0800 \end{pmatrix}$$

and the direct ETS cost, expressed in € mn:

$$Q_{\text{direct}} = x \odot q_{\text{direct}} = \begin{pmatrix} 5\,000 \\ 4\,000 \\ 8\,000 \\ 125\,000 \end{pmatrix} \odot \begin{pmatrix} 0.0180 \\ 0.0020 \\ 0.1250 \\ 0.0800 \end{pmatrix} = \begin{pmatrix} 90 \\ 8 \\ 4 \\ 10 \end{pmatrix}$$

In the case of the ETS, the output price variation is given by:

$$\begin{aligned} \Delta p &= \left(I_4 - A^{\top}\right)^{-1} q_{\text{direct}} \\ &= \begin{pmatrix} 1.1881 & 0.1678 & 0.1430 & 0.0715 \\ 0.3894 & 1.2552 & 0.4110 & 0.1718 \\ 0.4919 & 0.4336 & 1.6303 & 0.2993 \\ 0.2884 & 0.1891 & 0.3044 & 1.6087 \end{pmatrix} \begin{pmatrix} 0.0180 \\ 0.0020 \\ 0.1250 \\ 0.0800 \end{pmatrix} = \begin{pmatrix} 0.0219 \\ 0.0099 \\ 0.0108 \\ 0.0070 \end{pmatrix} \end{aligned}$$

Finally, we can compute the total ETS cost for each sector:

$$\begin{aligned} Q_{\text{total}} &= x \odot \Delta p \\ &= \begin{pmatrix} 5\,000 \\ 4\,000 \\ 8\,000 \\ 125\,000 \end{pmatrix} \odot \begin{pmatrix} 0.0219 \\ 0.0099 \\ 0.0108 \\ 0.0070 \end{pmatrix} = \begin{pmatrix} 109.2510 \\ 39.4476 \\ 86.2091 \\ 87.6102 \end{pmatrix} \end{aligned}$$

4.1.3 The pass-through rate modeling

The purpose of modeling the pass-through rate is to estimate the behavioral response of producers when facing the additional cost imposed by the carbon pricing mechanism. It is generally assumed that a firm facing carbon cost has the following option: (*i*) reduce the carbon intensity of the production until the shadow price of decarbonization equals the carbon cost; (*ii*) comply with the regulation by respecting the *polluter-pays* principle giving up part of its value-added; or (*iii*) pass the carbon cost on it customers. The third case represents the pass-through mechanism, such that the producer would keep the same level of added value[23] as before by passing the extra cost to customers (Sautel *et al.*, 2022). Thus, a critical aspect of the cascading pattern of carbon pricing is linked to the assumptions made on the cost-pass-through rate.

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[23] The mechanism only holds if the price elasticity of demand is sufficiently high to compensate for the loss of competitiveness.

In this study, we refer to the methodology developed by Roncalli and Semet (2024) to integrate pass-through mechanisms. Denote $\Phi = \operatorname{diag}(\phi)$ the pass-through rate matrix composed of individual pass-through rates such that $\phi = \left(\phi_1^1, \ldots, \phi_n^m\right)$. Including pass-through rates in equation (4) gives the following expression:

$$\Delta p = \left(I_{mn} - A^\top \Phi\right)^{-1} \Phi \Delta \upsilon = \tilde{\boldsymbol{\mathcal{L}}}\left(\boldsymbol{\phi}\right) \Delta \upsilon$$

where $\tilde{\boldsymbol{\mathcal{L}}}\left(\phi\right) = \left(I_{mn} - A^\top \Phi\right)^{-1} \Phi$. The lower bound of cascading price is reached when $\phi = \mathbf{0}_n$ while upper bound is reached when $\phi = \mathbb{1}_{mn}$.

Application to carbon pricing Given the previous specification, it becomes relatively easy to consider the pass-through mechanism in the carbon pricing framework. Let's apply the cost-pass-through rate model to a simplified cap-and-trade system. If we consider the capacity of producers to pass carbon costs through customers[24], costs from each side of the supply chain would be modified accordingly. For the producer, we have:

$$Q_{\text{producer}} = \left(\mathbb{1}_{mn} - \phi\right) \odot Q_{\text{direct}}$$

For the customer, we have:

$$Q_{\text{customer}} = x \odot \tilde{\boldsymbol{\mathcal{L}}}(\phi)\ q_{\text{direct}}$$

Then, we can deduce the total ETS cost for the whole economy:

$$\begin{aligned} Q_{\text{total}} &= Q_{\text{producer}} + Q_{\text{customer}} \\ &= x \odot \left(I_{mn} - \Phi + \tilde{\boldsymbol{\mathcal{L}}}(\phi)\right) q_{\text{direct}} \end{aligned}$$

In this context, the ETS cost on producers is defined as the direct cost linked to the payment of quotas less the part of this cost that it decided to pass through customers. The ETS cost to customers is the indirect cost it receives from the suppliers. Let's consider two extreme cases:

- $\phi = \mathbb{1}_{mn} \Longrightarrow \tilde{\boldsymbol{\mathcal{L}}}(\phi) = \tilde{\boldsymbol{\mathcal{L}}} \Longrightarrow \Delta p = \tilde{\boldsymbol{\mathcal{L}}}\ q_{\text{direct}}$
  In this situation, the producer bears no cost from the policy $Q_{\text{producer}} = \mathbf{0}_{mn}$ since it passes the carbon costs fully to its customers. Conversely, customers bear the total cost of the policy $Q_{\text{customer}} = Q_{\text{total}}$.
- $\phi = \mathbf{0}_{mn} \Longrightarrow \tilde{\boldsymbol{\mathcal{L}}}(\phi) = \mathbf{0}_{mn,mn} \Longrightarrow \Delta p = \mathbf{0}_{mn}$
  In this situation, the producer bears all the ETS cost such that $Q_{\text{producer}} = Q_{\text{direct}}$, while customers are not impacted $Q_{\text{customer}} = \mathbf{0}_{mn}$.

4.2 CBAM design and scenario construction

In the previous section, we provide a general overview of the methodology used in input-output modeling to estimate the carbon accounting framework required to support the macroeconomic analysis of carbon pricing. As the CBAM analysis involves differentiated treatment of carbon pricing at the country and product level, we should refine this methodology.

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[24] We use the term "customer" in reference to the downstream of the supply chain, in contrast to the producer or supplier, which is at the upstream of the supply chain. The terms should be regarded in concordance with direct emissions.

4.2.1 CBAM regulations and the EU ETS

Incorporating the CBAM into the previous modeling framework requires the application of a carbon tax to specific products in certain regions while restricting its cascading effects to imports destined for Europe. However, as remarked by Sautel *et al.* (2022, Chapter 2), no established methodology exists for such an analysis. Thus, most CBAM analyses using IO modeling have overcome this drawback by estimating direct CBAM exposure rather than estimating the total effect on the global supply chain (Rocchi *et al.*, 2018; Schotten *et al.*, 2021; Magacho *et al.*, 2024). Thus, it is not uncommon to approximate the direct impact of the CBAM using the following equation:

$$T^r_{\text{direct},i} = \tau\, \boldsymbol{\mathcal{CI}}^r_{\text{direct},i} \boldsymbol{\mathcal{X}}^{r\to s}_i \quad \forall\ s \in \mathbf{EU}\ \wedge\ i \in \mathbf{CBAM}$$

This approximation thus makes it possible to determine the CBAM compliance cost falling on EU imports. However, this static approximation fails to account for cascading effects in the supply chain since price variations remain confined to EU imports of CBAM-covered products and do not propagate.

In order to preserve the integrity of the supply chain while allowing the additional CBAM compliance costs to be passed on to the various entities, the carbon tax rate must be redefined as follows:

$$t^r_{\text{direct},i} = \begin{cases} \boldsymbol{\mathcal{CI}}^r_{\text{direct},i} \Delta\tau^r & \text{if } r \notin \mathbf{EU} \wedge i \in \mathbf{CBAM} \\ 0 & \text{otherwise} \end{cases}$$

where $\Delta\tau^s = \tau - \tau^s$ is the carbon price difference between the EU ETS, and the one applied in region s. The specified tax rate reflects the carbon price gap between the EU and third regions. To ensure that the compliance costs fall effectively and only on European imports, let's introduce an import's adjacency matrix $U = \left(U^{r,s}_{i,j}\right)$, which flags EU imports of CBAM-covered products from third regions. In this manner, we isolate trades likely to be covered by the CBAM, namely, European imports of the products covered by the program from third countries. The adjacency matrix is defined as:

$$U^{r,s}_{i,j} = \begin{cases} 1 & \text{if } s \in \mathbf{EU} \wedge i \in \mathbf{CBAM} \wedge r \notin \mathbf{EU} \\ 0 & \text{otherwise} \end{cases}$$

Then, we can retrieve the CBAM compliance cost rate of importer j in region s:

$$c^s_{\text{direct},j} = \sum_{r=1}^{m} \sum_{i=1}^{n} U^{r,s}_{i,j} A^{r,s}_{i,j} t^r_{\text{direct},i}$$

In matrix form, we obtain:

$$c_{\text{direct}} = \mathbb{1}^\top_{mn} \left(U \odot A \odot t_{\text{direct}}\right)$$

where $c_{\text{direct}} = \left(c^1_{\text{direct},1}, \ldots, c^m_{\text{direct},n}\right)$ is a row vector of size $1 \times mn$. A typical element of this vector describes the CBAM compliance rate faced by the production j in region s. The total compliance costs amount to:

$$\mathcal{C}_{\text{direct}} = x^\top \left(U \odot A \odot t_{\text{direct}}\right)$$

In this manner, CBAM compliance costs effectively fall on intermediary imports of CBAM-covered products coming from third regions and not on exports.

Then, we can diffuse the European CBAM compliance cost throughout the supply chain. Allowing for pass-through mechanisms, the price variation is defined as:

$$\Delta p = \left(I - A^\top \Phi\right)^{-1} \Phi c^\top_{\text{direct}}$$

Illustration Let's consider Example #1. Assuming that Region $\boldsymbol{\mathcal{A}}$ is imposing a carbon border adjustment on product S_1 to Region $\boldsymbol{\mathcal{B}}$. Region $\boldsymbol{\mathcal{A}}$ imposes a €100/tCO$_2$e on production while region $\boldsymbol{\mathcal{B}}$ sets the tax rate at €10.

The tax rate is only defined for the sector covered by the carbon border adjustment in region $\boldsymbol{\mathcal{B}}$:

$$t_{\text{direct}} = \begin{pmatrix} 0.0000 \\ 0.0000 \\ 0.0025 \\ 0.0000 \end{pmatrix}$$

The adjacency matrix of imports covered by the policy is defined as:

$$U = \begin{pmatrix} 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 1 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix}$$

Then, we can compute the compliance cost rate and the total compliance costs:

$$\begin{aligned} c_{\text{direct}} &= \mathbb{1}_4^\top \left(U \odot A \odot t_{\text{direct}} \right) \\ &= \begin{pmatrix} 1 & 1 & 1 & 1 \end{pmatrix} \begin{pmatrix} 0.0000 & 0.0000 & 0.0000 & 0.0000 \\ 0.0000 & 0.0000 & 0.0000 & 0.0000 \\ 0.1250 & 0.5000 & 0.0000 & 0.0000 \\ 0.0000 & 0.0000 & 0.0000 & 0.0000 \end{pmatrix} \\ &= \begin{pmatrix} 0.1250 & 0.5000 & 0.0000 & 0.0000 \end{pmatrix} \end{aligned}$$

and the total compliance costs:

$$\mathcal{C}_{\text{direct}} = x^\top \begin{pmatrix} 0.1250 & 0.5000 & 0.0000 & 0.0000 \end{pmatrix} = \begin{pmatrix} 1 & 4 & 0 & 0 \end{pmatrix}$$

Assuming that pass-through rates are all equal to one, diffusing the compliance cost throughout the supply chain gives the following price variation:

$$\Delta p = \begin{pmatrix} 0.2324 \\ 0.6763 \\ 0.2783 \\ 0.1306 \end{pmatrix}$$

EU importer effectively pays the CBAM compliance cost, the exporter's pass-through rate should be equal to one. Then, we can express the output price impact as:

$$\Delta p = \left(I_{mn} - A^\top \Phi \right)^{-1} I_{mn} \, t_{\text{direct}}$$

However, the tax impact would extend beyond CBAM importers, affecting both the domestic economies of exporting countries and their exports to non-EU regions.

4.2.2 Modeling EU ETS allowance allocation

Testing the CBAM as an alternative to free allocation to estimate carbon leakage risk, as is typically done (European Commission, 2021a), presents significant challenges using the input-output framework. Nonetheless, we stick with scenario analysis by considering several CBAM design options and market-based responses to account for a large range of possibilities in terms of economic and social impacts. We consider that the ETS cost only applies to producers that are producing goods under the coverage of the **ETS** within the EU borders. Then, we can state that the direct ETS cost rate is equal to:

$$q^s_{\text{direct},j} = \begin{cases} \tau \left(1 - \xi^s_j\right) \mathcal{CI}^s_{\text{direct},j} & \text{if } s \in \mathbf{EU} \wedge j \in \mathbf{ETS} \\ 0 & \text{otherwise} \end{cases}$$

4.2.3 Scenario design

To explore the multiple repercussions that the CBAM could have on the economy, we consider several scenario analyses based on the six options elaborated by the European Commission (2021a). In line with the MRIO model, three aspects are particularly diverging across scenarios: the depth of the value chain, the allocation method in the EU ETS, and the embedded emissions computation. For the purpose of this study, we consider three scenarios, each leveraging on the three diverging aspects.

Scenario 1 In the first scenario, we stick with the third option of the European Commission (2021a). The CBAM regulation is a CBAM market for import certificates[25] which covers the imports of basic materials and basic material products. European products under the CBAM are no longer receiving allowances for free. Embedded emissions are computed using the actual carbon intensity of the exporting country. This scenario appears as the base case scenario since the previously specified MRIO model does not need to be refined.

Scenario 2 In the second scenario, we are close to the first option of the European Commission (2021a). The CBAM regulation is a tax on imports that covers the imports of basic materials and basic material products. The CBAM importers are, again, no longer receiving allowances for free, but the embedded emissions are computed using a default value. In this case, we assume that default values correspond to the carbon intensity of the production within the EU borders. Direct carbon tax rates are computed using default values of carbon intensities:

$$t^s_{\text{direct},j} = \begin{cases} \overline{\mathcal{CI}}_{\text{direct},j} \Delta\tau^s & \text{if } s \notin \mathbf{EU} \wedge j \in \mathbf{CBAM} \\ 0 & \text{otherwise} \end{cases}$$

where

$$\overline{\mathcal{CI}}_{\text{direct},j} = \sum_{s=1}^{m} \left(\frac{\mathcal{CE}^s_{\text{direct},j}}{x^s_j} \right) \quad \text{for } s \in \mathbf{EU}$$

$\overline{\mathcal{CI}}_{\text{direct},j}$ is thus defined as the aggregated carbon intensity of the j^{th} CBAM-covered product within the EU. Default values are presented in Table 8. Values are expressed in kgCO$_2$e per monetary unit of output.

Table 8: CBAM-covered product's default values (in kgCO$_2$e/€)

	Aluminium	Cement	Fertiliser	Iron & steel
$\mathcal{CI}_{\text{direct}}$	0.39	7.73	0.99	0.68
$\mathcal{CI}_{\text{total}}$	1.52	8.75	1.48	1.54

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[25] Notice that there is no methodological gap between a tax on imports or a CBAM certificate market.

Scenario 3 As in option five, our third scenario enlarges the depth of the value chain. Finished products are now covered by the regulation. To select the concerned sectors, we perform a downstream analysis on the first tier of the supply chain. More specifically, we determine the most important products downstream of sharing a direct link with CBAM-covered products within the European economy. This selection process is made possible using a network representation. More detail on the network representation is available in Appendix A.3 on page 76.

From the four products initially covered, a list of 23 products is found to be strongly linked to CBAM-covered products. This list of products is presented in Table 9 with their ranking of importance. We also provide their degree $\mathbf{k}_i$ and weighted degree $\mathbf{k}_i^{\text{in}}$, as well as a centrality measure, namely the Katz-Bonacich ($\boldsymbol{\mathcal{KB}}$) measure. These metrics are presented in Appendix A.3 on page 76.

Table 9: Most critical products in CBAM network (downstream analysis)

Rank	Product	$\mathbf{k}_i$	$\mathbf{k}_i^{\text{in}}$	$\boldsymbol{\mathcal{KB}}_i$
1	Construction work	4	0.749	1.525
2	Fabricated metal products	2	0.319	1.226
3	Machinery and equipment	2	0.211	1.149
4	Motor vehicles	2	0.141	1.100
5	Cereal grains	1	0.117	1.082
6	Electrical machinery	2	0.096	1.068
7	Crops	1	0.074	1.052
8	Wheat	1	0.069	1.048
9	Oil seeds	1	0.068	1.048
10	Vegetables, fruit, nuts	1	0.061	1.043
11	Foundry work services	2	0.053	1.037
12	Furniture	2	0.044	1.031
13	Transport equipment	2	0.043	1.030
14	Medical, precision and optical instruments	2	0.030	1.021
15	Sugar cane	1	0.023	1.016
16	Plastics	1	0.021	1.015
17	Rubber and plastic products	2	0.018	1.013
18	Other business services	2	0.018	1.013
19	Raw milk	1	0.014	1.010
20	Cattle	1	0.014	1.010
21	Communication equipment	1	0.011	1.007
22	Pigs	1	0.009	1.006
23	Real estate services	1	0.008	1.006

4.3 Economic and social CBAM indicators

In what follows, we provide some economic and social indicators assessing the repercussions of the CBAM. Based on the input-output modeling, we provide some metrics regarding economic costs at the macro-level (*e.g.*, regions) and micro-level (*e.g.*, sectors) through cost-sharing impact, price index variation, competitiveness distortions, and carbon leakage potentials. Social indicators are composed of welfare variation and labor impact.

4.3.1 CBAM exposure indices

The CBAM impact is likely to hit trade relations for the products concerned, which might have economic consequences for exporting regions. Before taking into account the indirect mechanisms induced by the global value chain, we estimate the region's absolute and relative exposure[26] to CBAM. Both exposure types depend on two parameters: the carbon intensity of domestic production and EU trade dependency. Here, we determine the additional export cost by multiplying the carbon intensity with the ETS carbon price (expressed in €/tCO$_2$e). Export exposure is simply the ratio between CBAM product exports to the EU over total CBAM exports. Thus, the absolute CBAM exposure index ($\boldsymbol{\mathcal{AEI}}$) measures the additional cost of CBAM, adjusted by the proportion of exports to the EU market:

$$\boldsymbol{\mathcal{AEI}}^r = \sum_{i=1}^{n} \left[\frac{\boldsymbol{\mathcal{X}}_i^{r\to \text{EU}}}{\sum_{s\neq r} \boldsymbol{\mathcal{X}}_i^{r\to s}} \cdot \left(\tau \, \boldsymbol{\mathcal{CI}}^r_{\text{direct},i} \right) \right]$$

Note that the $\boldsymbol{\mathcal{AEI}}$ could be refined by incorporating relative factors, such as the carbon price gap. Additionally, some regions may gain a competitive advantage due to their lower carbon intensity compared to Europe. The relative exposure index thus accounts for both components:

$$\boldsymbol{\mathcal{REI}}^r = \sum_{i=1}^{n} \left[\frac{\boldsymbol{\mathcal{X}}_i^{r\to \text{EU}}}{\sum_{s\neq r} \boldsymbol{\mathcal{X}}_i^{r\to s}} \cdot \left(\Delta\tau^r \Delta\boldsymbol{\mathcal{CI}}^r_{\text{direct},i} \right) \right]$$

where $\Delta\tau^r = \tau - \tau^r$, and $\Delta\boldsymbol{\mathcal{CI}}^r_{\text{direct},i} = \overline{\boldsymbol{\mathcal{CI}}}_{\text{direct},i} - \boldsymbol{\mathcal{CI}}^r_{\text{direct},i}$. With this formulation, the index can take negative values, indicating a competitive advantage over EU producers.

4.3.2 Economic costs

Carbon leakage potential To define sectors at risk of carbon leakage, the quantitative methodology estimates the carbon and trade intensity of sector and sub-sectors of the EU ETS (Juergens and Barreiro-Hurlé, 2013). The carbon cost intensity of sector j can be defined as the additional costs induced by the pricing of direct and indirect emissions:

$$\boldsymbol{\mathcal{CCI}}_i^r = \frac{\tau \, \boldsymbol{\mathcal{CE}}^r_{\text{total},i}}{\upsilon_i^r}$$

In the first carbon leakage list (European Commission, 2009), this additional cost was assessed based on the total cost induced by a €30/tCO$_2$carbon price, adjusted for value-added. On the trade part, the trade intensity is measured as the ratio between exports plus imports to third countries and imports plus total output:

$$\boldsymbol{\mathcal{TI}}_i^r = \frac{\boldsymbol{\mathcal{X}}_i^{r\to s} + \boldsymbol{\mathcal{M}}_i^{r\leftarrow s}}{\boldsymbol{\mathcal{M}}_i^{r\leftarrow s} + x_i^r}$$

A sector was considered at risk if it fell under certain conditions[27] regarding these metrics. In the revised carbon leakage, list, the criteria for identifying sectors at risk has been narrowed to the carbon leakage risk indicator, which is the product between carbon and trade intensity:

$$\boldsymbol{\mathcal{CCR}}_i^r = \boldsymbol{\mathcal{CI}}^r_{\text{total},i} \cdot \boldsymbol{\mathcal{TI}}_i^r$$

As a rule, any sector i in region r with a score exceeding 0.2 is considered at risk of carbon leakage.

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[26] This approach follows the indices built by the World Bank, reflecting the economic vulnerability of emerging countries to CBAM implementation. More detail is provided at `https://www.worldbank.org/en/data/interactive/2023/06/15/relative-cbam-exposure-index`.

[27] If (i) $\boldsymbol{\mathcal{CCI}} > 5\% \wedge \boldsymbol{\mathcal{TI}} > 10\%$; (ii) $\boldsymbol{\mathcal{CCI}} > 30\%$; or (iii) $\boldsymbol{\mathcal{TI}} > 30\%$.

4.3.3 Social impact

Labor productivity and competitiveness Some extensions on labor impacts have been made possible within the Leontief framework (Miller and Blair, 2009, Chapter 6). In what follows, we refine the composition of the value-added matrix V by specifically identifying labor requirements[28]. Let's assume that $\iota = \left(\iota_1^1, \ldots, \iota_n^m\right)$ represents the row vector of labor compensation (*e.g.*, income paid to the workforce) in the j^{th} sector of the s^{th} region. Similarly, the row vector $\ell = \left(\ell_1^1, \ldots, \ell_n^m\right)$ defines the quantity of labor (*e.g.*, the total number of workers or the total number of hours worked) used by sector j in region s. It is possible to retrieve the average wage level of sector j in region s as: $w_j^s = \iota_j^s / \ell_j^s$, or in matrix form $w = \iota \; \text{diag}\left(\ell\right)^{-1}$. To gauge sectors' productivity, we estimate labor productivity as the ratio between value-added and employment requirement:

$$\mathcal{LP}_j^s = \frac{\upsilon_j^s}{\ell_j^s}$$

We have $\mathcal{LP} = \upsilon^\top \; \text{diag}(\ell)^{-1}$ describing the amount of value-added per worker or per hour worked. The higher the estimate, the greater the value-added generated by one unit of work. As long as CBAM potentially disturbs competitiveness, we define labor competitiveness as the ratio between value-added and labor compensation:

$$\mathcal{LC}_j^s = \frac{\upsilon_j^s}{\iota_j^s}$$

We have $\mathcal{LC} = \upsilon^\top \; \text{diag}(\iota)^{-1}$ translating the value-added generated per monetary unit of labor compensation.

4.4 Data and model calibration

4.4.1 The Exiobase by-product tables

This study uses the latest version (2022) of multi-regional input-output (MRIO) tables from Exiobase 3 (Stadler *et al.*, 2018). The tables capture trade relationships among 44 countries and 5 rest-of-the-world regions[29]. Exiobase stands out as one of the most granular MRIO databases, detailing sectoral activities at the product level using various national accounts. Over 200 traded products are estimated based on the UN Comtrade database to align import-export data across countries. This level of product disaggregation is well-suited for macro-level environmental analyses, particularly those aiming to inform consumption-oriented policies (Wood *et al.*, 2018). Since the CBAM policy targets specific products regulated under the EU ETS, our analysis leverages Exiobase's detailed product-level data. However, there appears to be a trade-off between regional and sectoral representativeness in MRIO. Although we managed to have a fair representation of countries that are part of the EU ETS (*i.e.*, 28 out of 33), Exiobase is limited in the regional disaggregation[30], particularly with regard to emerging countries (Wood *et al.*, 2014).

Through a social accounting matrix (SAM), Exiobase provides information on more than 400 industry-specific air emission categories derived from official statistics (*e.g.*, Edgar, Eurostat, IPCC, EEA). Our carbon accounting framework estimates emissions on the basis of carbon combustion[31]. As the scope of the EU ETS also integrates N_2O and PFCs emissions

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[28] Notice that the following methodology can be consistently applied to capital requirements.

[29] The complete list of regions is provided in Appendix 17, page 77.

[30] For example, the GTAP database covers 134 countries, and EORA includes roughly 190 countries.

[31] Specifically, we use the carbon dioxide as defined by the IPCC categories 1-4 and 6-7, excluding land use, land-use change, and forestry.

from fertilizer and aluminum production, respectively, emissions are expressed as carbon dioxide equivalent (CO_2e). In addition to environmental stressors, Exiobase provides detailed labor accounts. Employment is decomposed both in hours worked and number of employees, differentiated by three skill levels and gender[32]. Estimates are derived from data provided by the International Labor Organization (ILO), Eurostat, and OECD.

With respect to the CBAM, the initial set of targeted products can be reasonably approximated using Exiobase. For cement commodities, we use Exiobase's *Cement, lime and plaster* category. For iron and steel, Exiobase aggregates these goods under *Basic iron and steel and of ferro-alloys, and first products thereof.* Although the European Commission (European Commission, 2023, page 59) implicitly excludes ferro-alloys, we cannot separate them from this category. Additionally, we include *Secondary steel for treatment and re-processing of secondary steel into new steel*, since the CBAM also covers the secondary fusion of iron and steel (European Commission, 2023, page 196). For aluminium, we rely on *Aluminium and aluminium product* while excluding *Secondary aluminium for treatment, Re-processing of secondary aluminium into new aluminium*, in accordance with the Commission's guidance. We account for both *N-fertiliser* and *P- and other fertiliser* products, where nitrogen fertiliser includes nitrate, ammonia, ammonium, and urea, and phosphorus fertiliser includes diammonium and monoammonium phosphate. Although hydrogen is initially targeted by the CBAM, it may be embedded in another category that cannot be identified separately. Finally, for the electricity market, we consider all twelve electricity sources[33] in Exiobase, as well as *Steam and hot water supply services* and *Transmission services of electricity.*

4.4.2 Intra- versus extra-EU carbon pricing programs

To credit carbon pricing in third regions, the CBAM initiative should take implemented schemes into consideration. In Table 10, we present the sectoral and national coverage of GHG emissions from carbon pricing programs implemented in foreign regions. Carbon prices τ are taken from official sources (ICAP, 2023; World Bank, 2023) and reflect explicit carbon prices.

As can be seen, most of the programs fully price emissions coming from the energy and industrial sectors. These regions would benefit from their domestic pricing program to reduce the cost of CBAM. We consider the following countries to have a pricing program aligned with the CBAM regulation: Chile, Iceland, Japan, Mexico (carbon tax), Singapore, South Africa, Switzerland (ETS), Great Britain (ETS), Ukraine, Kazakhstan, New Zealand, and South Korea. Outside of this set of 20 countries, carbon pricing instruments are rather not implemented or abandoned. In this case, imports from these countries comply with the full price of the EU ETS.

Some carbon pricing policies are partially covering emissions, advocating for tax exemption and special treatment of some sectors. For instance, Argentina's carbon tax is not levied on natural gas in the Energy sector. The Canadian federal fuel charge is only paid by fuel distributors. The Colombian carbon tax applies to fossil fuel producers but excludes coal use and domestic natural gas. For Uruguay, the carbon tax applies to all liquid fuels except jet fuels. The carbon price support (CPS) in the UK imposes a carbon tax on industries that use fossil fuels for power generation only. Regarding its quantity-based instrument, the UK's ETS applies to a specified list of activities of installations in the power and industrial

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[32] Low-skilled workers have primary education or less than secondary education. Medium-skilled workers have upper secondary education or less than tertiary education. High-skilled workers have short-cycle tertiary or more (Bachelor's, Master's, or Doctoral level).

[33] Geothermal; biomass and waste; coal; gas; hydro; nuclear; petroleum and other oil derivatives; solar photovoltaic; solar thermal; tide, wave, ocean; wind; and other.

Table 10: Sectoral coverage (in % of nationwide emissions) and carbon prices (in €/tCO$_2$e) of implemented carbon pricing program (2022)

	Carbon pricing program	Energy	Industry	Buildings	Mining	Transport	Aviation	Coverage	τ
Carbon Tax	Argentina	◐	●	○	◐	●	○	20%	4.7
	Canada federal fuel charge	◐	◐	●	◐	●	●	30%	38.0
	Chile	●	●	○	◐	○	○	29%	4.7
	Colombia	◐	●	●	◐	●	●	23%	4.7
	Iceland	●	●	●	○	●	○	55%	32.5
	Japan	●	●	●	◐	●	○	75%	2.3
	Liechtenstein	◐	●	●	○	●	○	81%	123.4
	Mexico	●	●	●	◐	◐	●	44%	3.5
	Singapore	●	●	○	●	○	○	80%	3.5
	South Africa	●	●	●	●	●	●	80%	9.3
	Switzerland	◐	●	●	◐	○	○	33%	123.4
	Great Britain CPS	●	○	○	○	○	○	24%	22.5
	Ukraine	●	●	●	○	○	○	71%	0.9
	Uruguay	◐	◐	○	○	●	○	11%	130.4
ETS	Canada federal OBPS	◐	◐	○	○	○	○	1%	38.0
	China national	●	○	○	○	○	○	31%	8.7
	EU ETS	●	●	○	●	○	●	38%	82.2
	Indonesia	◐	○	○	○	○	○	26%	0.6
	Kazakhstan	●	●	○	●	○	○	46%	1.0
	Mexico pilot	●	●	○	●	○	○	40%	0.0
	Montenegro	◐	○	○	○	○	○		24.0
	New Zealand	●	●	●	●	●	●	49%	50.0
	South Korea	●	●	●	●	○	◐	74%	17.8
	Switzerland ETS	●	●	○	●	○	○	11%	61.0
	United Kingdom ETS	●	●	○	●	○	●	28%	94.0

● Full coverage, ◐ Partial coverage, ○ No coverage.

Source: Dao *et al.* (2024) & Author's calculations.

sectors. The latter should be considered to put against the CBAM. The Canadian output-based pricing system (OBPS) is mandatory only for industries that are emissions-intensive and trade-exposed in the industrial and electricity sectors. The Canadian OBPS is closer to the EU ETS than the federal fuel charge. The Chinese and Indonesian ETS are, for the time being, only covering emissions from the energy sector.

Overall, we notice that most carbon tax programs apply to power generation, which should be regarded as indirect emissions from the industrial viewpoint. In contrast, most ETS programs directly cover industrial emissions and, therefore, align with EU ETS and CBAM compliance. However, these estimates suggest that existing carbon pricing policies would hardly compensate the CBAM. Even if implemented, their carbon prices and emission coverage would not be sufficient to be exempted from CBAM compliance, especially in East Asia and Africa. The CBAM rationale regarding the global ambition of carbon pricing is thus valid.

4.4.3 The free allowances distribution

To accurately replicate the impact of the EU ETS, our model must incorporate the allocation of free allowances. Currently, free allowances are allocated using a benchmarking approach, which determines the top 10% of the most carbon-efficient installations as a benchmark and distributes allowances accordingly. However, replicating this methodology in an input-output analysis is challenging[34], as the benchmarking approach operates at the installation level, while our data lack that level of granularity.

Therefore, the only feasible approach is to link data from the EUTL database[35] to Exiobase. The EUTL database reports verified emissions, allocated free allowances, and surrendered emissions for each EU ETS installation. Additionally, Abrell (2021) matched each installation to its NACE code based on the leakage assessment of the European Commission. This enables the aggregation of installation-level information to the four-digit NACE classification. Using this bottom-up aggregation at the country level, we can estimate the ratio of verified emissions covered by free allowances. Results are provided in Table 19 on page 79. Estimates show that in 2022, on aggregate, 50% of verified emissions from installations were given for free. This figure may be slightly overestimated[36], as in Phase 4, 57% of total covered emissions were set to be auctioned (ICAP, 2023).

4.4.4 The pass-through rate attribution

To assign a pass-through rate to each sector product, we rely on the methodology developed in Roncalli and Semet (2024). Assuming that the pass-through rate follows a beta distribution, bounded between 0 and 1, it is possible to generate a list of pass-through types according to a set of values for the parameters (Desnos *et al.*, 2023, Table 33, page 115). In this approach, the pass-through rate is modeled as a price-demand elasticity by considering highly-elastic (20%), high-elastic (40%), medium-elastic (70%), and low-elastic (95%) types. The complete assignation of pass-through rates mapped to sector-product is provided in Table 18 on page 78. We propose a mapping between Exiobase's by-product classification and by-sector classification to link sectoral pass-through rates to products. Notice that pass-through rates are estimated at the product level but not at the product-region level. Thus, we assume that the pass-through rate is homogeneous between regions within the same product class.

5 Economic, social, and environmental implications of the CBAM

5.1 CBAM direct exposure

Insofar as the border carbon adjustment mechanism is a European regulation, the compliance costs will mainly impact European producers. Nevertheless, it is important to estimate the

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[34] Although the European Commission (2021b) provides free allowance distributions at the installation level for each country, these data cannot be directly linked to the input-output tables due to the absence of corresponding activity information.

[35] We use the latest available version (EUTL Version: 13.12 EUTLP01-12-2023) from Abrell (2021).

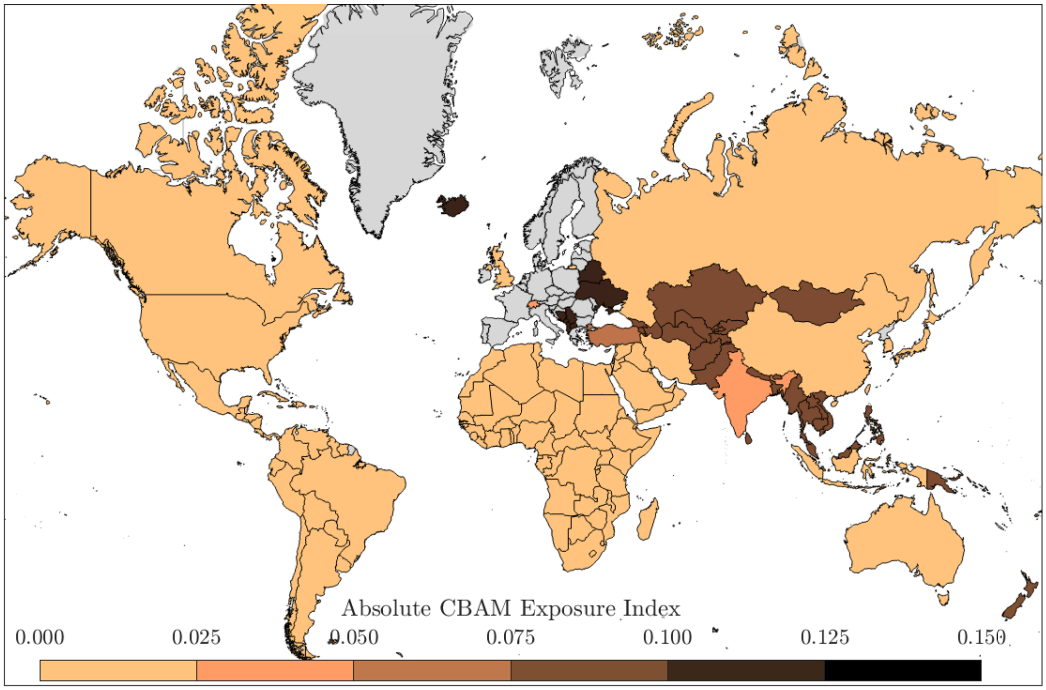
[36] In addition, we made some adjustments to ensure consistency. First, in a few cases, the ratio of free allowances to verified emissions exceeds 1, notably in the *Manufacture of wood*, *Information services activities*, and *Manufacture of paper and paper products* sectors. For these cases, we capped the ratio at 1. Second, some estimates of the four-digit NACE nomenclature were based on a very limited number of installations (sometimes only one), raising concerns about representativeness. To address this, we aggregated data at the two-digit level, providing more robust and consistent estimates.

exposure of exporting regions to this regulation. Determining these exposures becomes crucial, as the trade structure of the products in question will be modified as a function of the exporting regions' direct exposure to carbon pricing (Magacho *et al.*, 2024). In this section, we focus on the direct effects on third regions, excluding the underlying dynamics of the global value chain.

5.1.1 Absolute and relative CBAM exposure

The direct exposure of exporting regions to CBAM will primarily depend on the share of CBAM-covered products traded with European countries. While export volume largely determines exposure to the regulation, environmental efficiency (*i.e.*, carbon intensity) also plays a crucial role. These two characteristics make up the absolute CBAM exposure index[37], which is detailed in the world map representation in Figure 13.

Figure 13: Absolute CBAM exposure of third countries in 2022 ($\boldsymbol{\mathcal{AEI}}$)



Source: Exiobase 2022 & Author's calculations.

In absolute terms, very few regions face critical exposure to the regulation. This is primarily because more than 50% of regions have a CBAM-covered export dependency on Europe of less than 10% of their total CBAM exports. Exposure is highly concentrated in specific non-EU regions, particularly Ukraine, Belarus, Iceland, and Albania. In addition to their strong trade ties with the EU, these countries exhibit some of the lowest carbon efficiency in CBAM-covered production. While Great Britain and Switzerland are particularly dependent on the EU's imports (> 50%), they tend to have low carbon intensities. Then, we find a few countries from South and Central Asia, composing the rest of the world region, that are particularly exposed to CBAM regulation through trade.

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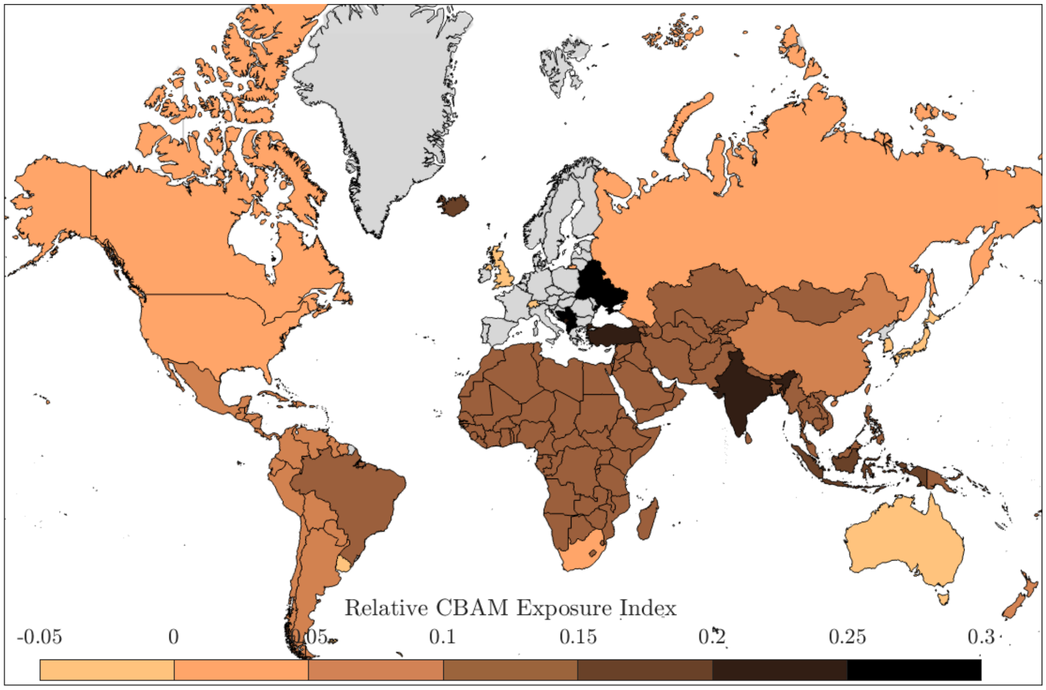
[37] Remember that the higher the index, the higher the product of the two components and, therefore, the higher the exposure.

While absolute exposure provides a first approximation of the impact of CBAM on foreign economies, it is possible to refine this measure by taking relative factors into account. The measure of trading volume remains the same, but the environmental exposure is likely to be slightly modified according to the presence or absence of implemented carbon pricing policies. In addition, the difference between domestic carbon intensity and that recorded in Europe could also favor the exporting economy. This improvement is taken into account in our relative CBAM exposure index[38] in Figure 14.

Figure 14: Relative CBAM exposure of third countries in 2022 ($\boldsymbol{\mathcal{REI}}$)



Source: Exiobase 2022 & Author's calculations.

Taking this relative indicator, we notice substantial differences in exposure. Even if the regions most affected by regulation remain the same as before, we note, in particular, an overexposure of African and Middle Eastern regions. They are relatively more exposed than other regions due to their inexistent carbon pricing programs favoring detrimental carbon intensities in CBAM-covered productions. On the South American continent, Brazil is also relatively more exposed than previously suggested. It records a carbon intensity of CBAM-covered products that is three times greater than that of the EU. For India, which is relatively more exposed than previously, the ratio is amounting to five. In contrast, some countries enjoy a marked advantage over their EU competitors. These include Australia, Uruguay, South Korea, and Japan, which are relatively less exposed to CBAM due to their relatively low export amounts. For Great Britain and Switzerland, they tend to be more carbon efficient than their European counterparts in producing CBAM goods.

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[38] Note that negative values are possible in this case since the carbon intensity and the carbon price at which emissions are priced are from differences between domestic and EU estimates.

5.1.2 Economic cost exposure of third regions to CBAM

In Table 11, we present the economic cost exposure of third countries to the CBAM regulation across various scenarios. Direct costs are expressed as a percentage of regional total output. Overall, CBAM impacts are very small, representing less than 1% of global production value. The most exposed regions are the rest of the world's European (WEU) region, Turkey (TUR), and Russia (RUS), with the African region (WAF) and India (IND) also appearing in the top five.

In Scenario 1, the total cost of the measure is the lowest, representing 0.052% of global output production. The rest of the world's European region is particularly exposed to CBAM, with about 1.52% of its production value subject to additional costs. When default carbon intensity values are assumed, the total cost increases to 0.175% of global production value. In this scenario, Turkey is especially exposed, with direct exposure amounting to 2.112% of its production value, followed by the rest-of-the-world European region (2.074%) and Russia (1.951%). Turkey tends to export CBAM-covered products more than the rest of the world's European region, albeit at a relatively lower carbon intensity. One consequence of Scenario 2 is that direct cost exposure becomes less differentiated by technology, placing greater emphasis on export volume over carbon efficiency. A trend that undermines the economic rationale of carbon pricing (Mehling and Ritz, 2020). Scenario 3 —where the CBAM scope is extended to include downstream products— yields results similar to Scenario 1, with direct exposure increasing by less than 6%.

Table 11: Direct economic cost exposure (in % of total output) to CBAM regulation

Rank	Scenario 1		Scenario 2		Scenario 3	
	World	0.052%	World	0.175%	World	0.055%
1	WEU	1.515%	TUR	2.121%	WEU	1.619%
2	TUR	0.623%	WEU	2.074%	TUR	0.641%
3	RUS	0.318%	RUS	1.951%	RUS	0.321%
4	IND	0.208%	WME	0.676%	IND	0.209%
5	WAF	0.152%	WAF	0.615%	WAF	0.166%
6	WEX	0.152%	IND	0.463%	WEX	0.155%
7	WME	0.142%	TWN	0.322%	WME	0.151%
8	BRA	0.092%	BRA	0.299%	ZAF	0.125%
9	TWN	0.060%	ZAF	0.278%	BRA	0.093%
10	ZAF	0.059%	WEX	0.266%	TWN	0.061%
11	WLA	0.045%	KOR	0.212%	WLA	0.058%
12	KOR	0.035%	WLA	0.092%	KOR	0.035%
13	CHN	0.028%	MEX	0.085%	CHN	0.028%
14	IDN	0.011%	IDN	0.082%	CAN	0.013%
15	MEX	0.009%	CHN	0.065%	IDN	0.011%
16	CAN	0.009%	GBR	0.047%	MEX	0.010%
17	JPN	0.008%	JPN	0.038%	AUS	0.009%
18	GBR	0.006%	USA	0.031%	JPN	0.008%
19	AUS	0.005%	AUS	0.028%	GBR	0.006%
20	USA	0.004%	CAN	0.025%	USA	0.005%

Source: Exiobase 2022 & Author's calculations.

Overall, the economic pressure exerted by the CBAM on EU main trade partners is almost non-existent. The extension of a CBAM policy to downstream products does not contradict this argument, which marginally increases the exposure in third regions. On the other hand, we note that the difference in methodology between an actual versus a default carbon intensity estimation could be relatively large. Indeed, the overall cost is three times higher using default values rather than actual estimates. However, the regional ranking does not vary across the three scenarios, emphasizing the critical role of trade intensities of basic materials. Finally, taking a direct economic cost exposure perspective reveals the potential income loss in third regions that do not implement carbon pricing policies. These regions are particularly vulnerable to CBAM, and although the estimated costs are small, they ultimately become government revenue repatriated to the EU.

5.2 CBAM impact on the supply chain

5.2.1 Economic costs at the regional level

Keeping trade patterns unchanged, the direct exposure of third countries transmits to compliance costs for EU importers. These costs materialize with the purchase of CBAM certificates from European importers. In Table 12, we summarize the CBAM economic costs and revenue generated by the various scenarios. In the base-case scenario, total costs amount to 0.48% of the European (EEU) total output value. The total amount of compliance costs generates around 0.31% of the total production value for governments, which lessens the net costs to merely 0.17%. Bulgaria (BGR), Belgium (BEL), and Greece (GRC) appear as the most impacted countries.

In Scenario #2, total aggregated costs rise by a factor of 3, increasing from 0.48% to 1.67% of total European output. The revenue potentially generated by the CBAM exceeds 1% of the total output value. The scenario assumptions disrupt the distribution of total costs among European countries, with Belgium, Italy (ITA), and Luxembourg (LUX) being the most affected. When looking at the cost decomposition in Table 13, we notice that the two scenarios diverge with respect to direct and indirect cost distribution. In Scenario #1, the average indirect-to-direct costs ratio is 0.51, while for Scenario #2, it reaches 0.63, suggesting an increase of around 20%. In most cases, direct costs are lower than indirect costs in the first scenario but tend to reverse in many countries in the second scenario. In this vein, resorting to default values exacerbates pass-through mechanisms induced by the CBAM on supply chains. In terms of net costs, Italy and Poland (POL) have the highest rates, which are particularly hit by indirect costs, exceeding 1% of their respective output value.

In Scenario #3, we notice a slight increase in total CBAM costs falling in European countries in comparison to the first one. Interestingly, net costs are similar to those in Scenario #1 (see Table 12), suggesting that increasing CBAM coverage marginally increases compliance costs but with limited impact on downstream customers. As a result, the amount of revenue increases while the indirect costs stay at the same level as in the first scenario. This also suggests that pass-through rates of downstream producers in comparison to initial CBAM-covered products are smoother. There are a few exceptions. For example, Belgium, the Netherlands (NLD), and Romania (ROU) are seeing above-average increases in their total costs compared with the other countries, which are stagnating at around 2–3 basis points. This demonstrates a greater economic dependency of these countries on semi-finished products. Still, as shown in Table 13, additional costs are constrained to importers through direct costs rather than cascading throughout the supply chain.

Another perspective on cost decomposition is to distinguish between costs incurred by importers of CBAM-covered products and those borne by downstream customers (see Table 13). In Scenario #1, serving as the base case, importers' bills amount to only 0.08% of total output value, leaving over 80% of compliance costs to downstream producers. On average,

Table 12: Regional CBAM revenue, total and net costs by scenario (in % of total output)

	Scenario #1			Scenario #2			Scenario #3		
	$\mathcal{C}_{\text{total}}$	$\mathcal{R}_{\text{total}}$	$\mathcal{C}_{\text{net}}$	$\mathcal{C}_{\text{total}}$	$\mathcal{R}_{\text{total}}$	$\mathcal{C}_{\text{net}}$	$\mathcal{C}_{\text{total}}$	$\mathcal{R}_{\text{total}}$	$\mathcal{C}_{\text{net}}$
World	0.09%	0.05%	0.04%	0.32%	0.17%	0.15%	0.09%	0.06%	0.04%
EEU	0.48%	0.31%	0.17%	1.67%	1.03%	0.64%	0.50%	0.33%	0.17%
BGR	1.33%	1.05%	0.28%	2.64%	1.93%	0.71%	1.34%	1.06%	0.28%
BEL	0.95%	0.77%	0.18%	4.20%	3.48%	0.72%	1.00%	0.82%	0.18%
GRC	0.93%	0.76%	0.17%	2.41%	1.89%	0.52%	0.97%	0.80%	0.17%
ITA	0.86%	0.54%	0.32%	3.49%	2.17%	1.32%	0.88%	0.55%	0.32%
POL	0.81%	0.51%	0.30%	2.77%	1.68%	1.09%	0.82%	0.52%	0.30%
LUX	0.72%	0.59%	0.13%	3.37%	2.81%	0.55%	0.74%	0.61%	0.13%
ROU	0.70%	0.47%	0.23%	2.16%	1.53%	0.62%	0.78%	0.54%	0.23%
NLD	0.61%	0.43%	0.18%	1.30%	0.83%	0.47%	0.68%	0.50%	0.18%
NOR	0.58%	0.44%	0.14%	1.89%	1.33%	0.56%	0.60%	0.46%	0.14%
SVN	0.58%	0.40%	0.18%	1.31%	0.79%	0.53%	0.59%	0.41%	0.18%
HRV	0.56%	0.45%	0.11%	0.65%	0.38%	0.27%	0.57%	0.46%	0.11%
ESP	0.51%	0.36%	0.15%	1.86%	1.28%	0.58%	0.52%	0.37%	0.15%
HUN	0.50%	0.30%	0.21%	1.23%	0.60%	0.63%	0.51%	0.31%	0.21%
LTU	0.48%	0.39%	0.09%	1.44%	1.10%	0.34%	0.50%	0.41%	0.09%
CZE	0.46%	0.21%	0.24%	1.70%	0.80%	0.90%	0.46%	0.22%	0.24%
PRT	0.45%	0.31%	0.14%	1.97%	1.38%	0.59%	0.49%	0.34%	0.14%
SVK	0.40%	0.20%	0.20%	1.22%	0.56%	0.66%	0.41%	0.21%	0.20%
DEU	0.33%	0.18%	0.16%	1.11%	0.53%	0.58%	0.34%	0.19%	0.16%
FIN	0.32%	0.20%	0.12%	1.80%	1.19%	0.62%	0.32%	0.20%	0.12%
DNK	0.28%	0.20%	0.08%	1.07%	0.77%	0.30%	0.28%	0.20%	0.08%
EST	0.27%	0.20%	0.07%	1.04%	0.74%	0.29%	0.28%	0.21%	0.07%
AUT	0.27%	0.13%	0.14%	0.70%	0.30%	0.40%	0.27%	0.13%	0.14%
LVA	0.26%	0.21%	0.06%	0.83%	0.63%	0.19%	0.28%	0.22%	0.06%
FRA	0.26%	0.15%	0.10%	0.69%	0.31%	0.38%	0.26%	0.16%	0.10%
IRL	0.20%	0.15%	0.05%	0.75%	0.54%	0.21%	0.21%	0.16%	0.05%
SWE	0.19%	0.09%	0.10%	0.73%	0.34%	0.39%	0.20%	0.10%	0.10%
MLT	0.17%	0.12%	0.04%	0.26%	0.15%	0.11%	0.18%	0.13%	0.05%
CYP	0.14%	0.12%	0.03%	0.56%	0.40%	0.17%	0.15%	0.12%	0.03%

the cost share of customers is four times higher than that of importers. Notably, the Czech Republic (CZE), Germany (DEU), and Austria (AUT) exhibit particularly high customer-to-producer cost ratios, with Germany's ratio reaching nearly 10 in Scenario #2. This may reflect the supply chain density of these countries —where importers of CBAM-covered goods supply many downstream customers— or indicate that these goods are predominantly used in domestic production. Although Scenario #3 reduces these ratios by increasing the share paid by importers, it cannot offset the cascading impact of the original CBAM. These results highlight the influence of cost pass-through rates in basic materials industries. Scenario #3 indicates that industries importing initial CBAM-covered products tend to raise their output prices almost proportionally to the cost increase. Importers partially circumvent the cost burden by shifting it onto downstream sectors, which may have limited capacity to pass on these costs further downstream. This distorts the intended cost-sharing mechanism of the policy and can diminish incentives for decarbonization.

Table 13: Regional CBAM costs decomposition by scenario (in % of total output)

	Scenario #1				Scenario #2				Scenario #3			
	$\mathcal{C}_{\text{direct}}$	$\mathcal{C}_{\text{indirect}}$	$\mathcal{C}_{\text{prod}}$	$\mathcal{C}_{\text{cust}}$	$\mathcal{C}_{\text{direct}}$	$\mathcal{C}_{\text{indirect}}$	$\mathcal{C}_{\text{prod}}$	$\mathcal{C}_{\text{cust}}$	$\mathcal{C}_{\text{direct}}$	$\mathcal{C}_{\text{indirect}}$	$\mathcal{C}_{\text{prod}}$	$\mathcal{C}_{\text{cust}}$
World	0.05%	0.04%	0.01%	0.08%	0.17%	0.15%	0.04%	0.28%	0.06%	0.04%	0.02%	0.08%
EEU	0.31%	0.17%	0.08%	0.40%	1.03%	0.64%	0.24%	1.43%	0.33%	0.17%	0.09%	0.41%
BGR	1.05%	0.28%	0.39%	0.94%	1.93%	0.71%	0.62%	2.01%	1.06%	0.28%	0.40%	0.95%
BEL	0.77%	0.18%	0.19%	0.76%	3.48%	0.72%	0.75%	3.45%	0.82%	0.18%	0.22%	0.78%
GRC	0.76%	0.17%	0.18%	0.75%	1.89%	0.52%	0.39%	2.01%	0.80%	0.17%	0.21%	0.76%
LUX	0.59%	0.13%	0.14%	0.58%	2.81%	0.55%	0.52%	2.85%	0.61%	0.13%	0.15%	0.59%
ITA	0.54%	0.32%	0.12%	0.74%	2.17%	1.32%	0.43%	3.06%	0.55%	0.32%	0.13%	0.75%
POL	0.51%	0.30%	0.14%	0.68%	1.68%	1.09%	0.39%	2.38%	0.52%	0.30%	0.14%	0.68%
ROU	0.47%	0.23%	0.10%	0.60%	1.53%	0.62%	0.44%	1.72%	0.54%	0.23%	0.15%	0.63%
HRV	0.45%	0.11%	0.16%	0.39%	0.38%	0.27%	0.13%	0.52%	0.46%	0.11%	0.17%	0.40%
NOR	0.44%	0.14%	0.08%	0.51%	1.33%	0.56%	0.26%	1.63%	0.46%	0.14%	0.09%	0.52%
NLD	0.43%	0.18%	0.14%	0.47%	0.83%	0.47%	0.26%	1.04%	0.50%	0.18%	0.18%	0.50%
SVN	0.40%	0.18%	0.12%	0.46%	0.79%	0.53%	0.20%	1.11%	0.41%	0.18%	0.12%	0.47%
LTU	0.39%	0.09%	0.20%	0.28%	1.10%	0.34%	0.40%	1.04%	0.41%	0.09%	0.21%	0.29%
ESP	0.36%	0.15%	0.12%	0.39%	1.28%	0.58%	0.36%	1.50%	0.37%	0.15%	0.13%	0.39%
PRT	0.31%	0.14%	0.08%	0.36%	1.38%	0.59%	0.35%	1.62%	0.34%	0.14%	0.11%	0.38%
HUN	0.30%	0.21%	0.09%	0.42%	0.60%	0.63%	0.16%	1.07%	0.31%	0.21%	0.09%	0.42%
CZE	0.21%	0.24%	0.05%	0.40%	0.80%	0.90%	0.18%	1.52%	0.22%	0.24%	0.06%	0.40%
LVA	0.21%	0.06%	0.11%	0.16%	0.63%	0.19%	0.24%	0.59%	0.22%	0.06%	0.12%	0.17%
SVK	0.20%	0.20%	0.05%	0.35%	0.56%	0.66%	0.15%	1.07%	0.21%	0.20%	0.06%	0.36%
DNK	0.20%	0.08%	0.06%	0.22%	0.77%	0.30%	0.22%	0.85%	0.20%	0.08%	0.06%	0.22%
FIN	0.20%	0.12%	0.06%	0.26%	1.19%	0.62%	0.30%	1.51%	0.20%	0.12%	0.06%	0.26%
EST	0.20%	0.07%	0.09%	0.18%	0.74%	0.29%	0.27%	0.76%	0.21%	0.07%	0.10%	0.18%
DEU	0.18%	0.16%	0.04%	0.29%	0.53%	0.58%	0.11%	1.01%	0.19%	0.16%	0.05%	0.30%
FRA	0.15%	0.10%	0.05%	0.20%	0.31%	0.38%	0.09%	0.60%	0.16%	0.10%	0.06%	0.20%
IRL	0.15%	0.05%	0.06%	0.15%	0.54%	0.21%	0.17%	0.57%	0.16%	0.05%	0.06%	0.15%
AUT	0.13%	0.14%	0.03%	0.23%	0.30%	0.40%	0.08%	0.62%	0.13%	0.14%	0.03%	0.24%
MLT	0.12%	0.04%	0.03%	0.14%	0.15%	0.11%	0.05%	0.21%	0.13%	0.05%	0.04%	0.14%
CYP	0.12%	0.03%	0.05%	0.10%	0.40%	0.17%	0.13%	0.43%	0.12%	0.03%	0.05%	0.10%
SWE	0.09%	0.10%	0.03%	0.17%	0.34%	0.39%	0.09%	0.64%	0.10%	0.10%	0.03%	0.17%

5.2.2 Impact on inflation

Imposing tariffs on imports by purchasing certificates at the EU ETS carbon price will likely raise producer prices. Passing compliance costs through output prices leads to a snowball effect: as the density of the value chain inflates, the price distortions tend to amplify. The phenomenon ends with the last tier of the supply chain, the one that directly deals with the final consumer. Two price indices are provided in Table 14, namely the producer (π_{PPI}) and consumer price indices (π_{CPI}) which are computed at the country level. We only present the 20 biggest estimates —ranked according to their π_{PPI} values— gathering principally European countries.

First, results suggest that price variations, although very small, are generally more pronounced for producers than for consumers. According to scenario #1, the general price index in Europe increases by 0.40% for the PPI and only by 0.27% for the CPI. Bulgaria (BGR), Belgium (BEL), and Greece (GRC) suffer the most from price increases. Inflationary pressures in Europe are substantially more pronounced in Scenario #2, with an increase of PPI of 1.43% and 0.92% for the CPI. Taking default values rather than actual values leads to an increase in price variations of around three times. In this case, six countries have a PPI above 2%, and the majority of countries have a PPI above 1%. Regarding the CPI, Belgium endures an increase of more than 2%. Seven countries have a CPI above 1%, with the most impacted countries, namely Belgium, Luxembourg (LUX), and Romania (ROU), having a trade deficit. Regarding Scenario #3, we notice close results to the first scenario, albeit CPI indexes tend to be more impacted than PPI's when the CBAM scope enlarges to downstream products.

Table 14: Regional producer (π_{PPI}) and consumer price index (π_{CPI}) estimates by scenario

	Scenario #1			Scenario #2			Scenario #3		
Rank	Region	π_{PPI}	π_{CPI}	Region	π_{PPI}	π_{CPI}	Region	π_{PPI}	π_{CPI}
	World	0.08%	0.06%	World	0.28%	0.20%	World	0.08%	0.06%
	EEU	0.40%	0.27%	EEU	1.43%	0.92%	EEU	0.41%	0.28%
1	BGR	0.94%	0.86%	BEL	3.45%	2.17%	BGR	0.95%	0.86%
2	BEL	0.76%	0.51%	ITA	3.06%	1.59%	BEL	0.78%	0.54%
3	GRC	0.75%	0.43%	LUX	2.85%	1.67%	GRC	0.76%	0.45%
4	ITA	0.74%	0.40%	POL	2.38%	1.49%	ITA	0.75%	0.41%
5	POL	0.68%	0.44%	BGR	2.01%	1.53%	POL	0.68%	0.45%
6	ROU	0.60%	0.44%	GRC	2.01%	0.96%	ROU	0.63%	0.47%
7	LUX	0.58%	0.44%	ROU	1.72%	1.66%	LUX	0.59%	0.45%
8	NOR	0.51%	0.24%	NOR	1.63%	0.92%	NOR	0.52%	0.25%
9	NLD	0.47%	0.37%	PRT	1.62%	1.05%	NLD	0.50%	0.41%
10	SVN	0.46%	0.39%	CZE	1.52%	0.94%	SVN	0.47%	0.40%
11	HUN	0.42%	0.33%	FIN	1.51%	0.89%	HUN	0.42%	0.33%
12	CZE	0.40%	0.26%	ESP	1.50%	1.18%	CZE	0.40%	0.27%
13	HRV	0.39%	0.40%	SVN	1.11%	0.89%	HRV	0.40%	0.41%
14	ESP	0.39%	0.30%	HUN	1.07%	0.83%	ESP	0.39%	0.31%
15	PRT	0.36%	0.24%	SVK	1.07%	0.98%	PRT	0.38%	0.26%
16	SVK	0.35%	0.31%	NLD	1.04%	0.81%	SVK	0.36%	0.32%
17	DEU	0.29%	0.19%	LTU	1.04%	0.87%	DEU	0.30%	0.20%
18	LTU	0.28%	0.22%	DEU	1.01%	0.64%	LTU	0.29%	0.23%
19	FIN	0.26%	0.17%	DNK	0.85%	0.64%	FIN	0.26%	0.17%
20	AUT	0.23%	0.17%	EST	0.76%	0.76%	AUT	0.24%	0.17%

5.2.3 Economic costs at the sector level

In Table 15, we decompose the price variation induced by the CBAM across sectors. Standard deviation noted σ and mean μ are computed at the sector level. If Materials and Industrial record the largest average price variations, the Health Care sector appears third in Scenarios #1 and #3. The Energy sector records the third largest average price variation in Scenario #3. Results also informed on a relatively larger heterogeneity of price variations in the Materials and Energy sectors.

Table 15: Standard deviation $\sigma(\Delta p)$ and mean $\mu(\Delta p)$ of sector prices in Europe by scenario

	Scenario #1		Scenario #2		Scenario #3	
	$\sigma(\Delta p)$	$\mu(\Delta p)$	$\sigma(\Delta p)$	$\mu(\Delta p)$	$\sigma(\Delta p)$	$\mu(\Delta p)$
Communication services	0.22%	0.09%	1.03%	0.29%	0.22%	0.09%
Consumer Discretionary	0.75%	0.24%	4.53%	1.11%	0.75%	0.25%
Consumer Staples	0.61%	0.19%	0.74%	0.35%	0.61%	0.23%
Energy	1.33%	0.30%	7.13%	1.25%	1.33%	0.31%
Financial	0.04%	0.03%	0.19%	0.13%	0.04%	0.04%
Health Care	0.57%	0.34%	1.79%	1.13%	0.57%	0.35%
Industrial	0.92%	0.48%	3.90%	1.80%	0.92%	0.48%
Information Technology	0.04%	0.07%	0.15%	0.25%	0.04%	0.07%
Materials	2.22%	0.68%	9.13%	2.43%	2.22%	0.68%
Real estate	0.05%	0.07%	0.12%	0.20%	0.05%	0.07%
Utilities	0.95%	0.26%	4.73%	0.99%	0.96%	0.27%

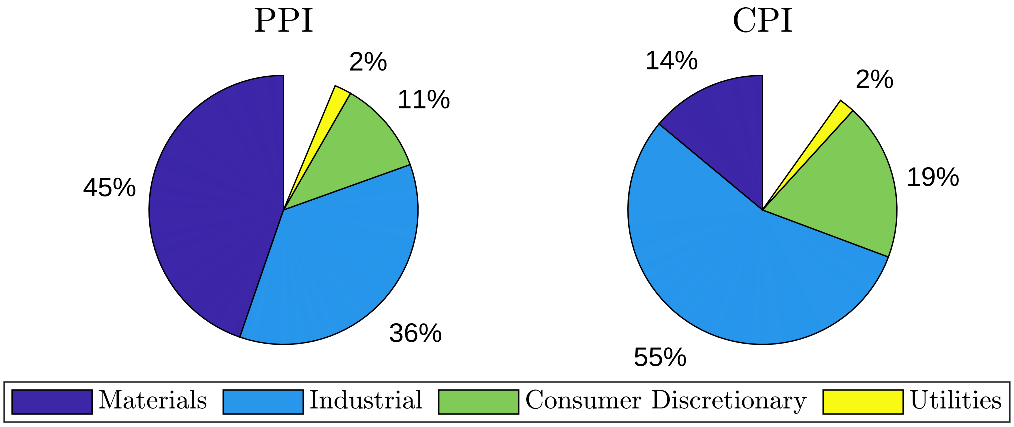
In Table 16, direct and indirect costs are disaggregated at the sector level following the GICS (Global Industry Classification Standard) nomenclature. Sector weights (w_i) in total European output are also provided. Unsurprisingly, Materials producers bear the largest direct costs amounting to 1.59% in Scenarios #1 and #3, and almost 6% in Scenario #2. This sector also receives the largest share of indirect costs due to pass-through mechanisms, more than 2% in scenario #1 and 0.55% in Scenarios #1 and #2. The industrial sector arrives second in Scenario #1 and #2 but is surpassed by Consumer Staples in Scenario #3, which takes 0.50% of total costs. As marked by the largest weight, amounting to more than 35% of total output, the contribution of this sector in the PPI basket is important.

Table 16: European direct and indirect costs across sectors by scenario

	Scenario #1		Scenario #2		Scenario #3		
	$\mathcal{C}_{\text{direct}}$	$\mathcal{C}_{\text{indirect}}$	$\mathcal{C}_{\text{direct}}$	$\mathcal{C}_{\text{indirect}}$	$\mathcal{C}_{\text{direct}}$	$\mathcal{C}_{\text{indirect}}$	w_i
Communication Services	0.03%	0.04%	0.13%	0.13%	0.03%	0.04%	3.56%
Consumer Discretionary	0.14%	0.13%	0.58%	0.53%	0.15%	0.14%	19.54%
Consumer Staples	0.18%	0.07%	0.20%	0.22%	0.42%	0.08%	6.06%
Energy	0.13%	0.09%	0.49%	0.31%	0.13%	0.09%	1.61%
Financial	0.00%	0.02%	0.00%	0.07%	0.00%	0.02%	4.85%
Health Care	0.07%	0.06%	0.20%	0.23%	0.07%	0.07%	6.13%
Industrial	0.28%	0.19%	0.81%	0.70%	0.28%	0.19%	36.55%
Information Technology	0.02%	0.05%	0.08%	0.17%	0.02%	0.05%	1.91%
Materials	1.59%	0.55%	5.75%	2.08%	1.59%	0.55%	10.02%
Real estate	0.01%	0.04%	0.04%	0.12%	0.01%	0.04%	6.10%
Utilities	0.08%	0.14%	0.24%	0.51%	0.08%	0.14%	3.60%

As basic materials, the initial list of CBAM-covered products will likely hit harder prices for intermediary rather than final consumption. As a result, when we consider the contribution of each sector in the two price indexes[39] in Figure 15, we notice that Materials account for 45% of the PPI increase. In contrast, the CPI is overweighted on goods from the Industrial sector. Furthermore, Consumer Discretionary contribution is almost two times larger in the CPI rather than the PPI. These contributions explain why consumer price variations are lesser than producer price variations.

Figure 15: Main sectors contribution to PPI and CPI variations (Scenario #1)



Value-added impact

Competitiveness

5.3 Policy efficiency

5.3.1 Carbon leakage backstop

5.3.2 Social impact

Price effect

Income effect

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[39] We illustrate only the sectors contribution for Scenario #1 since the results are very close to the others scenarios.

6 Conclusion

To achieve carbon neutrality, Europe will have to increase its mitigation policies' ambitions. Carbon pricing remains the cornerstone of this transformation, largely due to sustained efforts in the European carbon market to become the global benchmark. Yet, despite the global surge in carbon pricing adoptions, Europe still acts unilaterally in its environmental initiatives. Its heightened ambition —particularly in expanding the mechanism to include sectors benefiting exemptions— compels it to tighten the rules to level the playing field and avoid carbon leakage. In this study, we propose a descriptive approach to the CBAM by analyzing the parameters on which this mechanism will be based. Using multiregional input-output tables, we adopt a global supply chain perspective. Our results provide a reference framework for analyzing the carbon price cascading effects induced by the CBAM.

CBAM-covered products account for approximately 1.24% of global GDP, with a predominant concentration in China, but also in Europe. Our findings show that the direct impact of the CBAM on non-European countries is very limited, mainly because the goods concerned amounted to €56 billion in 2022, representing only 2% of EU imports. The iron and steel sector dominates (65% of imports), followed by aluminum (28%), primarily exported by Russia, Africa, and Great Britain, which together account for 15% of combined flows. Although China is the largest producer (48% of total production covered by the CBAM) and the main carbon emitter (60% of global emissions covered by the CBAM), it ranks only fifth among the largest EU exporters. Yet, together with India, China contributes nearly 45% of the total emissions embedded in EU imports, amounting to 107 MtCO$_2$e in 2022. This represents almost 48% of Europe's direct domestic emissions from CBAM-covered production. Such a difference is partly explained by higher carbon intensities, with the iron and steel sector emitting twice as much and cement ten times as much as within the EU borders. When breaking down the different emissions scopes, upstream transport activities and downstream finished goods manufacturing show the strongest links with these products. Special attention should be paid to these downstream sectors as they may lead to carbon leakage. Moreover, with upstream emissions nearly twice as high as downstream emissions, the risk of resource shuffling is not ruled out by our results.

Although the economic impacts may initially appear limited, certain regions seem more vulnerable due to their high value-added intensity. This is notably the case for Russia, Mexico, and Canada. The retaliation risk coming from these countries against Europe could materialize. Vulnerabilities also stem from significant disparities in labor productivity and competitiveness. While high-income European countries exhibit the highest productivity across all CBAM-covered products, they tend to be less competitive than their main trading partners, particularly in the production of iron and steel. The degree of comparative advantage of these countries casts a sword of Damocles over European exports. This effect is especially pronounced for industries that depend on CBAM-covered inputs, namely metal products, motor vehicles, transport equipment, and electrical machinery .

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A Technical appendix

A.1 Estimation and analysis of the A matrix

As noted in Desnos *et al.* (2023), in some cases, the A matrix may not be sub-stochastic due to the intermediary demand of some sectors greater than their total output: $\sum_{j=1}^{n} Z_{i,j} > x_i$. However, the input-output Leontief model requires several assumptions of the matrix A (Peterson and Olinick, 1982), notably that each industry spends no more than it receives: $\sum_{j=1}^{n} a_{i,j} x_j \leq x_i$. This creates elements of matrix $A_{i,j}$ being greater than unity[40]. As in the Exiobase input-output table at the sector level, the composition of the final demand for products is the cause of this issue, since it encompasses changes in inventories and valuables that can take negative values. As suggested by Desnos *et al.* (2023), one way to obtain a better estimate of the technical coefficients is to replace the net output x_i by the total intermediary demand when the condition $\sum_{j=1}^{n} Z_{i,j} > x_i$ is satisfied:

$$x_i \longleftarrow \max\left(x_i, \sum_{j=1}^{n} Z_{i,j}, \sum_{j=1}^{n} Z_{j,i}\right)$$

In total, 264 values are corrected from the $9\,800 \times\ 1$ column vector.

Sparsity To further ensure that matrix A is conformed to calculations, we analyze the nonnegative matrix A using the sparsity ratio. This ratio estimates the number of elements with values less than or equal to a specific threshold ϵ divided by the total number of elements (Desnos *et al.*, 2023):

$$\text{sparsity}(A, \epsilon) = \frac{\#\{A_{i,j} < \epsilon\}}{\text{card } A}$$

When $\epsilon = 0$, the sparsity ratio is the zero-sparsity of A which estimates the number of zero-valued elements. Considering $\epsilon = 0$, $\epsilon = 10^{-9}$, and $\epsilon = 10^{-3}$, we obtain sparsity ratios of 64.99%, 72.24% and 99.55% respectively. These estimates are relatively high compared to the sectoral version of Exiobase 2022. Desnos *et al.* (2023) found a zero-sparsity ratio of matrix A ($7\,987 \times\ 7\,987$) around 35%, two times less than the by-product input-output matrix. The increased number of elements from the by-sector to the by-product matrix gives rise to a surge in sparsity.

To give a better illustration of the sparsity of the A matrix, we present in Figure 16 the sparsity pattern of the global supply chain. Each cross presented in the plot represents a value of $A_{i,j} > 5\%$. The diagonal Milky Way of crosses represents country submatrices' dependence. Off-diagonal elements represent the main trade exchange between partners. First, we notice that the bulk of substantial trading is located within countries. Second, a bunch of countries dominate the global supply chain, namely China, Germany, Russia, the USA, Ireland, and the aggregated regions of the rest of the world. This is notably the case for the aggregate of African and Middle-East countries which are underrepresented in the list of countries.

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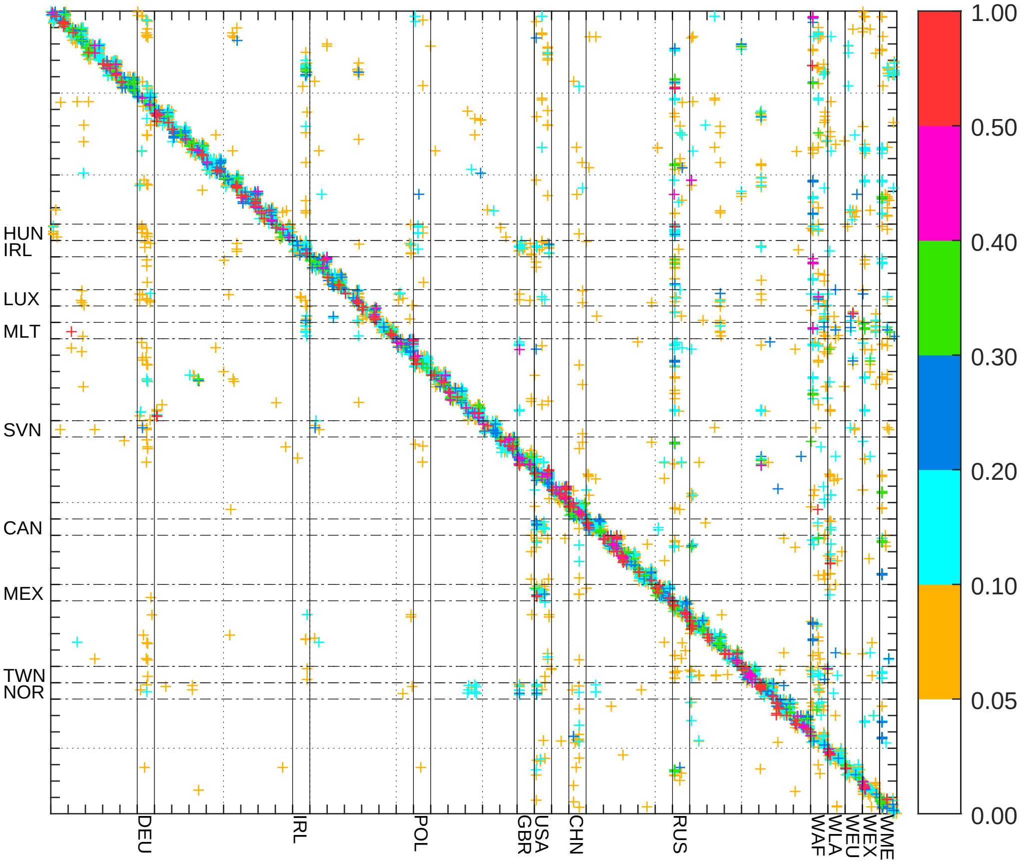
[40] Notice that $\sum_{i=1}^{n} a_{i,j} < 1 \ \forall\ j$ is generally accepted in open models since a part of primary inputs use is coming from the payment sector (e.g., labor, capital, etc.).

Figure 16: Sparsity pattern of the A matrix (Exiobase 2022)



Source: Exiobase 2022.

A.2 Matrix representation in the MRIO model

$$Z = \begin{bmatrix} \begin{pmatrix} z_{11}^{11} & \dots & z_{1n}^{11} \\ \vdots & \ddots & \vdots \\ z_{n1}^{11} & \dots & z_{nn}^{11} \end{pmatrix} & \dots & \begin{pmatrix} z_{11}^{1m} & \dots & z_{1n}^{1m} \\ \vdots & \ddots & \vdots \\ z_{n1}^{1m} & \dots & z_{nn}^{1m} \end{pmatrix} \\ \vdots & \ddots & \vdots \\ \begin{pmatrix} z_{11}^{m1} & \dots & z_{1n}^{m1} \\ \vdots & \ddots & \vdots \\ z_{n1}^{m1} & \dots & z_{nn}^{m1} \end{pmatrix} & \dots & \begin{pmatrix} z_{11}^{mm} & \dots & z_{1n}^{mm} \\ \vdots & \ddots & \vdots \\ z_{n1}^{mm} & \dots & z_{nn}^{mm} \end{pmatrix} \end{bmatrix}$$

$$A = \begin{bmatrix} \begin{pmatrix} a_{11}^{11} & \dots & a_{1n}^{11} \\ \vdots & \ddots & \vdots \\ a_{n1}^{11} & \dots & a_{nn}^{11} \end{pmatrix} & \dots & \begin{pmatrix} a_{11}^{1m} & \dots & a_{1n}^{1m} \\ \vdots & \ddots & \vdots \\ a_{n1}^{1m} & \dots & a_{nn}^{1m} \end{pmatrix} \\ \vdots & \ddots & \vdots \\ \begin{pmatrix} a_{11}^{m1} & \dots & a_{1n}^{m1} \\ \vdots & \ddots & \vdots \\ a_{n1}^{m1} & \dots & a_{nn}^{m1} \end{pmatrix} & \dots & \begin{pmatrix} a_{11}^{mm} & \dots & a_{1n}^{mm} \\ \vdots & \ddots & \vdots \\ a_{n1}^{mm} & \dots & a_{nn}^{mm} \end{pmatrix} \end{bmatrix}, \quad X = \begin{bmatrix} \begin{pmatrix} x_1^1 \\ \vdots \\ x_n^1 \end{pmatrix} \\ \vdots \\ \begin{pmatrix} x_1^m \\ \vdots \\ x_n^m \end{pmatrix} \end{bmatrix}.$$

$$Y = \begin{bmatrix} \begin{pmatrix} Y_1^{1,s} \\ \vdots \\ Y_n^{1,s} \end{pmatrix} & \dots & \begin{pmatrix} Y_1^{1,m} \\ \vdots \\ Y_n^{1,m} \end{pmatrix} \\ \vdots & \ddots & \vdots \\ \begin{pmatrix} Y_1^{m,s} \\ \vdots \\ Y_n^{m,s} \end{pmatrix} & \dots & \begin{pmatrix} Y_1^{m,m} \\ \vdots \\ Y_n^{m,m} \end{pmatrix} \end{bmatrix}, \quad y = \begin{bmatrix} \sum_{s=1}^m Y_1^{1s} \\ \vdots \\ \sum_{s=1}^m Y_n^{1s} \\ \vdots \\ \sum_{s=1}^m Y_1^{ms} \\ \vdots \\ \sum_{s=1}^m Y_n^{mm} \end{bmatrix}$$

$$(I - A)^{-1} = \begin{bmatrix} I - A^{11} & -A^{12} & \dots & -A^{1m} \\ -A^{21} & I - A^{22} & \dots & -A^{2m} \\ \vdots & \vdots & \ddots & \vdots \\ -A^{m1} & -A^{m2} & \dots & I - A^{mm} \end{bmatrix}^{-1}$$

A.3 The supply chain as a graph network

A directed and weighted network is defined as a triple $G = (V, E, a)$, where V represents a set of n nodes, E is the set of ordered pairs of elements in V (directed edges), and a is a non-negative real weight assigned to each edge. Two nodes are considered adjacent if there exists at least one edge (i, j) from node i to node j.

The graph can be represented by its $n \times n$ adjacency matrix $A = (a_{i,j})$, where element (i, j) represents the weight $a_{i,j}$ of the edge from node i to j. Missing edges correspond to zero weights in the adjacency matrix such that $a_{i,j} > 0$ if $(i, j) \in E$ and $a_{i,j} = 0$ otherwise.

To understand node dependencies, it is generally assumed to concentrate on neighborhood $\mathcal{N}_i$, which is the neighbors of node i to which it is linked $\mathcal{N}_i = \{j : a_{i,j} > 0\}$. Then, we can defined the degree, $\mathbf{k}_i$ of node i as the cardinality of its neighborhood:

$$\mathbf{k}_i = \#\mathcal{N}_i$$

For a directed weighted network, it is more common to consider the weighted degree of a node. We define the out-degree $\mathbf{k}_i^{\text{out}}$, and the in-degree $\mathbf{k}_i^{\text{in}}$ as follows:

$$\mathbf{k}_i^{\text{out}} = \sum_j^n a_{i,j}$$

$$\mathbf{k}_i^{\text{in}} = \sum_j^n a_{j,i}$$

The out-degree of a node is the weighted sum of its outgoing edges, while the in-degree is the weighted sum of edges entering node i. In the downstream analysis of the CBAM-product network, the in-degree reflects a node's relative importance, whereas in the upstream analysis, importance is captured by the out-degree.

The widely used eigenvector centrality measures a node's importance based on the principle that a node is considered important if it is connected to other important nodes. It is mathematically defined as:

$$\lambda c_i = \sum_{j \neq i} a_{j,i} c_j$$

where λ is a positive scalar. In this case, the centrality of each node i is proportional to the sum of the centrality of its neighbors. While eigenvector centrality is commonly used as a standard centrality measure, it is not optimal for directed networks that are not strongly connected. Therefore, we employ the Katz-Bonacich centrality measure, which assigns each node a baseline centrality β:

$$c_i = \frac{1}{\lambda} \sum_{j \neq i} a_{j,i} c_j + \beta$$

In matrix form, we define the vector of Katz-Bonacich centrality measure as:

$$\boldsymbol{\mathcal{KB}} = \beta \left(I - \frac{1}{\lambda} A^\top \right) \mathbb{1}$$

where $\beta = 0.75$ in our computations. For the downstream analysis, we keep nodes with $\mathbf{k}_i^{\text{out}} > 0.005$, and $\boldsymbol{\mathcal{KB}}_i > 1.005$.

Table 17: Regions in the input-output tables (Exiobase 2022)

Code	ISO	Name	Region	Sub-region	EU+
ZA	ZAF	South Africa	Africa	Sub-Saharan Africa	
BR	BRA	Brazil	Americas	Latin America	
CA	CAN	Canada	Americas	Northern America	
MX	MEX	Mexico	Americas	Latin America	
US	USA	United States	Americas	Northern America	
CN	CHN	China	Asia	Eastern Asia	
CY	CYP	Cyprus	Asia	Western Asia	
ID	IDN	Indonesia	Asia	South-eastern Asia	
IN	IND	India	Asia	Southern Asia	
JP	JPN	Japan	Asia	Eastern Asia	
KR	KOR	South Korea	Asia	Eastern Asia	
TR	TUR	Turkey	Asia	Western Asia	
TW	TWN	Taiwan	Asia	South-eastern Asia	
AT	AUT	Austria	Europe	Western Europe	✓
BE	BEL	Belgium	Europe	Western Europe	✓
BG	BGR	Bulgaria	Europe	Eastern Europe	✓
CH	CHE	Switzerland	Europe	Western Europe	
CZ	CZE	Czech Republic	Europe	Eastern Europe	✓
DE	DEU	Germany	Europe	Western Europe	✓
DK	DNK	Denmark	Europe	Northern Europe	✓
ES	ESP	Spain	Europe	Southern Europe	✓
EE	EST	Estonia	Europe	Northern Europe	✓
FI	FIN	Finland	Europe	Northern Europe	✓
FR	FRA	France	Europe	Western Europe	✓
GB	GBR	Great Britain	Europe	Northern Europe	
GR	GRC	Greece	Europe	Southern Europe	✓
HR	HRV	Croatia	Europe	Southern Europe	✓
HU	HUN	Hungary	Europe	Eastern Europe	✓
IE	IRL	Ireland	Europe	Northern Europe	✓
IT	ITA	Italy	Europe	Southern Europe	✓
LT	LTU	Lithuania	Europe	Northern Europe	✓
LU	LUX	Luxembourg	Europe	Southern Europe	✓
LV	LVA	Latvia	Europe	Northern Europe	✓
MT	MLT	Malta	Europe	Southern Europe	✓
NL	NLD	Netherlands	Europe	Western Europe	✓
NO	NOR	Norway	Europe	Northern Europe	✓
PL	POL	Poland	Europe	Eastern Europe	✓
PT	PRT	Portugal	Europe	Southern Europe	✓
RO	ROU	Romania	Europe	Eastern Europe	✓
RU	RUS	Russia	Europe	Eastern Europe	
SK	SVK	Slovakia	Europe	Eastern Europe	✓
SI	SVN	Slovenia	Europe	Southern Europe	✓
SE	SWE	Sweden	Europe	Northern Europe	✓
AU	AUS	Australia	Oceania	Oceania	
WA	WAF	World (Africa)	Africa		
WE	WEU	World (Europe)	Europe		
WF	WEX	World (Rest of the world)	World		
WL	WLA	World (Latin America)	Americas		
WM	WME	World (Middle East)	Middle-East		

Source: Exiobase 2022.

Table 18: Attribution of pass-through parameters (α and β) to representative sectors

Group	Sector	Type	α	β	ϕ
Accommodation and food service activities	Accommodation	High	4	6.0	0.40
	Food services	High	4	6.0	0.40
Agriculture, forestry and fishing	Crop and animal production and hunting	Highly	3	12.0	0.20
	Fishing and aquaculture	Low	12	0.6	0.95
	Forestry and logging	Medium	14	6.0	0.70
Construction	Construction of buildings	Medium	14	6.0	0.70
Education	Education	Low	12	0.6	0.95
Electricity	Electricity, gas, steam and air conditioning supply	Low	12	0.6	0.95
Financial and insurance activities	Activities auxiliary to financial and insurance services	Medium	14	6.0	0.70
	Financial service activities, except insurance	Medium	14	6.0	0.70
	Insurance, reinsurance and pension funding	Low	12	0.6	0.95
Information and communication	Computer programming and consultancy	Medium	14	6.0	0.70
	Other computing activities	Medium	14	6.0	0.70
Manufacturing	Manufacture of basic metals	Low	12	0.6	0.95
	Manufacture of beverages	High	4	6.0	0.40
	Manufacture of chemicals and chemical products	Highly	3	12.0	0.20
	Manufacture of coke and refined petroleum products	Low	12	0.6	0.95
	Manufacture of computer, electronic and optical goods	Medium	14	6.0	0.70
	Manufacture of electrical equipment	Medium	14	6.0	0.70
	Manufacture of fabricated metal products	Medium	14	6.0	0.70
	Manufacture of food products	High	4	6.0	0.40
	Manufacture of furniture	High	4	6.0	0.40
	Manufacture of leather and related products	High	4	6.0	0.40
	Manufacture of machinery and equipment n.e.c.	Medium	14	6.0	0.70
	Manufacture of motor vehicles, trailers and semi-trailers	Medium	14	6.0	0.70
	Manufacture of other non-metallic mineral products	Highly	3	12.0	0.20
	Manufacture of other transport equipment	Medium	14	6.0	0.70
	Manufacture of paper and paper products	Highly	3	12.0	0.20
	Manufacture of rubber and plastic products	Medium	14	6.0	0.70
	Manufacture of textiles	High	4	6.0	0.40
	Manufacture of tobacco products	High	4	6.0	0.40
	Manufacture of wearing apparel	High	4	6.0	0.40
	Manufacture of wood and wood and cork products	Medium	14	6.0	0.70
Mining and quarrying	Extraction of crude petroleum and natural gas	Low	12	0.6	0.95
	Mining of coal and lignite	Low	12	0.6	0.95
	Mining of metal ores	Low	12	0.6	0.95
	Mining support service activities	Low	12	0.6	0.95
	Other mining and quarrying	Highly	3	12.0	0.20
	Other mining and quarrying	Low	12	0.6	0.95
Other service activities	Activities of extraterritorial organizations and bodies	Low	12	0.6	0.95
	Computer programming, consultancy and others	Medium	14	6.0	0.70
	Human health activities	Low	12	0.6	0.95
	Public administration, defence and social security	Low	12	0.6	0.95
	Rental and leasing activities	Low	12	0.6	0.95
	Sports activities and recreation	Medium	14	6.0	0.70
Real estate	Real estate activities	Low	12	0.6	0.95
Transportation and storage	Air transport	Highly	3	12.0	0.20
	Land transport and transport via pipelines	Low	12	0.6	0.95
	Postal and courier activities	Medium	14	6.0	0.70
	Warehousing and support activities for transportation	Medium	14	6.0	0.70
	Water transport	Highly	3	12.0	0.20
Water supply, and sewerage	Remediation activities	Low	12	0.6	0.95
	Sewerage	Medium	14	6.0	0.70
	Waste collection, treatment and disposal activities	Low	12	0.6	0.95
	Water collection, treatment and supply	Medium	14	6.0	0.70
Wholesale and retail trade	Retail trade, except of motor vehicles and motorcycles	High	4	6.0	0.40
	Retail trade, except of motor vehicles and motorcycles	Low	12	0.6	0.95
	Wholesale and retail trade and repair of motor vehicles	Low	12	0.6	0.95
	Wholesale trade, except of motor vehicles	Medium	14	6.0	0.70

Source: Exiobase & Author's calculations.

Table 19: Aggregated estimates of absolute and cumulative free allowances allocation (2022)

	Absolute				Cumulative			
Region	#	Verified emissions (in MtCO$_2$e)	Free allowances	Share (in %)	#	Verified emissions (in MtCO$_2$e)	Free allowances	Share (in %)
Germany	1 560	339.69	128.11	0.38	1 560	339.69	128.11	0.12
Poland	529	173.73	42.32	0.24	2 089	513.41	170.42	0.16
Italy	660	75.70	45.08	0.60	2 749	589.12	215.50	0.20
France	910	65.93	54.31	0.82	3 659	655.04	269.81	0.25
Spain	499	59.78	48.02	0.80	4 158	714.82	317.82	0.29
Czech Republic	219	56.52	15.89	0.28	4 377	771.34	333.71	0.31
Netherlands	301	49.42	39.54	0.80	4 678	820.76	373.25	0.35
Austria	174	29.32	20.96	0.72	4 852	850.08	394.21	0.36
Belgium	237	22.67	18.16	0.80	5 089	872.75	412.37	0.38
Norway	120	22.15	12.52	0.57	5 209	894.90	424.90	0.39
Greece	83	20.25	11.23	0.55	5 292	915.15	436.13	0.40
Finland	278	19.30	13.32	0.69	5 570	934.45	449.45	0.42
Sweden	454	18.78	18.16	0.97	6 024	953.23	467.60	0.43
Romania	130	18.74	14.19	0.76	6 154	971.97	481.79	0.45
Ireland	71	15.79	7.91	0.50	6 225	987.76	489.71	0.45
Hungary	138	15.49	8.50	0.55	6 363	1 003.25	498.21	0.46
Slovakia	92	14.86	13.03	0.88	6 455	1 018.11	511.24	0.47
Denmark	274	11.47	4.92	0.43	6 729	1 029.57	516.15	0.48
Bulgaria	93	11.06	6.68	0.60	6 822	1 040.63	522.83	0.48
Portugal	123	11.04	8.50	0.77	6 945	1 051.67	531.33	0.49
Estonia	42	8.39	2.51	0.30	6 987	1 060.07	533.84	0.49
Croatia	33	5.05	3.40	0.67	7 020	1 065.11	537.24	0.50
Lithuania	65	4.96	4.52	0.91	7 085	1 070.07	541.76	0.50
Slovenia	32	4.82	1.42	0.29	7 117	1 074.90	543.17	0.50
Iceland	8	2.16	1.82	0.84	7 125	1 077.06	544.99	0.50
Latvia	52	2.07	1.29	0.62	7 177	1 079.13	546.29	0.50
Luxembourg	21	1.32	1.25	0.95	7 198	1 080.45	547.54	0.51
Cyprus	6	1.22	1.19	0.98	7 204	1 081.67	548.72	0.51
Malta	2	0.20	0.14	0.71	7 206	1 081.86	548.86	0.51

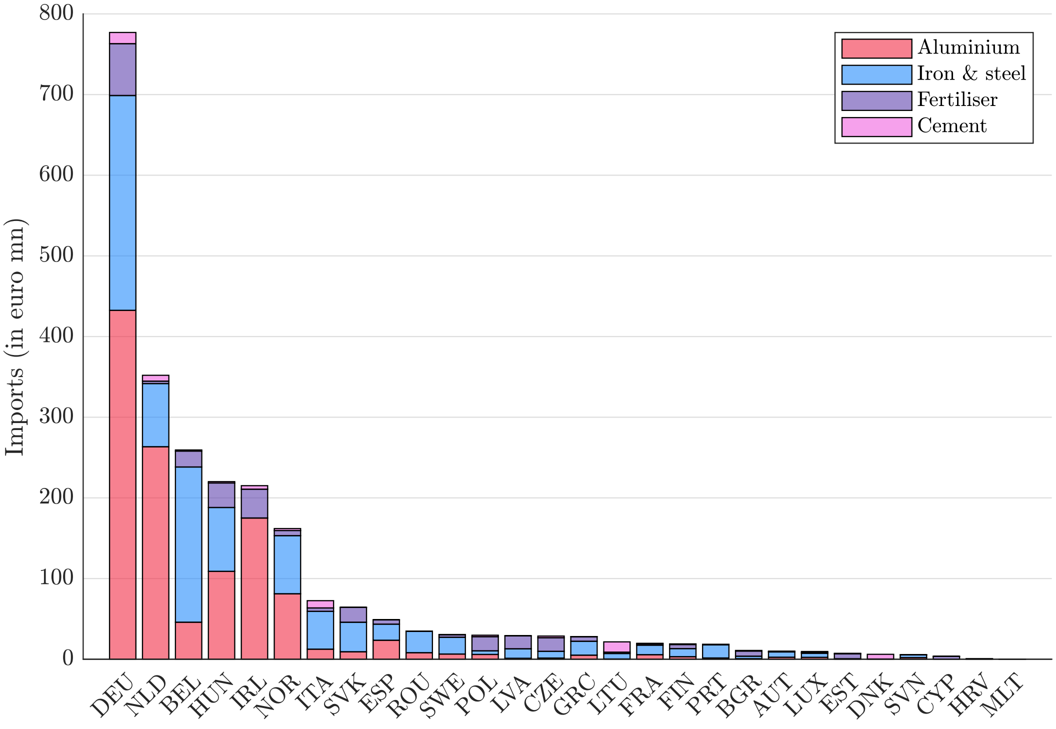
Source: EUTL (2023) & Author's calculations.

Table 20: Direct and total carbon intensities (in kgCO$_2$e/€) of CBAM products in Europe

	Aluminium		Cement		Fertiliser		Iron & steel	
Region	$\mathcal{CI}_{\text{direct}}$	$\mathcal{CI}_{\text{total}}$	$\mathcal{CI}_{\text{direct}}$	$\mathcal{CI}_{\text{total}}$	$\mathcal{CI}_{\text{direct}}$	$\mathcal{CI}_{\text{total}}$	$\mathcal{CI}_{\text{direct}}$	$\mathcal{CI}_{\text{total}}$
Austria	0.24	0.59	0.52	0.79	0.47	0.70	0.29	0.62
Belgium	0.02	0.54	1.07	1.49	0.40	0.64	0.37	0.91
Bulgaria	0.19	1.57	1.96	2.70	0.38	1.03	5.21	5.71
Cyprus	0.10	0.49	1.87	2.69	0.22	0.53	0.08	0.31
Czech Republic	0.06	0.64	1.97	3.19	0.31	1.03	0.73	1.48
Germany	0.08	0.67	0.95	1.28	0.86	1.02	0.27	0.74
Denmark	0.06	0.35	0.99	1.24	0.05	0.27	0.06	0.32
Estonia	0.01	0.69	0.67	1.45	0.06	0.51	0.01	0.40
Spain	0.24	0.87	0.85	2.03	1.04	1.39	0.11	0.72
Finland	0.01	0.47	0.49	0.73	1.24	1.64	0.08	0.40
France	0.04	0.38	0.63	0.90	0.50	0.62	0.30	0.55
Greece	0.20	1.05	2.52	3.47	0.26	0.61	0.03	0.59
Croatia	0.02	0.31	1.69	1.98	0.35	0.54	0.05	0.33
Hungary	0.05	0.69	0.86	1.40	2.00	3.59	0.23	1.11
Ireland	0.42	0.81	0.40	0.64	0.01	0.12	0.04	0.18
Italy	0.07	0.53	0.47	0.87	0.04	2.42	0.17	0.73
Lithuania	0.01	0.46	1.42	2.12	0.26	0.37	0.06	0.91
Luxembourg	0.00	0.51	7.22	8.09	0.05	0.28	0.10	0.58
Latvia	0.16	0.38	1.54	2.09	0.07	0.34	0.07	0.23
Malta	17.81	18.08	0.00	0.00	5.29	5.68	0.71	1.22
Netherlands	0.25	1.03	0.92	1.28	1.10	1.69	2.01	2.39
Poland	0.21	0.89	1.50	2.28	0.31	0.82	0.48	1.21
Portugal	19.02	19.58	3.03	3.91	0.27	0.63	0.21	0.75
Romania	0.09	0.51	1.10	1.77	0.46	1.00	0.60	1.09
Sweden	0.16	0.57	0.71	0.95	2.07	2.27	0.33	0.69
Slovenia	0.13	0.48	0.64	1.11	0.06	0.28	0.11	0.44
Slovakia	0.04	0.51	1.40	2.22	2.42	2.70	2.49	2.91
Norway	0.24	0.70	1.80	2.03	0.59	0.87	0.54	0.96
Average	1.43	1.94	1.40	1.95	0.76	1.20	0.56	1.02
Median	0.09	0.58	1.03	1.63	0.37	0.76	0.22	0.72

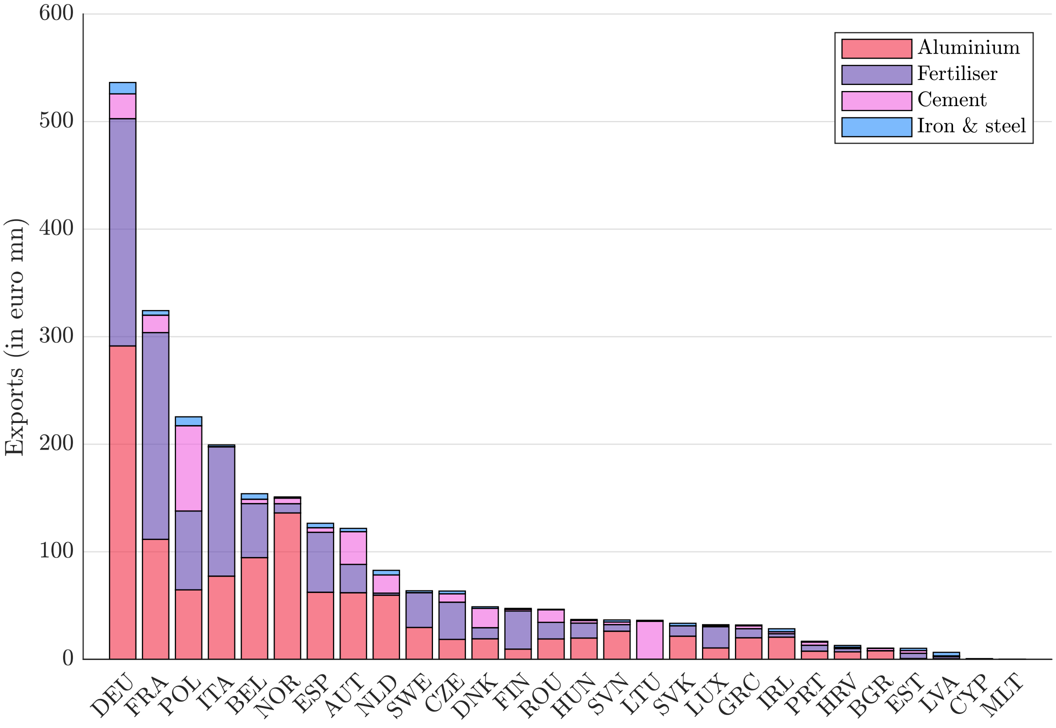
Source: Exiobase 2022 & Author's calculations.

Figure 17: European imports of CBAM products from European countries (in €mn)



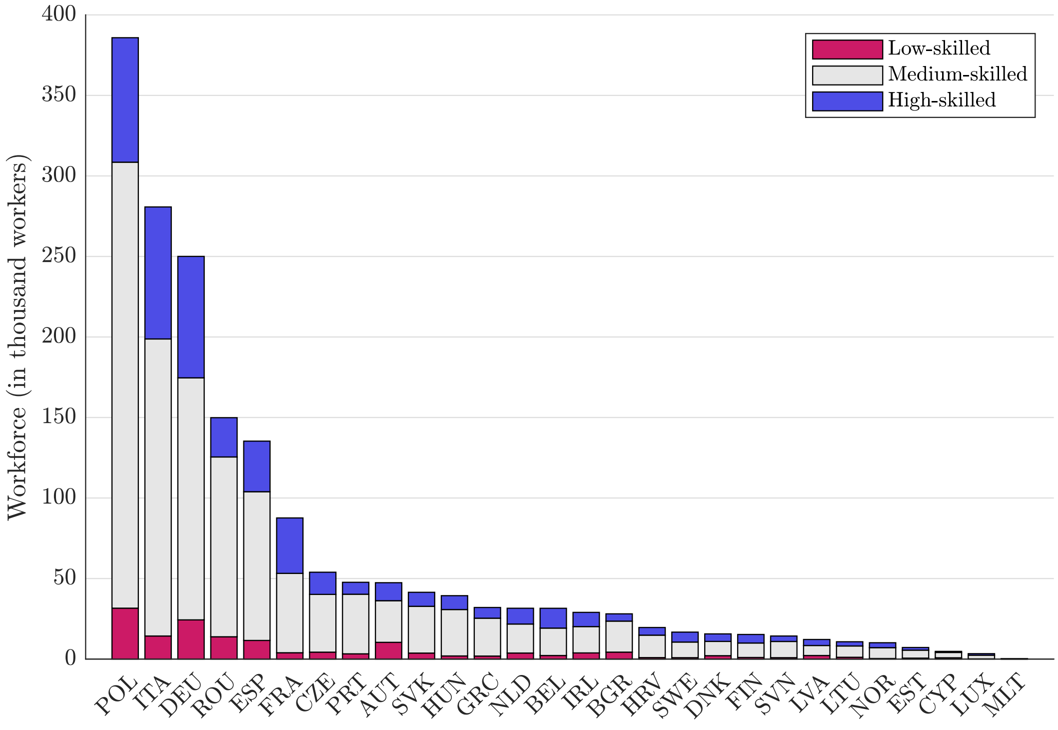
Source: Exiobase 2022 & Author's calculations.

Figure 18: European exports of CBAM products to European countries (in €mn)



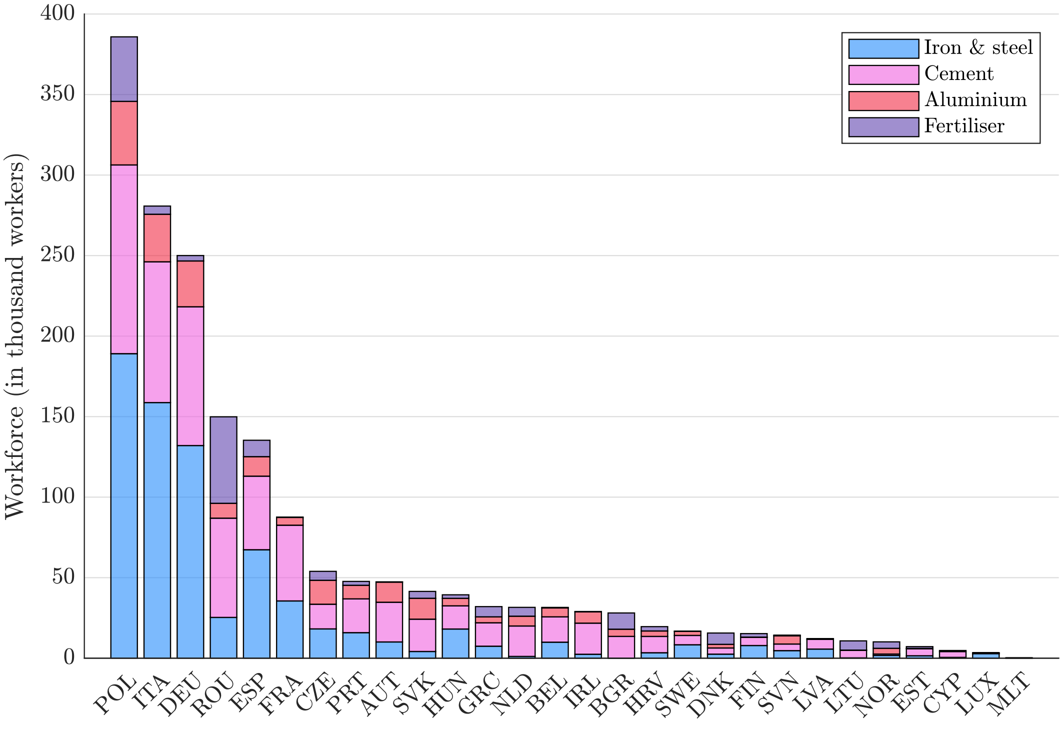
Source: Exiobase 2022 & Author's calculations.

Figure 19: European workforce decomposition of CBAM products by skill



Source: Exiobase 2022 & Author's calculations.

Figure 20: European total workforce by CBAM product



Source: Exiobase 2022 & Author's calculations.