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Production and Consumption-based Emissions of Ireland

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Abstract: This paper provides a snapshot of Ireland's greenhouse gas (GHG) emissions using both production-based accounting (PBA) and consumption-based accounting (CBA) approaches. PBA accounts for emissions within Ireland's borders, attributing them to domestic production activities. In contrast, CBA captures emissions embedded in goods and services consumed in Ireland, including those associated with imports, while excluding emissions from exports. Thus, CBA reflects Ireland's global emissions footprint. Comparing CBA and PBA offers valuable policy insights into Ireland's contribution to global emissions. Using GTAP 11 data, the analysis reveals that CBA emissions exceed PBA emissions by 8 per cent to 16 per cent, depending on the treatment of electricity- and cattle-related emissions. The implications of adopting a CBA framework for assigning emissions responsibility vary by sector. For example, emissions from animal agricultures embedded in exports would not be attributed to Ireland under CBA, whereas emissions embedded in imported fuels would be.

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I INTRODUCTION

There is a general consensus that anthropogenic greenhouse gas (GHG) emissions are a concern and that action is required to mitigate climate change and its associated impacts (UNFCCC, 2015). The impacts of climate change are becoming evident; in 2023, Ireland experienced extreme weather conditions including high temperatures and above-average rainfall (Met Éireann, 2024). To combat climate change, policy actions aimed at reducing emissions have become more prominent over the past decade, as reflected in Ireland's Climate Action Plans (Department of the Environment, Climate and Communication, 2023).

Given the public good nature of GHG emissions reduction, effective mitigation requires global cooperation, such as through the United Nations Framework Convention on Climate Change, United Nations Framework Convention on Climate Change (UNFCCC) and the Conference of Parties (COP) negotiations that led to the Paris Agreement (UNFCCC, 2016). The core variable in quantifying policy targets is the level of emissions reduction. To compare the impact of policy actions across countries, it is essential to have a consistent method for measuring emissions.

There are multiple approaches to calculating a country's emissions. One is the production-based accounting (PBA) approach, which assigns GHG emissions to the country where they are emitted. This includes emissions from production processes as well as from household consumption of GHG-emitting products, such as transport fuels. The PBA approach has been officially adopted for the calculation of National Emissions Inventories (NEI) under the UNFCCC, and for setting emissions reduction targets in the Paris Agreement (Afionis *et al*., 2017). However, this approach does not account for emissions embedded in goods consumed in one country but produced in another. For example, if a good is consumed in Country A but produced in Country B, the PBA approach assigns the emissions to the producing Country, B. Yet, since the good is used in Country A, it can be argued that country A should bear responsibility for those emissions.

A major equity concern with the production-based accounting (PBA) approach is that developed countries can outsource carbon-intensive production to less developed nations while continuing to import the resulting goods, thereby sustaining high consumption levels without reflecting these emissions in their own inventories (Tukker *et al*., 2020). This practice undermines international mitigation efforts: Peters *et al*. (2011) demonstrate that net emissions transfers from developing to developed countries offset reductions achieved by Annex B nations under the Kyoto Protocol by a factor of five. Consequently, significant contributors to climate change avoid emissions-based obligations, as outsourced emissions remain absent from National Accounts. Trade-embedded emissions represent approximately 27 per cent of global CO_2 emissions (Yamano and Guilhoto, 2020), and their exclusion disproportionately penalises poorer countries engaged in the most carbon-intensive stages of global supply chains (Grasso, 2016). Addressing these inequities is essential to ensure global cooperation on greenhouse gas mitigation and uphold principles of climate justice.

An alternative approach, consumption-based accounting (CBA) has been developed to estimate emissions embedded in internationally traded commodities and allocate them to the consuming countries. In essence, CBA emissions equal PBA emissions minus emissions embedded in exports, plus emissions embedded in imports. Thus, adjusting PBA emissions for the trade-related emissions yields CBA emissions.

Following this logic, the aim of this study is to calculate and compare Ireland's PBA and CBA emissions. Currently, CBA emissions are not calculated using a standardised international procedure unlike national inventories. However, the importance of trade-embedded emissions is increasingly recognised in policy. For example, the European Union has introduced the Carbon Border Adjustment Mechanism (CBAM), which initially covers the most emission-intensive commodities, such as cement, iron, steel, aluminium, fertilisers, electricity, and hydrogen (European Commission, 2025). CBAM aims to incentivise cleaner production outside the EU for goods imported into the EU and to prevent producers from avoiding emissions-based penalties by relocating production.

The remainder of this paper is structured as follows. Section II presents a brief review of the applied literature on CBA emissions. Section III describes the method and data. Section IV presents the findings, and Section V discusses their relevance. Section VI concludes.

II LITERATURE

Interest in consumption-based accounting (CBA) emissions has grown significantly in recent years, supported by improvements in international databases. A commonly used method for calculating CBA emissions is through Multi-Region Input-Output (MRIO) tables (Malik *et al*., 2019).

An Input-Output (IO) table illustrates how inputs are used across different sectors, effectively representing production technology – how inputs are combined to produce outputs. Since IO tables are expressed in monetary terms, they also reflect the cost structure of production. Additionally, they show how supply is allocated to elements of final demand. MRIO tables extend this framework by incorporating inputs and outputs across multiple countries, capturing inter-sectoral and international linkages. For example, an MRIO table would show how Ireland's agriculture sector relies on both domestically produced fertilisers and imported machinery to generate output.

Several MRIO databases are available:

- EORA covers 190 countries and between 25 to 500 sectors, depending on the country, from 1990 to 2022 (Lenzen *et al*., 2012; 2013). A simplified version, EORA26, aggregates data into 26 sectors;
- EXIOBASE 3 includes 163 industries across 44 countries (Stadler *et al*., 2018; Merciai and Schmidt, 2018);
- OECD-ICIO (Inter-Country Input-Output tables) comprises 76 countries plus a rest-of-the-world region, and 45 sectors (OECD, 2021);
- WIOD (World Input-Output Database) covers 43 countries and 56 sectors (Timmer *et al*., 2015; Groningen Growth and Development Centre, 2024).

These databases are often enhanced with greenhouse gas (GHG) emissions data to create environmentally extended MRIO tables, which are used to analyse the environmental impacts of economic activities. This approach builds on the input-output modelling framework pioneered by Leontief (1970).

Numerous studies have applied environmentally extended MRIOs to diverse topics. Wood *et al*. (2018) use EXIOBASE 3 to assess the environmental impact of changes in consumption patterns, focusing on food and clothing. Yang *et al*. (2020) examine emissions trends in the Asia-Pacific region from 1995 to 2015. Persson *et al*. (2019) investigate Sweden's international trade in hazardous chemicals and its environmental consequences. Castellani *et al*. (2019) compare life-cycle and MRIO-based approaches to assess the environmental impact of household consumption in Europe. Wu *et al*. (2019) use the EORA database to analyse global energy use, identifying the United States and China as particularly large energy consumers.

One of the most established international input-output databases with environmental extensions is the Global Trade Analysis Project (GTAP). Developed in the 1990s, GTAP was originally designed to support a large-scale computable general equilibrium model for analysing international trade. The latest version, GTAP 11, includes 65 production sectors and 141 countries, with data for the year 2017. It covers 99 per cent of global GDP and 96.4 per cent of the world's population (Aguiar *et al*., 2022). A previous version, GTAP 7 (based on 2004), was used by Davis and Caldeira (2010) to estimate global PBA and CBA emissions. For Ireland, they report PBA emissions of 43.9 $MtCO_2$ and CBA emissions of 55.4 $MtCO_2$.

As more MRIO databases and GTAP versions have become available, researchers have examined the consistency of results across sources. Owen *et al*. (2014) conduct a decomposition analysis comparing consumption-based emissions across EORA, GTAP, and WIOD. They identify differences in Leontief inverses, emissions data, and final demand data as key sources of variation. Moran and Wood (2014) perform a similar analysis across EORA, WIOD, EXIOBASE, and OpenEU, using a CBA approach based on CO_2 emissions from fossil fuel combustion. Their results for Ireland in 2002 vary widely: 43.0 $MtCO_2$ (EORA), 55.2 $MtCO_2$ (OpenEU), 42.0 $MtCO_2$ (WIOD), and 61.0 $MtCO_2$ (EXIOBASE).

Rodrigues *et al*. (2018) harmonise five MRIO databases to assess uncertainty in global CBA emissions. Nakano *et al*. (2009) report PBA emissions of 41 $MtCO_2$ and CBA emissions of 50 $MtCO_2$ for Ireland in 2000 – a 22 per cent difference – based on OECD IO tables, the STAN Trade Database, and IEA's CO_2 Emissions Database. In contrast, Yamano and Guilhoto (2020) find PBA emissions of 52.8 $MtCO_2$ and CBA emissions of 46.7 $MtCO_2$ for 2015.

Several studies have calculated CBA emissions. For Ireland, Nakano *et al*. (2009) report PBA emissions of 41 $MtCO_2$ and CBA emissions of as 50 $MtCO_2$ for 2000, and Davis and Caldeira (2010) estimate Irish PBA emissions at 43.9 $MtCO_2$ and CBA emissions at 55.4 $MtCO_2$ for 2004. Wood *et al*. (2019) using multiple data sources report average, PBA and CBA emissions of 43.6 and 45.7 $MtCO_2$, respectively, for 2016. In addition to empirical studies, policy debates have emerged around the justice and practicality of using CBA as a policy measure (Grasso, 2016; Duus-Otterstrom and Hjorthen, 2019).

These studies highlight the variability of results depending on the data source and methodology used. Such variation is expected but underscores the importance of multiple empirical studies for cross-validation and comparability. A notable gap in the literature is the lack of sectoral-level analysis of PBA and CBA emissions for individual countries. This paper addresses that gap by presenting sector-specific PBA and CBA emissions for Ireland using GTAP 11 data (Aguiar *et al.*, 2022). It also examines the geographical origins of emissions embedded in imports, offering insights into Ireland's global emissions footprint.

III METHOD AND DATA

Calculating production-based (PBA) and consumption-based (CBA) emissions requires a clear conceptual understanding of these accounting approaches. We define PBA emissions as those attributable to activities within Ireland. Specifically, this includes emissions from domestic production and fuel consumption by households. CBA emissions are defined as the sum of emissions from production activities undertaken to meet domestic demand, plus emissions from domestic fuel consumption. The difference between PBA and CBA emissions reflects the emissions embedded in imported and exported goods. We will shortly discuss the literature concerning these definitions in what follows.

However, the empirical literature reveals that these concepts are not always as straightforward as expected. Afionis *et al*. (2017) identify production-based emissions as the principle adopted by the UNFCCC. Wiedmann *et al*. (2010, p. 19) equate the production-based perspective with a territorial perspective. The European

Environment Agency (2013) emphasises the allocation of emissions to economic activities, distinguishing between territorial and PBA approaches, and incorporating corrections based on the residence principle. Sakata *et al*. (2024, p. 13) identifies two versions of production-based emissions: one based on the territorial principle and another on the residence principle. Barrett *et al*. (2013) highlight the consistency of PBA emissions with the system of National Accounts.

Definitions of CBA emissions consistently stress the importance of accounting for emissions embedded in international trade to ensure an equitable solution to emissions reduction. The European Environment Agency (2013) relates consumption emissions to the national consumption of goods and services, regardless of their origin. Sakata *et al*. (2024, p. 13) emphasises the inclusion of GHG emissions produced along global supply chains. Kokoni and Skea (2014) refer to life-cycle analysis as a source of emissions data across production stages. Barrett *et al*. (2013, p. 453) define CBA emissions as "...production-based emissions minus the emissions from the production of exports, plus the emissions from the production of imports." Karakaya *et al*. (2019) link the difference between PBA and CBA to the trade balance and the embedded CO_2 therein. Summarising various approaches, Tukker *et al*. (2020, p. S5) note that PBA emissions are the responsibility of producers, while CBA emissions are the responsibility of final consumers.

As a rule of thumb, PBA emissions are typically considered those resulting from domestic production, while CBA emissions reflect the emissions associated with domestic consumption. This implies subtracting emissions embedded in exports and adding those embedded in imports. Conceptually, CBA emissions can be linked to a country's final demand vector. This understanding underpins the widespread use of MRIO (Multi-Region Input-Output) models in CBA studies. A common implementation involves applying final demand data to an IO structure to estimate consumption-based emissions (Peters, 2008; Wiedmann *et al*., 2010; Mozner, 2013; Chandrakumar *et al*., 2020; Yamano and Guilhoto, 2020; Brown *et al*., 2021; Mangir and Sahin, 2022; Rahman *et al*., 2022).

However, MRIO-based studies face challenges related to the underlying databases. Wiedmann (2009) notes that, beyond the uncertainties inherent in single-region IO tables, MRIOs introduce additional complexities. These include converting data from different countries into a common currency and generating consistent bilateral trade data at the sectoral level. Kokoni and Skea (2014) distinguish between parametric uncertainty, which relates to data compilation, consistency and missing values, and structural uncertainty, which arises from choices in sector aggregation. Nijdam *et al*. (2005, p. 162) emphasise that IO tables are monetary, not physical, meaning sectors with varying emission intensities may be aggregated, potentially obscuring sector-specific emissions. The existence of multiple MRIO databases, each with distinct data management processes, contributes to variation in results and has led to a subfield focused on database comparison and harmonisation (Owen, 2015; 2017; Wieland *et al*., 2018; Giljum *et al*., 2019).

Given these limitations, a more reliable data source is needed to calculate PBA and CBA emissions for Ireland. This study uses the GTAP 11 database (Aguiar *et al*., 2022), one of the most established multi-country databases containing production, trade, and emissions data at the sectoral level. The GTAP database is supported by a global network of academic and institutional contributors (GTAP, 2025a; 2025b; 2025c). It has been widely used in GHG emissions research, particularly for estimating emissions embedded in international trade (Davis and Caldeira, 2010; Peters *et al*., 2011; Homma *et al*., 2012; Steininger *et al*., 2018; Rodrigues *et al*., 2018; Meng *et al*., 2023), despite the absence of a systematically updated GTAP MRIO database. Accordingly, GTAP 11 is considered a robust and reliable source for this analysis. However, the lack of a GTAP 11 MRIO structure limits methodological options, preventing the use of MRIO-based techniques even if preferred.

Here, we define PBA emissions as those attributable to activities within Ireland and CBA emissions as the sum of emissions from production activities undertaken to meet domestic demand, plus emissions from domestic fuel consumption. Our calculations rely on understanding both production processes and the flow of commodities across economies. PBA emissions are calculated as emissions from domestic production and fuel use, whether the fuels are produced locally or imported. For each production sector, three sources of emissions are considered: (1) combustion – fossil fuel use during production; (2) process emissions – non-combustion emissions such as calcination in cement production; and (3) endowment emissions – emissions from factors of production, such as methane from cattle. Details on how production-related emissions were prepared using the GTAP 11 database are provided in Appendix A.

3.1 Additional Data Processing

Some aspects of the GTAP 11 dataset and the nature of certain industries necessitate additional data processing. Two key adjustments relate to electricity-related emissions and cattle-related emissions. These adjustments are necessary to account for several limitations in the GTAP dataset and would improve the calculations of all countries CBA and PBA emissions.

In the GTAP database, emissions from electricity generation are attributed solely to the electricity production sector. Consequently, if a good is produced using electricity, the emissions associated with electricity generation are not included in the emissions calculations for that good. For example, if a good is exported from the United Kingdom to Ireland, the emissions from electricity used in its production are excluded. This leads to an underrepresentation of emissions embedded in trade, particularly because electricity itself is not widely traded internationally.

To address this, electricity-related emissions are reallocated across all production sectors in each country based on their electricity usage. Each sector's share of electricity consumption is used as a weighting factor to distribute the electricity generation emissions proportionally. Details of this procedure are provided in Appendix A, Section A.1.1. For a better understanding of CBA and PBA this additional data processing would be recommended for countries applying the GTAP database to calculate emissions.

The second issue concerns emissions from livestock, particularly cattle, in agriculture. In the GTAP framework, live animals such as cattle are treated as capital goods within the agricultural sector. As a result, methane emissions from cattle are recorded as agricultural emissions. When cattle meat is processed and exported, these emissions are not reflected in the manufacturing sector's emissions, even though the final product is a manufactured food item.

This treatment significantly underrepresents the emissions embedded in food products produced by the manufacturing industry. For instance, GTAP 11 data show export shares of 17 per cent for the cattle sector, 22 per cent for other animal products, and just 0.02 per cent for raw milk. However, according to the Central Statistics Office's Meat Supply Balance for 2017, Ireland exported 1.019 thousand tonnes of meat from a gross indigenous production of 1.183 thousand tonnes – an export rate of 86 per cent. If cattle-related emissions remain solely within the agriculture sector, the emissions embedded in traded animal products are substantially underestimated.

To illustrate, consider a cattle farm and a meat packaging plant. The farm, part of the agricultural sector, owns the cattle and is responsible for methane emissions. Once the cattle are slaughtered, the meat is processed and packaged by the manufacturing sector for export. Although the manufacturing sector is the exporter, the emissions remain recorded in agriculture. To ensure realistic emissions accounting, cattle-related emissions must be reallocated to the food manufacturing sector.

Accordingly, emissions from slaughtered cattle are reassigned to the manufacture of food, beverage and tobacco products sector. In Ireland, bovine meat products (CMT) and other meat products (OMT) use cattle as inputs. Therefore, emissions originally recorded in agriculture are reallocated to these commodities. This adjustment is necessary due to the treatment of cattle as capital goods in GTAP 11. Even in an MRIO structure, cattle-related emissions would be underrepresented without this reallocation. The methodology mirrors that used for electricity emissions. Further details are provided in Appendix A, Section A.1.2. This adjustment would be recommended for all countries, but particularly for countries with high cattle-based agricultural exports or imports.

3.2 Calculation of PBA and CBA Emissions

The calculation of CBA emissions, given PBA emissions, necessitates accounting for the emissions embedded in international trade. To do this, the emissions embedded in traded commodities need to be calculated using emissions coefficients, i.e. coefficients that show the emissions level per unit of production for each trade partner of Ireland and for each commodity imported by Ireland. The exposition of the technical details on the calculation of PBA and CBA emissions in Appendix A.2 starts with these coefficients. These coefficients are then used to calculate emissions embedded in trade.

We account for two additional considerations regarding emissions embedded in international trade. First, a portion of imported commodities is used domestically in the production of goods that are subsequently exported. In such cases, the importing country should not be held responsible for the emissions embedded in these imports, as the goods are not ultimately consumed domestically.

To address this, we define re-exported emissions as the emissions embedded in imported goods that are used as inputs in the production of goods exported to another country. Since neither the imported goods nor the goods produced from them are consumed within the importing country, the associated emissions should be excluded from the calculation of CBA emissions. The methodology for calculating re-exported emissions is detailed in Appendix A.2.1.

The second issue concerns the need to account for indirectly imported emissions. Consider Ireland's imports from Country A. To produce the goods exported to Ireland, Country A may rely on input commodities imported from another country – say, Country B. In this case, Country A's exports to Ireland include re-exported components originating from Country B. These goods, along with the emissions embedded in their production, ultimately reach Ireland, even though they were not directly imported from Country B. As such, Ireland indirectly imports both the goods and the associated emissions from Country B. These indirectly imported emissions must be included in Ireland's CBA calculations to accurately reflect its global emissions footprint. The methodology for calculating these emissions is detailed in Appendix A.2.2.

There is also a need to differentiate between domestic and international emissions from the air transport sector (ATP) due to the way international aviation emissions are allocated in the GTAP 11 database and to ensure alignment with the IPCC's methodology (IPCC, 2008). Typically, aviation- and maritime-related emissions are recorded in international bunkers (IPCC, 2008). In the GTAP 11 database, bunker emissions data are allocated to countries with respect to their international trade data (Chepeliev, 2020a, p. 13), which results in disproportionately high emissions attributed to Ireland's ATP sector. To correct for this, exported emissions from the ATP sector are excluded from Ireland's PBA emissions calculations. This adjustment ensures that only domestic aviation emissions are considered, in line with IPCC guidelines.

The calculation of CBA is done by adding emissions due to consumer use of fuel commodities to production emissions. The calculation of CBA is finalised by correcting PBA emissions for traded emissions. The details are available in Appendix A.2.3.

The calculations performed in this study yield three distinct sets of results, based on how emissions are treated across sectors:

- Case I, No redistribution: No production emissions reallocation is done;
- Case II, ELY redistribution: Electricity emissions are reallocated per Equation A.5;
- Case III, ELY and CTL redistribution: Both electricity- and cattle-related emissions are reallocated per Equations A.5 and A.9.

To improve the clarity of exposition and manage the volume of data generated, an aggregation of results has been undertaken. The GTAP 11 database comprises 65 production activities, each of which produces a single commodity. Given the three calculation cases and the number of commodities involved, the resulting dataset is too large to be examined comprehensively. To address this, a sectoral aggregation has been applied. The sectors are grouped in a way that ensures representation of the main contributors to Ireland's emissions, while the number of sectors presented is limited to maintain exposition clarity. The aggregation scheme used is detailed in Appendix Table B.1.

IV RESULTS

The results of the conducted analysis are presented in three stages. Firstly, the PBA emissions values are presented. Secondly, the emissions embedded in the international trade of Ireland are presented. Finally, the PBA and the CBA emissions of Ireland are compared.

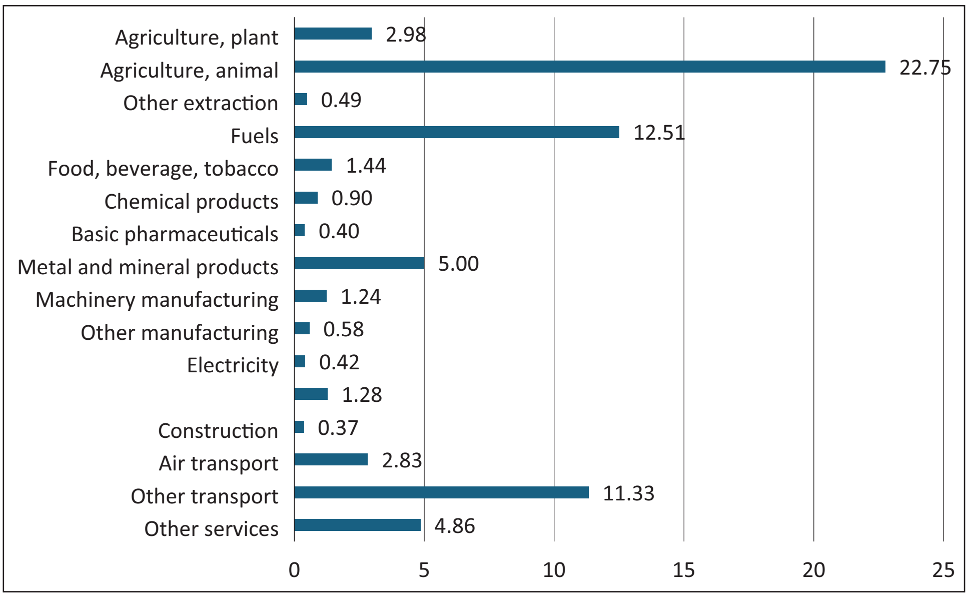
4.1 Production-based Emissions

PBA emissions calculated for Ireland are presented in Appendix B, Table B.2. A visualisation of the PBA emissions for Case III, where both electricity and cattle-related emissions are reallocated, can be observed in Figure 1. Under this case, total PBA emissions are 69.39 MtCO_2eq.

A review of the values in Table B.2 raises two key observations. First, the values under Case II (electricity reallocation) and Case III (electricity and cattle reallocation) are identical. The only difference between these cases is the redistribution of the cattle-related emissions in Case III. As described in Equation A.9, cattle-related emissions are transferred from the cattle commodity and reallocated to meat-related food manufacturing commodities, i.e. bovine meat products (CMT) and the meat products not elsewhere classified (OMT) in the GTAP 11 database. However, due to the sector aggregation defined in Appendix Table B.1, this reallocation keeps the emissions within the broader agriculture sector. As a result, the aggregated emissions values remain unchanged between Cases II and III. While this reallocation does not affect PBA emissions, it does influence emissions embedded in international trade. Therefore, Figure 1 is based on Case III, which includes both electricity and cattle-related emissions redistribution.

Second, there is a noticeable reduction in PBA emissions when electricity emissions are reallocated, i.e. comparing Case I to Case II. PBA emissions decrease from 73 $MtCO_2eq$ to 69 $MtCO_2eq$. This reallocation is based on the coefficients in Equation A.3, which reflect intermediate electricity use in both final and intermediate domestic uses, $\bar{Q}^{d}_{ELY,r}$. The redistribution isolates the emissions embedded in the electricity used as an intermediate input. Some emissions are assigned to final uses and are therefore not redistributed to non-electricity sectors. Again, Case III is considered the most informative and is used for visualisation. Comparing Case I and Case II, emissions increase for all sectors. However, a reduction in electricity emissions from 12.2 $MtCO_2eq$ to 0.4 $MtCO_2eq$ is observed due to the differences in intermediate and final use of electricity as well as the implied redistribution of emissions. The reduction in electricity emissions is larger than the sum of the increases in the other sectors. Hence, there is a fall in the PBA emissions.

Figure 1: Production-Based Account Emissions ($MtCO_2eq$, 2017) in Case III



Source: Authors' compilation based on GTAP11 (Aguiar *et al.*, 2022).

Figure 1 shows that the sectors with the highest PBA emissions are the animal agriculture sector (23 $MtCO_2eq$), fuels (13 $MtCO_2eq$), other transport (11 $MtCO_2eq$) and the metal and mineral products (5 $MtCO_2eq$). Together, these sectors account for approximately 75 per cent of Ireland's total PBA emissions.

The emissions from animal-related agriculture, primarily methane emissions from cattle amount to 17.8 $MtCO_2eq$. Fuel-related emissions include household consumption, with petroleum and coal products being the primary sources. Within the metal and mineral products sector, 3.3 $MtCO_2eq$ are attributed to mineral products not elsewhere classified sector.[1] While the database lacks sufficient granularity, it is likely that cement production is a major contributor to this category.

The redistribution of electricity does not alter the relative importance of these sectors. The primary change is the reduction in electricity-related emissions between Case I and Case II, which is an expected outcome of the adopted emissions redistribution.

4.2 Emissions Embedded in Trade

To calculate CBA emissions, we first need to estimate the emissions embedded in international trade. This is done in accordance with Equations A.11, A.12 and A.14, with results presented in Appendix B, Table B.3. It should be noted that the air transport (ATP) emissions in the table are processed only as specified by the relevant equations. Additional adjustments to ATP-emissions, as described in Equations A.15 and A.16, are not included in the data presented.

Under Case I (no redistribution) the largest amount of emissions embedded in direct and indirect imports are observed for the fuel (7.5 $MtCO_2eq$), chemical products (3.5 $MtCO_2eq$), and animal agriculture (2.1 $MtCO_2eq$) sectors. Regarding fuel-related imported emissions, the largest item is the directly imported emissions from petroleum and coal products (3.1 $MtCO_2eq$). It should be noted that this emissions figure relates to fuel production processes abroad and not due to the combustion of imported fuels. The second- and third-largest items are the indirectly imported gas (2.2 $MtCO_2eq$) and petroleum and coal products (1.1 $MtCO_2eq$). Regarding animal-related agriculture trade, the emissions are embedded in the directly imported emissions from cattle (1.8 $MtCO_2eq$).

Regarding exports under Case I, the sector with the highest emissions in exports is the ATP sector with 15.3 $MtCO_2eq$ emissions. It should be kept in mind that this number includes data on international aviation bunkers allocated to Ireland (Chepeliev, 2020a, p. 13). To understand this reallocation, consider a flight by an Irish aviation firm. The emissions due to flights between countries undertaken by this firm are allocated to an entity, the international bunker. This is not any country, and can be imagined as a fictional entity that gets assigned international aviation and maritime emissions. In the GTAP database, these emissions are allocated to countries that produce the flight service, using the shares of countries in global international aviation. In the case of the Irish aviation firm, the emissions related to a flight between any other two countries (for example, from Brazil to Australia),

[1] This sector corresponds to sector 23 under the ISIC Revision 4 classification, which includes cement production according to a correspondence table between GTAP and ISIC Rev 4 sectors (GTAP Data Bases: Two Concordances, 2019).

emissions would be recorded in international bunkers. In the GTAP database, these are allocated to Ireland based on its share in the global international aviation services provision. Thus, the exported emissions of the air transport sector are relatively high.

The next largest is the exports from the animal agriculture sector (3.6 $MtCO_2eq$), with cattle accounting for the majority of this figure (3.1 $MtCO_2eq$). Finally, the third largest emissions exporter is the chemical products sector with 1.6 $MtCO_2eq$ exported emissions.

Overall, the data suggest that Ireland is a net exporter of emissions, with a net export of 5.9 $MtCO_2eq$. However, this is largely influenced by how transport-related emissions are processed. If air transport emissions are excluded, a standard practice in national emissions inventories, Ireland becomes a net importer of emissions. This exclusion aligns with the IPCC (2008) methodology, which assigns emissions from international flights to international bunkers, rather than to individual countries. As such, these emissions are not included in national inventories.

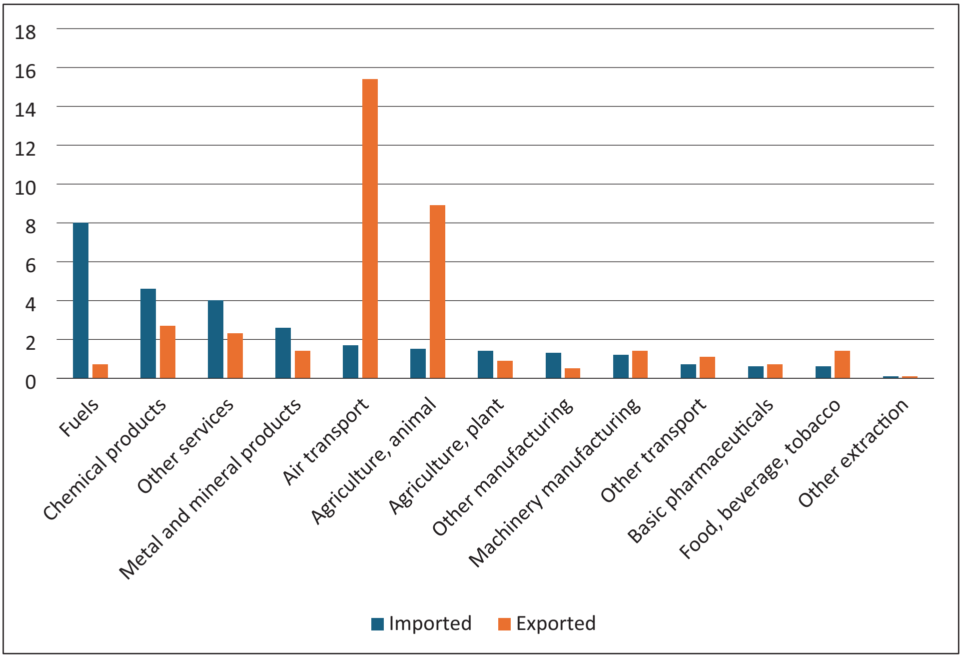
Under Case I in Table B.3, Ireland is a of net importer of emissions from fuel commodities with a total of 6.8 $MtCO_2eq$, primarily from petroleum and coal products. Additionally, the chemical products sector is a significant net importer, contributing 1.9 $MtCO_2eq$.

The reallocation of electricity emissions (Case II) does not substantially alter the amount of fuel-related imported emissions. Petroleum, coal products and gas remain the largest contributors. However, the second- and third-largest sources of imported emissions shift from the chemical products to other services sectors (3.9 $MtCO_2eq$). Within other services, business services not elsewhere classified account for the largest share. This increase in the ranking of business services is an expected outcome of the electricity emissions redistribution and points to the importance of energy inputs and the related emissions embedded in service trade. Ranking fourth is metal and mineral products with imported emissions of 2.6 $MtCO_2eq$. Though detailed data are not available, this sector includes cement production, which is a likely the key driver of these.

In terms of exported emissions, the air transport services sector remains the largest contributor. Following this are animal agriculture commodities with 3.9 $MtCO_2eq$, chemical products with 2.7 $MtCO_2eq$, and other services 2.3 $MtCO_2eq$. In Case II, when air transport is omitted, Ireland becomes a net importer of emissions with a net import of 10.2 $MtCO_2eq$, most of which is attributable to fuels (7.3 $MtCO_2eq$), especially petroleum and coal products.

Figure 2 visually presents emissions embedded in international trade under Case III, where both electricity and cattle-related emissions are redistributed. The figure confirms the high emissions embedded in the exports of air transport services and animal agriculture sectors. These sectors are net exporters of emissions. Considerable imported emissions are embedded in fuel imports.

Figure 2: Emissions Embedded in Trade (Case III, Electricity and Cattle Emissions Redistributed, $MtCO_2eq$, 2017)



Source: Authors' compilation based on GTAP11 (Aguiar et al, 2022).
Note: The figure excludes three sectors (construction, water and waste management and electricity) for which trade embedded emissions are zero.

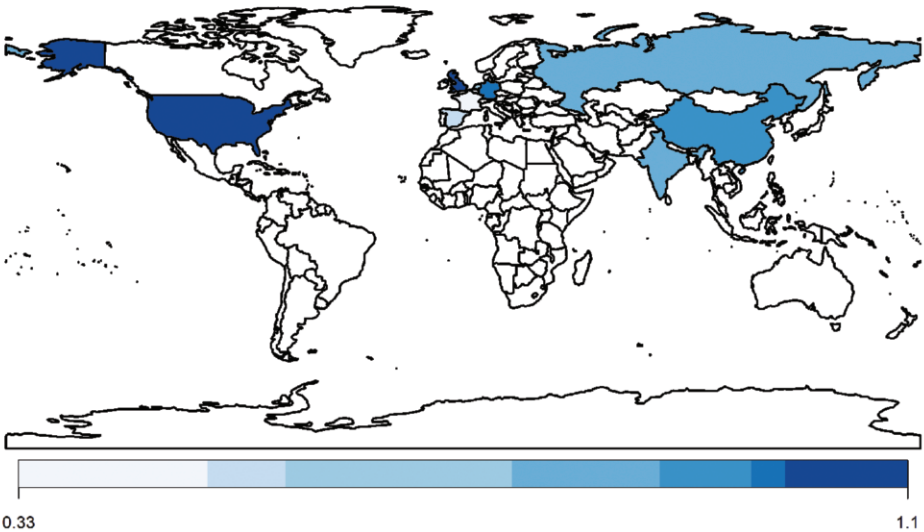
The reallocation of cattle-related emissions within the animal agriculture sector, in addition to electricity emissions redistribution, will impact only the international trade-embedded emissions of the animal agriculture sector. Comparing Cases II and III, the imported emissions of Ireland for this sector decrease to 1.5 $MtCO_2eq$ and the exported emissions increase to 8.9 $MtCO_2eq$. The sector becomes a net exporter of 7.4 $MtCO_2eq$ emissions. This reduces the net emissions imports of Ireland from 10.2 $MtCO_2eq$ to 4.5 $MtCO_2eq$, excluding air transport-related emissions.

Additionally, the chemical products and metal and mineral products sectors exhibit high emissions content in international trade. Under Case III, Ireland is a net exporter of 9.1 $MtCO_2eq$ emissions, which represents approximately 13 per cent of total PBA emissions (69.4 $MtCO_2eq$).

4.3 Geographical Sources of Imported Emissions

Identifying the countries from which Ireland imports emissions, or in other words, where Irish consumption is creating emissions abroad, is valuable. To delve into the details of this, Figure 3 is presented; for the interested reader, the underlying data are available in Appendix B, Table B.4. The figure shows the geographical distribution of directly imported emissions under Case III, (redistribution of both electricity and cattle-related emissions).

Figure 3: Sources of Imported Emissions



Source: Authors' compilation based on GTAP 11 (Aguiar *et al.*, 2022).
Note: The figure is based on data with electricity and cattle emissions redistributed. The underlying data are $MtCO_2eq$. White-shaded countries have been excluded from the figure to maintain exposition clarity.

Two countries account for a large portion of the directly imported emissions. Of the 20.1 $MtCO_2eq$ of directly imported emissions, 5.8 $MtCO_2eq$ (29 per cent of the total) originates from the United Kingdom, and 3.1 $MtCO_2eq$ (15 per cent of the total) originates from the United States of America (US). Large shares of imported emissions also come from Germany (0.98 $MtCO_2eq$, 4.8 per cent of total), China (0.95 $MtCO_2eq$, 4.7 per cent of total), Russia (0.87 $MtCO_2eq$, 4.3 per cent of total), the Netherlands (0.6 $MtCO_2eq$, 3 per cent of total), and India (0.8 $MtCO_2eq$, 3.9 per cent of total).

A further detailing of imported emissions is presented in Table 1, where the sum of imported and indirectly imported emissions is presented with respect to their sector and their source country. Most of the imported emissions are embedded in the fuel sector. These mostly originate from the United Kingdom, the US, Russia and the Netherlands. The second sector is the chemical products sector, where emissions mainly come from the United Kingdom, the US and Germany. The other services sector also accounts for a large share of imported emissions due to the reallocation of embedded emissions in electricity. The largest of these shares also originates from the United Kingdom, the US and Germany. Next in terms of imported emissions is the metal and mineral products sector, where emissions are mainly imported from the United Kingdom, China and Germany. Regarding the animal agriculture product sector, the emissions mainly come from the United Kingdom.

Table 1: Sector and Country Details of Total (Directly and Indirectly) Imported Emissions ($MtCO_2eq$, 2017)

	UK	*US*	*Germany*	*China*	*Russia*	*Netherlands*	*India*
Agriculture, plant	0.555	0.036	0.059	0.004	0.000	0.148	0.006
Agriculture, animal	1.065	0.071	0.025	0.002	0.000	0.055	0.000
Other extraction	0.013	0.001	0.001	0.002	0.000	0.001	0.007
Fuels	4.956	0.687	0.011	0.005	0.431	0.185	0.074
Food, beverage, tobacco	0.293	0.025	0.054	0.004	0.003	0.035	0.002
Chemical products	1.141	0.799	0.296	0.172	0.255	0.181	0.109
Basic pharmaceuticals	0.079	0.156	0.102	0.097	0.000	0.015	0.008
Metal and mineral products	0.973	0.140	0.193	0.238	0.008	0.023	0.247
Machinery manuf.	0.344	0.107	0.185	0.106	0.035	0.021	0.018
Other manuf.	0.505	0.098	0.094	0.110	0.007	0.037	0.039
Electricity	0.006	0.000	0.000	0.000	0.000	0.000	0.000
Water and waste management	0.000	0.001	0.000	0.000	0.000	0.000	0.000
Construction	0.006	0.000	0.000	0.001	0.000	0.000	0.000
Air transport	0.570	0.231	0.022	0.005	0.060	0.041	0.000
Other transport	0.059	0.085	0.008	0.009	0.047	0.023	0.001
Other services	0.439	1.021	0.203	0.272	0.068	0.115	0.324
SUM	11.005	3.457	1.254	1.027	0.914	0.881	0.835

Source: Authors' compilation based on GTAP 11 (Aguiar *et al.*, 2022).
Note: The data are for the case under which both electricity and cattle emissions are reallocated.

4.4 Comparison of PBA and CBA Emissions

The final stage of the analysis compares Ireland's production-based (PBA) and consumption-based (CBA) emissions. This comparison is based on the values presented in Table 2. The total amount of CBA emissions is greater than the total amount of PBA emissions for all the considered cases. If no redistribution of emissions is done, the total of the CBA emissions is 12 per cent higher than the total PBA emissions. Upon the redistribution of electricity emissions, the total amount of CBA emissions becomes 16 per cent higher than the total PBA emissions.

Table 2: Production vs Consumption-Based Account Emissions of Ireland ($MtCO_2eq$)

	No redistribution		*ELY redistribution*		*ELY & CTL redistribution*	
	PBA	*CBA*	*PBA*	*CBA*	*PBA*	*CBA*
Agriculture, plant	2.9	3.3	3.0	3.5	3.0	3.5
Agriculture, animal	22.4	20.8	22.8	21.0	22.8	15.3
Other extraction	0.2	0.2	0.5	0.5	0.5	0.5
Fuels	12.5	19.3	12.5	19.8	12.5	19.8
Food, beverage, tobacco	0.7	0.4	1.4	0.7	1.4	0.7
Chemical products	0.3	2.1	0.9	2.9	0.9	2.9
Basic pharmaceuticals	0.2	0.1	0.4	0.4	0.4	0.4
Metal and mineral products	4.2	5.1	5.0	6.3	5.0	6.3
Machinery manufacturing	0.5	0.3	1.2	1.1	1.2	1.1
Other manufacturing	0.1	0.4	0.6	1.3	0.6	1.3
Electricity	12.2	11.9	0.4	0.4	0.4	0.4
Water and waste management	0.9	1.0	1.3	1.3	1.3	1.3
Construction	0.3	0.3	0.4	0.4	0.4	0.4
Air transport	2.8	3.8	2.8	3.8	2.8	3.8
Other transport	11.3	10.8	11.3	10.9	11.3	10.9
Other services	2.2	2.5	4.9	6.5	4.9	6.5
SUM	73.6	82.3	69.4	80.6	69.4	74.9
CBA/PBA ratio	1.12		1.16		1.08	

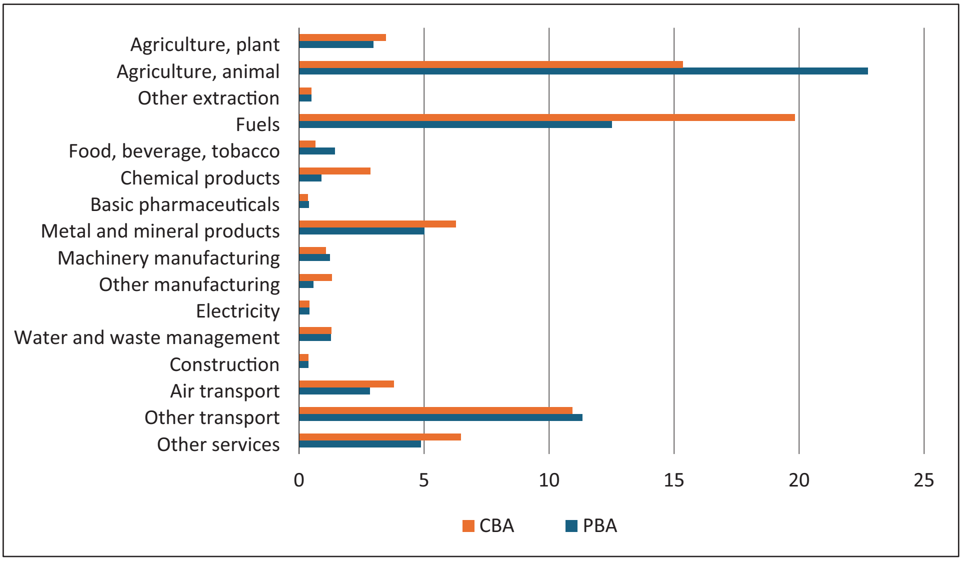
Source: Authors' compilation based on GTAP 11 (Aguiar *et al.*, 2022).

With cattle-related emissions redistributed, the emissions embedded in animal agriculture exports increase, and the excess of CBA over PBA decreases to 8 per cent.

The PBA and CBA emissions for the case with electricity and cattle emissions redistribution (Case III) are presented in Figure 6. The figure shows the relatively high emissions in the agriculture sector. PBA is higher than CBA, pointing to net export emissions from animal agriculture. Fuels also account for a considerable portion of the emissions, as Ireland is a net importer of these commodities. The transport sector is the third-largest source of PBA and CBA emissions. Finally, the metal and mineral products sector is observed to be a relatively large emissions source.

The comparison highlights the importance of considering consumption-based emissions in climate policy. While Ireland's PBA emissions reflect domestic production activities, its CBA emissions provide a more comprehensive view of its global emissions footprint, accounting for the climate impact of imported goods and services.

Figure 4: PBA vs CBA Emissions ($MtCO_2eq$, 2017)



Source: Authors' compilation based on GTAP 11 (Aguiar *et al.*, 2022).

Comparable data publicly available for a comparison of PBA and CBA emissions is limited. Our World in Data reports territorial emissions for Ireland in 2017 as 39.08 $MtCO_2$ and consumption-based emissions as 49.80 $MtCO_2$.[2] The CBA emissions are 27 per cent higher than the PBA emissions. EORA-based results show territorial emissions of 59.7 $MtCO_2eq$ and CBA of 72.1 $MtCO_2eq$ for Ireland in 2017, an excess of 21 per cent.[3] Davis and Caldeira (2010) use GTAP 7 data supplemented from various sources to calculate global CBA emissions. Their supplementary information reports a PBA of 43.90 $MtCO_2$ compared to a CBA of 55.40 $MtCO_2$ for Ireland in 2004, implying an excess of 26 per cent. Nakano *et al.* (2009) report a PBA value of 41 $MtCO_2$ and a CBA value of 50 $MtCO_2$ in 2000, now an excess of 22 per cent. Their results are based on OECD Input-Output tables, the STAN Trade Database and IEA's CO_2 Emissions Database. Wood *et al*. (2019) calculate CBA values from multiple MRIOs and examine the variations in the obtained results. They report a modal average PBA of 43.57 $MtCO_2$ and a CBA of 45.73 $MtCO_2$ for Ireland in 2016. In this case, CBA emissions exceed PBA emissions by 5 per cent. With a slightly different calculation approach and using the EXIOBASE database augmented by other data sources, de Bruin and Yakut (2022) calculate the PBA as 61 $MtCO_2eq$ and CBA as 106 $MtCO_2eq$; CBA is 74 per cent more than PBA year 2019.

[2] https://ourworldindata.org/co2-and-greenhouse-gas-emissions#explore-data-on-co2-and-greenhouse-gas-emissions. Note that the reported data refer only to CO_2 and not CO_2 equivalent.
[3] See: https://www.worldmrio.com/footprints/carbon/.

Our estimates are in line with the estimates found in the literature. Deviations can be attributed to the way data are composed in the GTAP 11 database. A comparison of the emissions data in the GTAP 11 database and the EUROSTAT Greenhouse Gas Emissions data for Ireland implies that the GTAP 11 data slightly overstate the level of emissions (both consumption and production). Once that is taken into account, the CBA and PBA values presented are in line with those of other studies. Sector-specific deviations of PBA and CBA emissions are due to the emissions embedded in international trade. Furthermore, one should note that this study considers methane and nitrous oxide and reports CO_2 equivalent emissions. Most studies referred to here present only CO_2 emissions. The addition of non-CO_2 GHGs contributes to the relatively higher values we report here.

The analysis is based on the GTAP 11 database, a well-established source of international data with sectoral detail that has been in use for several decades. While GTAP is a valuable resource, its use requires caution. The current version of GTAP 11 refers to data from 2017, and like any large dataset compiled from multiple independent sources, the data integration process involves adjustments that may affect the raw data.

The calculated values should therefore be interpreted carefully. Two data-related concerns are particularly noteworthy. First, although GTAP 11 is among the most reliable multi-country databases available, it is subject to data gathering and harmonisation practices. For example, consider how international trade flows are handled: a given trade flow is reported by both the exporting and importing countries. In some cases, the reported values may differ significantly. This inconsistency poses a challenge for GTAP, which is designed to support a computable general equilibrium (CGE) model that requires a single consistent value for each bilateral trade flow.

To reconcile these discrepancies, GTAP assesses the reliability of reported trade data and may, in some cases, disregard data from certain countries entirely (Gehlhar, 1996). However, this should not be viewed as a shortcoming of GTAP 11. Similar data reconciliation processes are standard practice in the construction of MRIO databases as well (Stadler *et al*., 2018, p. 505; Ferreira, 2018; Yamano *et al*., 2023, pp. 16-25).

Secondly, irrespective of the data source used, the calculation of country-specific emissions may require approaches tailored for each individual country. For example, in GTAP 11, the international aviation emissions data are assigned to countries by their air transport service exports. In the case of Ireland, this overestimates the domestic air transport emissions and requires a data intervention. This may be an issue in both the GTAP database and other databases.

This study further processed the data via redistributions of electricity and cattle emissions. We believe that these interventions have increased the reliability of the analysis. The redistribution of cattle emissions made the emissions-related outcomes more consistent with the observations regarding Ireland's agricultural emissions. Reallocation of electricity-related emissions enabled a better representation of emissions embedded in international trade. Given these, the approach with these reallocations (Case III) is a better accounting of the PBA and CBA emissions.

V DISCUSSION

There are three key dimensions to consider when evaluating consumption-based accounting (CBA) of emissions: methodological considerations, political and policy adoption and implications for Ireland.

The first dimension concerns the methodology used to calculate CBA emissions. This is an ongoing debate in the literature. CBA emissions can be calculated as a straightforward accounting exercise, similar to compiling emissions data in the Common Reporting Format (CRF) or converting national emissions inventories into air emissions accounts compatible with economic statistics. Alternatively, CBA can be estimated using Multi-Region Input-Output (MRIO) models, which, while widely used, come with technical challenges as previously discussed.

For CBA emissions to be adopted internationally, a standardised MRIO database is needed – one that is supported by a sufficient number of countries and maintained regularly. While technical superiority is desirable, consensus and consistency are more critical. As Kokoni and Skea (2014, p. 392) note:

> *The dataset adopted does not need to be the 'best'. The examples of QWERTY keyboards and Betamax vs VHS video systems show that technically superior standards do not necessarily acquire universal acceptance.*

What is needed is an agreed-upon data source and a transparent, replicable data processing methodology.

Currently, MRIO-based CBA emissions are viewed more as informative indicators than as formal targets. However, the introduction of policies such as the Carbon Border Adjustment Mechanism (CBAM) reflects growing awareness of carbon leakage and signals a shift toward addressing it. This suggests that CBA-related work may gain prominence in the near future, along with efforts to harmonise international data collection methods.

Once a methodology is in place, the next challenge is the adoption of CBA emissions as a policy indicator or target. This raises several issues. Peters (2008, p. 20) notes that implementing restrictions on emissions embedded in imports requires extensive international policy coordination – a task that is inherently complex. Even without cross-border coordination, aligning domestic policies is difficult.

De Palma *et al.* (2025) highlight the multi-dimensional challenges of policy coordination, using the EU's proposed internal combustion engine ban after 2034 as a case study.

Pan *et al.* (2022) report that adopting a CBA approach would reduce mitigation burdens for developing economies while increasing them for developed countries. This creates a disincentive for developed nations to embrace CBA as an official metric of emissions responsibility. Steininger *et al.* (2014) highlight a number of preconditions to the success of CBA emissions accounting, in particular that there must be a clean technology transfer. Moreover, implementing these technologies requires transforming the capital stock, and the funding of this transition poses a significant challenge.

The third dimension relates to the Irish context. Imported emissions reveals that they originate primarily from Ireland's major trading partners. Fuel-related emissions are imported from the United Kingdom, the United States, Russia and the Netherlands. Emissions embedded in chemical products largely come from the United Kingdom, the United States and Germany. Animal agriculture-related emissions are predominantly imported from the United Kingdom. Ireland as an EU country is governed by national and EU level policies. The EU Emissions Trading System (EU ETS) is the cornerstone of the European Union's climate policy. It operates as a cap-and-trade mechanism, setting a limit (cap) on the total volume of greenhouse gas emissions from high-emitting sectors such as power generation, manufacturing and aviation. Within this cap, companies receive or purchase emission allowances, which they can trade with one another. Over time, the cap is reduced to ensure a gradual decline in emissions, thereby incentivising low-carbon innovation and investment. Hence any changes in national accounting methods would not impact emitters whose emissions fall under the EU ETS system.

In parallel, national emissions targets are established under the Effort Sharing Regulation (ESR), which covers sectors not included in the EU ETS – such as agriculture, transport, buildings and waste. These targets are binding and vary by Member State, reflecting differences in economic capacity and historical emissions. Each country must implement domestic policies to meet its ESR obligations, contributing to the EU's overall climate goals. Any changes in accounting methods would impact non-ETS emissions and households and producers that emit these.

Ireland's climate policy framework is outlined in the Climate Action Plan (CAP), published annually by the Department of Climate, Energy and the Environment. According to the CAP 2025 Main Report, agriculture remains a major source of emissions, accounting for 34 per cent of Ireland's GHG emissions (DCEE, 2025, p. 25). In 2023, methane represented 72.1 per cent of agricultural emissions (DCEE, 2025, p. 122). Under current accounting standards, these emissions are Ireland's responsibility.

Consider a shift to CBA emissions as the main indicator of emissions responsibility. The emissions embedded in the production of animal agriculture products become the responsibility of importers. With the cattle-related emissions reallocation, 8.9 $MtCO_2eq$ would no longer be attributed to Ireland. On the other hand, Ireland imports 8 $MtCO_2eq$ of emissions embedded in fuel commodities. In net terms, these two large items nearly cancel each other out.

Another important consideration is the treatment of aviation emissions. Currently, these are allocated to international bunkers. Under a CBA approach, emissions from air transport services exported by Ireland – amounting to over 15 $MtCO_2eq$ – would be assigned to the importing countries. This would not affect Ireland's emissions responsibility under either the current inventory system or a CBA framework, as these emissions are not attributed to the country providing the service.

Any change in CBA emissions would relate to shifts in trade patterns. In this context, the CBAM is important. The CBAM is to cover cement, iron, steel, aluminium, fertilisers and electricity. For Ireland, the issue has unique dimensions that interact with the introduction of the CBAM. Ireland's import shares of these goods from non-EU countries, in general, and the UK in particular are non-negligible, as can be seen in Table 3. If these imports are subject to CBAM, they could become more expensive and impact price formation in Ireland. The issue boils down to the price sensitivity of these imports and the extent to which they can be substituted with within-EU alternatives.

Table 3: Shares of CBAM-related Products in Ireland's Total Imports (%)

	Non-EU countries, including UK	*GBR and Northern Ireland*
Electric current (35)	100	100
Fertilisers, manufactured (56)	57	9
Non-metallic mineral manufactures, n.e.s. (66)	72	45
Iron and steel (67)	63	39
Non-ferrous metals (68)	60	25

Source: Compiled and calculated by authors from CSO, External Trade statistics, Value of Merchandise Trade (TSA09 and TSA10).

VI CONCLUSION

This study highlights the substantial differences between production-based (PBA) and consumption-based (CBA) emissions accounting for Ireland. While PBA emissions are concentrated in animal agriculture, fuels, electricity, and transport, CBA emissions – 8 to 16 per cent higher – reflect Ireland's reliance on imported fuels, chemicals, and services, as well as its role as an exporter of air transport and agricultural products. These findings emphasise the need to consider trade-related emissions to accurately capture Ireland's global carbon footprint. Although methodological complexity limits widespread adoption of CBA, the GTAP-based framework developed here provides a foundation for international comparisons and future research on cross-country and time-series analysis. From a policy perspective, adopting CBA would redistribute agricultural emissions abroad while increasing accountability for imported carbon-intensive goods, reinforcing the importance of equity and transparency in climate accounting.

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Appendix A

This appendix details the calculation of emissions based on the GTAP11 data. First, production-related emissions are presented. This is followed by certain steps undertaken to process the dataset in relation to electricity and animal-related agriculture emissions. The variable abbreviations follow the notation of the GTAP11 database for ease of reference.

A.1 Production Emissions

Production-related emissions in any country or region *r* and production sector *a* are calculated as follows:

$$EMISS^{prod}_{a,r} = \Sigma_f[MDF_{f,a,r} + MMF_{f,a,r}] = \Sigma_{e=CO_2,CH_4,N_2O}\, GWP_e EMI\_ENDW_{e,a,r} + \Sigma_{e=CO_2,CH_4,N_2O} GWP_e[EMI\_QO_{e,a,r} + \Sigma_c[EMI\_IO_{e,c,a,r} + + EMI\_IOP_{e,c,a,r}]] \quad (A.1)$$

Where:

- $MDF_{f,a,r}$ and $MMF_{f,a,r}$ are CO_2 emissions due to the use of domestic and imported fuels in the production activity of sector *a*. The fuels, *f*, referred to in the GTAP 11 database are coal (COA), oil (OIL), gas (GAS), petroleum and coal products (P_C) and gas distribution (GDT).
- GWP_e is the global warming potential coefficient for each greenhouse gas *e*. The GHGs covered by this study are CO_2, CH_4 and N_2O. Following IPCC (2015), the global warming potential coefficients are reported as 28 for CH_4 and 265 for N_2O in the GTAP 11 database.
- $EMI\_ENDW_{e,a,r}$ refers to emissions of GHG *e* due to the use of factor endowments in production activity *a* in region *r*. The GTAP 11 database allocates some of the emissions to the endowments of factors of production used in the production process. In the endowment-related emissions part of the GTAP 11 database, only capital and land are included as endowments. And of these endowment emissions, capital emissions related to agriculture account for 90 per cent of endowment emissions for Ireland. In other words, this refers to emissions from the cattle (Chepeliev, 2021, p. 39). Since these are of primary importance for the Irish agriculture sector, they have been included in the calculations.
- $EMI\_QO_{e,a,r}$ refers to production process emissions, i.e. emissions not resulting from combustion but resulting from the production of final goods. The procedure used to generate the GTAP database considers emissions due to four emission drivers: output by industries, endowment by industries, input use by industries and consumption by households (Chepeliev, 2020b). This conceptualisation is used to relate emission data sources to the sectors defined in the GTAP database. Appendix D of Chepeliev (2020b, p. 20-22) shows the

details of these production process emissions. Some examples are fugitive emissions, industrial process emissions of metal production, and the treatment of waste.

- $EMI\_IO_{e,c,a,r}$ refers to non-CO_2 emissions linked to fossil fuel combustion-related to the commodity c by the production activity in sector a.
- $EMI\_IOP_{e,c,a,r}$ refers to process emissions linked to intermediate demand for commodity c by the production activity in sector a. These are not related to combustion; that is, they are not released due to the burning of fuel. Rather, these process emissions are released when inputs are transformed during the production process. A typical example is the release of CO_2 due to the heating of limestone while cement is produced; this process is known as calcination.

We have made three adjustments to the GTAP database concerning electricity, agriculture, and aviation emissions. These adjustments are detailed in the following sections.

A.1.1 Emissions Embedded in Electricity

Let the total use of the domestic electricity commodity ($\bar{Q}^d_{ELY,r}$) be the following:

$$\bar{Q}^d_{ELY,r} = \Sigma_a INT^d_{ELY,a,r} + CON^d_{ELY,r} + INV^d_{ELY,r} + GOV^d_{ELY,r} + EXP_{ELY,r} \tag{A.2}$$

where $INT^d_{ELY,a,r}$ is the intermediate use of the electricity commodity by activity a in region r, $CON^d_{ELY,r}$ is the domestic consumption expenditure on electricity, $INV^d_{ELY,r}$ is the domestic investment expenditure on electricity, $GOV^d_{ELY,r}$ is the domestic government expenditure on electricity, $EXP_{ELY,r}$ is the exported electricity. Given this, the share of the intermediate use of electricity relative to the total domestic use of electricity is:

$$shareELY_{a,r} = \frac{INT_{ELY,a,r}}{\bar{Q}^d_{ELY,r}} \tag{A.3}$$

and the reallocation of the emissions embedded in the electricity input to all the other a activities is calculated as:

$$dEMISS_{a,r} = shareELY_{a,r}\, EMISS^{prod}_{ELY,r} \tag{A.4}$$

where $EMISS^{prod}_{ELY,r}$ is the emissions embedded in the electricity commodity.[4] It should be noted that this term isolates the emissions embedded in the electricity

[4] It should be noted that the make matrix of the GTAP 11 database is diagonal. That is, each activity produces one commodity. Therefore, the concepts of activity and commodity are interchangeable. Hence the indices of activity, a, and commodity, c are interchangeable, implying that $EMISS^{prod}_{a,r}$ and $EMISS^{prod}_{c,r}$ are also interchangeable. With this, $EMISS^{prod}_{ELY,r}$ would represent both the emissions from the activity of electricity production and the emissions embedded in the electricity commodity.

commodity to reallocate it to activities. Hence, production activity emissions are restated as follows:

$$EMISS^{prod}_{a,r} = \begin{cases} EMISS^{prod}_{a,r} + dEMISS_{a,r}, \ a \neq ELY \\ dEMISS_{a,r}, \quad a = ELY \end{cases} \tag{A.5}$$

A.1.2 Animal Products Emissions

The emissions reallocation is similar to electricity emissions reallocation. The total use of cattle output ($\bar{Q}_{CTL,r}$) is as follows:

$$\bar{Q}_{CTL,r} = \Sigma_a INT^d_{CTL,a,r} + CON^d_{CTL,r} + INV^d_{CTL,r} + GOV^d_{CTL,r} + EXP^d_{CTL,r} \tag{A.6}$$

The shares are:

$$shareCTL_{a,r} = \frac{INT_{CTL,a,r}}{\bar{Q}^d_{CTL,r}} \tag{A.7}$$

Along the lines of Equation A.4, the implied reallocation of emissions is:

$$dEMISS\_CTL_{a,r} = shareCTL_{a,r}\, EMISS^{prod}_{CTL,r} \tag{A.8}$$

In the case of cattle, this reallocation is from the cattle (CTL) in the agriculture sector to two commodities in the food sector: bovine meat products (CMT) and meat products not elsewhere classified (OMT). Hence, production emissions for these commodities become:

$$\begin{aligned} EMISS^{prod}_{CMT,r} &= EMISS^{prod}_{CMT,r} + dEMISS_{CMT,r}\, EMISS^{prod}_{OMT,r} = EMISS^{prod}_{OMT,r} \\ &+ dEMISS_{OMT,r}\, EMISS^{prod}_{CTL,r} = EMISS^{prod}_{CTL,r} \\ &- dEMISS_{CMT,r} - dEMISS_{OMT,r} \end{aligned} \tag{A.9}$$

A.2 Calculation of PBA and CBA Emissions

Emission coefficients that show emissions per monetary unit of output of commodity c in region r are:

$$\varepsilon_{c,r} = \frac{EMISS^{prod}_{c,r}}{Q_{c,r}} \tag{A.10}$$

Given these emission coefficients, the emissions embedded in exports and imports would be:

$$EMISS^{exp}_{c,r} = \Sigma_{dst}\, \varepsilon_{c,r}\, EXP_{c,r,dst}$$
$$EMISS^{imp}_{c,r} = \Sigma_{src}\, \varepsilon_{c,src}\, IMP_{c,src,r} \quad \text{(A.11)}$$

where $EXP_{c,r,dst}$ would be an export of commodity c from country r to destination country dst. Similarly, $IMP_{c,src,r}$ is the imports of commodity c from origin country src to country r. Regarding the emissions embedded in trade, further calculations are done with respect to reexported emissions and indirectly imported emissions. The relevant calculation steps are as follows:

A.2.1 Re-exported Emissions

Let us begin with re-exported goods and the emissions embedded therein. What we know at this point is the emissions embedded in the imports of commodity c, calculated as $EMISS^{imp}_{c,r}$ in Equation (A.11). We will augment this with two considerations. Firstly, some of the imported goods are used as intermediate inputs. Therefore, some of the imported emissions are embedded in intermediate inputs. To isolate these, we will use the share of imported intermediate goods in total imports. Secondly, these imported intermediate good emissions need to be allocated to exports. In order to do this, we use the ratio of exports to production.

Let the intermediate imports of commodity c by region r that are used in production activity a be $INT\_IMP_{c,a,r}$. Then, the aggregate intermediate input of commodity c that is imported by all production activities would be $\Sigma_a INT\_IMP_{c,a,r}$. Also, $IMP_{c,src,r}$ is the imports of commodity c from each source country. Hence, the aggregate import of commodity c aggregated over all source countries would be $\Sigma_{src} IMP_{c,src,r}$. Given these, the share of imported intermediate inputs in aggregate imports is:

$$shr\_import_{c,r} = \frac{\Sigma_a\, INT\_IMP_{c,a,r}}{\Sigma_{src} IMP_{c,src,r}}$$

We know the imported emissions $EMISS^{imp}_{c,r}$ and thus we can multiply this by the share of intermediate inputs that are imported, $shr\_import_{c,r}$, to get the emissions from the imported intermediate inputs, $shr\_import_{c,r} EMISS^{imp}_{c,r}$.

As the second step, we need to know the share of total production of commodity c in the country to which it is exported. To do this, we first calculate the exports of commodity c from country r to all destination countries, i.e. $\Sigma_{dst} EXP_{c,r,dst}$. We then need to calculate all production of commodity c in country r, which is $Q_{c,r}$. Thus, the share of production exported is:

$$shr\_export_{c,r} = \frac{\Sigma_{dst}\, EXP_{c,r,dst}}{Q_{c,r}}$$

Now that we have these shares, we can calculate the re-exported emissions for country r[5]. As noted above, the emissions embedded in imported intermediate commodities is $shr\_import_{c,r}EMISS^{imp}_{c,r}$. To see how much of these imported intermediate emissions are exported, we will multiply it with the export share, $shr\_export_{c,r}$:

$$REXP\_EMISS_{c,r} = shr\_export_{c,r}[shr\_import_{c,r}EMISS^{imp}_{c,r}] \qquad (A.12)$$

Thus we have a measure of the re-exported emissions, i.e. the emissions initially imported as intermediate inputs, used in production and ended as a part of exported emissions.

A.2.2 Indirectly Imported Emissions

Consider the example in text where Ireland imports commodities from country A. In order to produce the goods that it exports to Ireland, country A has to import intermediate inputs from other countries, say country B. Using the terminology developed so far, what we are referring to is actually the re-exported emissions of country A. The emissions imported by Country A in the form of intermediate inputs are then exported to other countries. The question is, how can we isolate the re-exported emissions of country A that come to Ireland?

In order to do this, we apply the share of each destination country in an exporting country's total exports. Let $EXP_{c,src,dst}$ be the export flow of commodity c originating from a source country src and going to a destination country dst. The aggregate exports of the source country is these exports aggregated over destination countries, i.e. $\Sigma_{dst}EXP_{c,src,dst}$. Then, the share of each destination country in the total exports of an exporting country would be:

$$exp\_dst_{c,src,dst} = \frac{EXP_{c,src,dst}}{\Sigma_{dst}EXP_{c,src,dst}} \qquad (A.13)$$

This share can be used to allocate re-exported emissions of a source country to its export partners, i.e. the destination countries. From the perspective of the recipient of the trade flow, i.e. the destination country, the indirectly imported emissions from all the trade partners would be:

$$IND\_IMP\_EMISS_{c,dst} = \Sigma_{src}\, exp\_dst_{c,src,dst}REXP\_EMISS_{c,src} \qquad (A.14)$$

[5] Since the GTAP 11 database is not a Multi-Region Input-Output database, intermediate commodity trade by source and destination countries is not available. In other words, we do not know which sector in Ireland is importing which good from which country. What we observe in the database is the imports of Ireland. Therefore, these shares had to be used to approximate the intermediate commodity trade and the embedded emissions.

A.2.3 PBA and CBA Emissions

We can calculate PBA and CBA emissions by applying the equations described below. The PBA emissions by commodity are calculated by adding the emissions due to fuel consumption by consumers to production emissions. Fuel consumption emissions by consumers, $EMISS_{c,r}^{cons}$, are defined in the GTAP 11 database as the emissions associated with the households' (consumers') use of fuel commodities, i.e. coal (COA), oil (OIL), gas (GAS), petroleum and coal products (P_C), and gas manufacture and distribution (GDT). Hence, the calculation of PBA emissions is:

$$PBA_{c,r} = \begin{cases} EMISS_{c,r}^{prod} + EMISS_{c,r}^{cons}, & c \neq \text{ATP} \\ EMISS_{ATP,r}^{prod} + EMISS^{con}S_{ATP,r} - EMISS_{ATP,r}^{exp}, & c = \text{ATP} \end{cases} \tag{A.15}$$

where $EMISS_{ATP,r}^{exp}$ is the exported emissions for the air transport (ATP) sector.

Finally, the CBA emissions would be calculated by first adding the imported emissions and the indirectly imported emissions and then subtracting the exported and re-exported emissions to PBA as follows:

$$CBA_{c,r} =$$

$$\begin{cases} PBA_{c,r} + EMISS_{c,r}^{imp} - EMISS_{c,r}^{exp} + IND\_IMP\_EMISS_{c,r} - EXP\_EMISS_{c,r}, & c \neq \text{ATP} \\ PBA_{c,r} + EMISS_{c,r}^{imp} - EMISS_{c,r}^{exp} + IND\_IMP\_EMISS_{c,r} - EXP\_EMISS_{c,r} \\ \quad + EMISS_{c,r}^{exp}, \quad c = \text{ATP} \end{cases} \tag{A.16}$$

Note that for CBA emissions, the export emissions in the ATP sector are both deducted and added to the PBA amount. If this addition of ATP's exported emissions is not done in the CBA emissions calculation, the exported emissions for the ATP sector would be deducted twice.

APPENDIX B

Table B.1: Sector List

Sector abbreviation	*Name*	*GTAP11 abbreviation*	*Name*
FUEL	Fuels	COA	Coal
		OIL	Oil
		GAS	Gas
		P_C	Petroleum, coal products
		GDT	Gas manufacture, distribution
AGR	Agriculture, plant	PDR	Paddy rice
		WHT	Wheat
		GRO	Cereal grains nec
		V_F	Vegetables, fruit, nuts
		OSD	Oil seeds
		C_B	Sugar cane, sugar beet
		PFB	Plant-based fibres
		OCR	Crops nec
		FRS	Forestry
ANM	Agriculture, animal	CTL	Bovine cattle, sheep and goats, horses
		OAP	Animal products nec
		RMK	Raw milk
		WOL	Wool, silk-worm cocoons
		FSH	Fishing
		CMT	Bovine meat products
		OMT	Meat products nec
XTR	Other extraction	OXT	Other Extraction (formerly omn Minerals nec)
FBT	Food, beverage, tobacco	VOL	Vegetable oils and fats
		MIL	Dairy products
		PCR	Processed rice
		SGR	Sugar
		OFD	Food products nec
		B_T	Beverages and tobacco products
CHM	Chemical products	CHM	Chemical products
BPH	Basic pharmaceuticals	BPH	Basic pharmaceutical products
MTL	Metal and mineral products	NMM	Mineral products nec
		I_S	Ferrous metals
		NFM	Metals nec
		FMP	Metal products

Table B.1: Sector List (Contd.)

Sector abbreviation	*Name*	*GTAP11 abbreviation*	*Name*
OMANUF	Other manufacturing	TEX	Textiles
		WAP	Wearing apparel
		LEA	Leather products
		LUM	Wood products
		PPP	Paper products, publishing
		RPP	Rubber and plastic products
		OMF	Manufactures nec
MANUF	Machinery manufacturing	ELE	Computer, electronic and optical products
		EEQ	Electrical equipment
		OME	Machinery and equipment nec
		MVH	Motor vehicles and parts
		OTN	Transport equipment nec
ELY	Electricity	ELY	Electricity
WTR	Water and waste management	WTR	Water
CNS	Construction	CNS	Construction
OTP	Other transport	OTP	Transport nec
		WTP	Water transport
ATP	Air transport	ATP	Air transport
OSR	Other services	TRD	Trade
		AFS	Accommodation, Food and service activities
		WHS	Warehousing and support activities
		CMN	Communication
		OFI	Financial services nec
		INS	Insurance (formerly isr)
		RSA	Real estate activities
		OBS	Business services nec
		ROS	Recreational and other services
		OSG	Public Administration and defence
		EDU	Education
		HHT	Human health and social work activities
		DWE	Dwellings

Source: Authors' compilation.

Table B.2: Production-Based Account Emissions (MtCO2eq)

	Case I: No redistribution	*Case II: ELY redistribution*	*Case III: ELY&CTL redistribution*
Agriculture, plant	2.9	3.0	3.0
Agriculture, animal	22.4	22.8	22.8
Other extraction	0.2	0.5	0.5
Fuels	12.5	12.5	12.5
Food, beverage, tobacco	0.7	1.4	1.4
Chemical products	0.3	0.9	0.9
Basic pharmaceuticals	0.2	0.4	0.4
Metal and mineral products	4.2	5.0	5.0
Machinery manufacturing	0.5	1.2	1.2
Other manufacturing	0.1	0.6	0.6
Electricity	12.2	0.4	0.4
Water and waste management	0.9	1.3	1.3
Construction	0.3	0.4	0.4
Air transport	2.8	2.8	2.8
Other transport	11.3	11.3	11.3
Other services	2.2	4.9	4.9
SUM	73.6	69.4	69.4

Source: Authors' compilation based on GTAP11 (Aguiar *et al.*, 2022).

Table B.3: Emissions Embedded in Ireland's International Trade ($MtCO_2eq$)

	Case I: No redistribution			*Case II: ELY redistribution*			*Case III: ELY&CTL redistribution*		
	Imported (direct and indirect)	*Exported and re-exported*	*Net imported*	*Imported (direct and indirect)*	*Exported and re-exported*	*Net imported*	*Imported (direct and indirect)*	*Exported and re-exported*	*Net imported*
Agriculture, plant	1.2	0.9	0.4	1.4	0.9	0.5	1.4	0.9	0.5
Agriculture, animal	2.1	3.6	–1.6	2.1	3.9	–1.7	1.5	8.9	–7.4
Other extraction	0.1	0.0	0.0	0.1	0.1	0.0	0.1	0.1	0.0
Fuels	7.5	0.7	6.8	8.0	0.7	7.3	8.0	0.7	7.3
Food, beverage, tobacco	0.4	0.7	–0.4	0.6	1.4	–0.8	0.6	1.4	–0.8
Chemical products	3.5	1.6	1.9	4.6	2.7	2.0	4.6	2.7	2.0
Basic pharmaceuticals	0.2	0.3	–0.1	0.6	0.7	–0.1	0.6	0.7	–0.1
Metal and mineral products	1.9	0.9	1.0	2.6	1.4	1.3	2.6	1.4	1.3
Machinery manufacturing	0.4	0.5	–0.2	1.2	1.4	–0.2	1.2	1.4	–0.2
Other manufacturing	0.5	0.2	0.3	1.3	0.5	0.7	1.3	0.5	0.7
Electricity	0.2	0.6	–0.4	0.0	0.0	0.0	0.0	0.0	0.0
Water and waste management	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Construction	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Air transport	1.7	15.3	–13.6	1.7	15.4	–13.7	1.7	15.4	–13.7
Other transport	0.7	1.1	–0.4	0.7	1.1	–0.4	0.7	1.1	–0.4
Other services	1.3	1.0	0.3	4.0	2.3	1.6	4.0	2.3	1.6
SUM	21.5	27.3	–5.9	28.8	32.3	–3.5	28.2	37.3	–9.1

Source: Authors' compilation based on GTAP11 (Aguiar *et al.*, 2022).

Note: Imported emissions refers to $EMISS^{imp}_{c,r}$, Equation (11). Indirect imported emissions refers to $IND\_IMP\_EMISS_{c,r}$, Equation (14). Exported emissions refers to $EMISS^{exp}_{cr}$, Equation (11). Re-exported emissions refers to $REXP\_EMISS_{c,r}$, Equation (12). Net imported emissions is calculated as $[EMISS^{imp}_{c,r} + IND\_IMP\_EMISS_{c,r}] – [EMISS^{exp}_{c,r} + REXP\_EMISS_{c',r}]$

Table B.4: Emissions Embedded in Imports by Origin Country

Country Code	*Imported emissions ($MtCO_2eq$)*	*Share (%)*	*Country Code*	*Imported emissions ($MtCO_2eq$)*	*Share (%)*
GBR	5.86	29.16	UKR	0.11	0.53
USA	3.08	15.35	EGY	0.09	0.45
DEU	0.98	4.87	MEX	0.09	0.45
CHN	0.95	4.75	BRA	0.09	0.46
RUS	0.87	4.35	CZE	0.07	0.36
NLD	0.61	3.04	DZA	0.09	0.46
IND	0.78	3.89	GRC	0.07	0.34
FRA	0.49	2.46	IRN	0.09	0.43
ESP	0.50	2.47	DNK	0.06	0.31
BEL	0.33	1.64	CHE	0.02	0.12
ITA	0.41	2.03	TWN	0.07	0.34
NOR	0.37	1.84	THA	0.07	0.35
NGA	0.34	1.68	HUN	0.06	0.28
POL	0.29	1.44	LTU	0.05	0.25
KOR	0.21	1.04	PHL	0.07	0.33
SAU	0.25	1.23	ARG	0.06	0.30
TUR	0.21	1.03	XWF	0.06	0.30
SWE	0.16	0.78	BGR	0.05	0.25
CAN	0.21	1.03	SGP	0.03	0.16
JPN	0.16	0.81	AUT	0.03	0.17
PRT	0.13	0.66	HRV	0.04	0.21
ZAF	0.13	0.63	MYS	0.04	0.20
COL	0.12	0.60	IDN	0.04	0.20
FIN	0.10	0.49	AUS	0.04	0.19
BLR	0.10	0.49	PAN	0.04	0.22

Source: Authors' compilation based on GTAP11 (Aguiar *et al*., 2022).