INSTITIÚID TAIGHDE EACNAMAÍOCHTA AGUS SÓISIALTA
ESRI ECONOMIC & SOCIAL RESEARCH INSTITUTE

ESRI Working Paper No. 791

August 2024

Production and consumption-based Accounts of Ireland's Emissions

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Acknowledgements:
This work was funded by the Irish Environmental Protection Agency Project No 2022-CE-1104: Irish Consumption-based Emissions.

Abstract
This paper aims to calculate emissions in Ireland by applying a production-based Accounting (PBA) approach and a consumption-based Accounting (CBA) approach. PBA considers emissions in Ireland to be all emissions emitted in the geographic region of Ireland, whereas CBA includes all emissions resulting from the consumption of residents of Ireland. CBA accounts for emissions embedded in trade, where production-related emissions embedded in goods imported into Ireland are assigned to Ireland, whereas the production emissions of goods produced in Ireland which are exported are discounted from Ireland's emissions. Applying GTAP 11 data, our estimates show that CBA emissions for Ireland are between 8% and 16% larger than PBA emissions, depending on assumptions regarding the allocation of electricity and cattle-related emissions. The emissions embedded in international trade are embedded in the flows with Ireland's major trade partners: the United Kingdom, the United States of America, Germany, China and Russia. Imported emissions are concentrated in the fuel, chemical products and services sectors.

JEL codes: Q51; Q56; Q57

Keywords: consumption-based accounting; production-based accounting; trade embedded emissions

1 INTRODUCTION

There is a general consensus that anthropogenic greenhouse gas (GHG) emissions from production and consumption are changing our climate, resulting in negative impacts for economies and societies, particularly in the future. The impacts of climate change are becoming evident. In 2023, Ireland experienced extreme weather conditions with high temperatures and above-average rainfall.[1] To combat climate change, policy actions aimed at emission reductions have become more prominent over the past decade.

Given the public good nature of GHG emission reduction, to ensure effective mitigation, efforts need to be undertaken in a global cooperative context, such as the United Nations Framework Convention on Climate Change, Conference of the Parties (UNFCCC CoP) negotiations that have led to the Paris Agreement (UNFCCC, 2016). The core variable in quantifying policy targets is the country-level of emissions. To compare the impact of policy actions across countries on emission reduction, it is essential to have a consistent measurement of these emissions. The dominant measurement approach applied to calculate a country's emissions is the production-based Accounting (PBA) approach.

This approach assigns GHG emissions to the country where they are emitted (e.g., Benini et al., 2014). This includes the emissions from production processes in the country, as well as the emissions from households' consumption of GHG-emitting products. The PBA approach is used in calculating the National Emission Inventories (NEI) for the UNFCCC; this approach was also used in calculating emissions and reduction targets for the Paris Agreement (Afionis et al., 2017; Peters, 2008).

However, this approach does not consider the emissions embedded in goods that are consumed in Ireland but produced elsewhere; consider a good consumed in country A but produced in country B. The PBA approach would assign the relevant emissions to the producing country, B. However, the good is used in country A, and thus, it can be argued that country A should be accountable for these emissions.

Hence, the PBA approach has been criticised for not accounting for emissions embedded in international trade. The emission content of internationally traded goods has been estimated at 27% of global CO_2 emissions in 2015 (Yamano &

[1] See https://www.met.ie/annual-climate-statement-for-2023 Access date: July 2, 2024

Guilhoto, 2020). This is a considerable share of global emissions, warranting further consideration in the emissions accounting process.

A significant concern regarding the PBA approach is that developed countries can outsource their production activities to less developed countries and then import the produced goods while maintaining the same high levels of consumption, thereby sidestepping international emissions reduction obligations (Tukker et al., 2020). Indeed, Peters et al. (2011) find that the change in net emissions transfers from developing to developed countries offsets PBA reductions achieved by the Annex B countries of the Kyoto Protocol by a factor of five. In this case, the largest polluters would continue to contribute the most to climate change but would be able to avoid any emissions-based penalties as their pollution would not show up in their national accounts. Ultimately, this system of emissions accounting penalises those countries – typically poorer – that are involved in the more carbon-heavy stage of the global supply chain (Grasso, 2016).

To address this, the European Union created the Carbon Border Adjustment Mechanism (CBAM). Initially, the system will cover cement, iron, steel, aluminium, fertilisers, electricity, and hydrogen. This is planned to extend to cover other sectors under the ETS. CBAM seeks to incentivise cleaner production outside of the EU for goods that are then imported into the EU and to ensure producers cannot avoid emissions-based penalties by relocating production. This is found in the Treaty on the Functioning of the European Union (adopted 9 May 2008) on pages 0132-0133 in article 191, paragraph 2, where it is stated "... that environmental damage should as a priority be rectified at source and that the polluter should pay".[2]

As such, it is important to estimate the emissions embedded in internationally traded commodities. An alternative emission accounting approach, the consumption-based Accounting (CBA) approach, assigns emissions to countries based on where the goods or services are consumed (Chen et al., 2018). In essence, CBA emissions are equal to PBA emissions minus the emissions embedded in exports plus the emissions embedded in imports. Hence, correcting PBA emissions for the emissions embedded in internationally traded commodities would result in CBA emissions.

[2] See https://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=CELEX:12008E191:EN:HTML Access date: July 2, 2024.

A number of studies have calculated CBA emissions. For Ireland, Nakano et al. (2009) report the PBA in 2000 as 41 $MtCO_2$ and CBA as 50 $MtCO_2$. Davis & Caldeira (2010) use the GTAP 7 dataset and report PBA emissions of 43.90 $MtCO_2$ compared to CBA emissions of 55.40 $MtCO_2$ for 2004. Wood et al. (2019) use multiple data sources and state that, on average, the PBA and CBA in 2016 were 43.57 and 45.73 $MtCO_2$, respectively. In addition to empirical studies, policy debates have also arisen regarding various issues with CBA emissions, such as whether they are just or practical as a policy measure (Grasso, 2016; Duus-Otterström & Hjorthen, 2019).

The empirical studies report aggregate PBA and CBA values but do not delve into the sector details of the emission measures. Inspired by the policy relevance of a CBA and PBA comparison and the lack of detailed data on CBA for Ireland, this study calculates the PBA and CBA emissions of Ireland. Over time, data on production, trade, and emissions have become available to more countries. Using a well-established database, GTAP 11, this study presents sector details of PBA and CBA emissions for Ireland.

The plan of the paper is as follows. The next section presents a brief review of the applied literature on CBA emissions. Section 3 describes the method and the data. Section 4 presents the findings of the analysis, and Section 5 concludes.

2 LITERATURE

With increased interest in CBA emissions and improved international databases, the number of studies on CBA emissions has increased. A frequently employed method to calculate CBA emissions is to use Multi-Region Input-Output (MRIO) tables (Malik et al., 2019).

An Input-Output (IO) table shows how inputs are used by different sectors and the production costs of creating an input in a country or region. An MRIO table extends this by allowing inputs to come from different countries. As such, they show interactions between sectors across multiple countries. For instance, an MRIO would allow the Irish agriculture sector to rely on domestically produced fertilizers and imported machines to produce output.

There are various MRIO databases available. The EORA database claims to account for 190 countries and 15 909 sectors from 1990 to 2022, supplemented by an aggregated version called EORA 26 (Lenzen et al., 2012, 2013).[3] EX-

[3] https://worldmrio.com/ Access date: July 2, 2024.

IOBASE 3 covers 163 industries for 44 countries (Stadler et al., 2018; Merciai & Schmidt, 2018).[4] OECD-ICIO (Organisation for Economic Cooperation and Development, Inter-Country Input-Output tables) has 76 countries and a rest-of-the-world region, and 45 sectors.[5] The WIOD (World Input-Output Database) accounts for 43 countries and 56 sectors.[6]

Such databases are enhanced with GHG (greenhouse gas) emissions data to generate what is called environmentally extended MRIO tables. These were used, coupled with the input-output modelling approach pioneered by (Leontief, 1970), to analyse GHG emissions due to economic actions. Wood et al. (2018) present a method to analyse the environmental impact of consumption pattern changes and apply it to food and clothing using the EXIOBASE 3 data. Another study examines the evolution of emissions given the growth in the Asia-Pacific economies from 1995 to 2015 (Yang et al., 2020). Concerned with the use of hazardous chemicals, Persson et al. (2019) focus on Sweden's international trade in hazardous chemicals and the implied environmental impacts. For Europe, Castellani et al. (2019) compare a life-cycle analysis and an MRIO-based analysis by examining the environmental impact of household consumption. The EORA database (Lenzen et al., 2012, 2013) has been used to analyse global energy usage (Wu et al., 2019), identifying the USA and China as especially large users of energy.

One of the international input-output databases with environmental extensions is the GTAP (Global Trade Analysis Project) database. Originating in the 1990s, the Global Trade Analysis Project (GTAP) is one of the most established multi-country databases with production, international trade and emissions data at production sector levels. The database was originally developed to support a large-scale general equilibrium model, the GTAP Model, that was designed to analyse international trade issues.

The most recent version of the GTAP database (version 11) includes 65 production sectors and 141 countries, with 2017 as the most recent year. The database represents 99% of the world's Gross Domestic Product (GDP) and 96.4% of the global population (Aguiar et al., 2022). Davis & Caldeira (2010) employ the GTAP 7 database based on the year 2004, supplemented by other data sources

4 https://exiobase.eu/index.php Access date: July 2, 2024

5 https://www.oecd.org/en/data/datasets/inter-country-input-output-tables.html Access date: July 2, 2024

6 https://www.rug.nl/ggdc/valuechain/wiod/?lang=en Access date: July 2, 2024

to estimate global PBA and CBA emissions. They estimate that for Ireland, PBA emissions are 43.9 MtCO_2 whereas CBA emissions are 55.4 MtCO_2.

Owen (2015) investigates why EORA, GTAP version 7, and WIOD databases generate different results for CBA emissions. The analysis highlights that these databases use different data sources, and the use of different data sources drives the deviations of results across databases. While conducting comparisons, Owen (2015, p. 53-54) reports CBA emissions of 59 MtCO_2 in 2007 for Ireland.

As different MRIO databases and GTAP versions became available, the question of consistency across databases was further investigated. Owen et al. (2014) conduct a decomposition analysis to examine the variation in consumption-based emissions, among others, across the EORA, GTAP and WIOD databases. They identify the variations in Leontief inverses, the emissions data and the differences in the final demand data as the sources of variation in the results obtained across databases. Concerned with the robustness of MRIOs for environmental policy analysis, Moran & Wood (2014) conduct a similar analysis across the EORA, WIOD, EXIOBASE, and the OpenEU databases. Their calculations use a CBA approach based on releasing CO_2 from burning fossil fuels. They report a CBA of 43.029 MtCO_2 for Ireland from EORA, 55.210 MtCO_2 from OpenEU, 41.985 MtCO_2 from WIOD and 61.013 MtCO_2 from EXIOBASE. Following that, Rodrigues et al. (2018) harmonise five different MRIOs to examine the level of uncertainty in global CBA emissions. Nakano et al. (2009, p. 22) report a PBA value of 41 MtCO_2 and a CBA value of 50 MtCO_2 for 2000; CBA is 22% greater than PBA. Their results are based on OECD Input-Output tables, STAN Trade Database and IEA's CO_2 Emissions Database. Following that, Yamano & Guilhoto (2020, p. 46) find 52.8 MtCO_2 PBA emissions compared to 46.7 MtCO_2 CBA emissions.

The studies focusing on calculating emissions based on the two methods display considerable variety. Steubing et al. (2022) implement the life cycle assessment and environmentally extended MRIO methods on databases, such as ecoinvent[7] and EXIOBASE, and compare them in terms of their implications for carbon footprints. Some works even analyse city-level emissions conducted for China (Mi et al., 2016, 2019) and Europe (Harris et al., 2020). However, what is missing from these studies is an in-depth analysis of the sectoral distribution of PBA and CBA emissions. The main contribution of this paper is in this regard. We

[7] https://ecoinvent.org/

present PBA and CBA emissions with sector details for Ireland using GTAP data. We also comment on the geographical origins of the imported emissions.

3 METHOD AND DATA

Karakaya et al. (2019) point to the trade balance and the embedded CO_2 therein as the difference between PBA and CBA. While summarizing the principles of different approaches to environmental accounts, Tukker et al. (2020, p. 55) point out that PBA emissions are the responsibility of the producer of the good and service, whereas CBA emissions are the responsibility of the final consumers. In this section, we present the conceptual approach adopted to calculate PBA and CBA emissions, and we show the emission calculations.

3.1 A conceptual introduction to PBA and CBA emissions

Here, we define PBA emissions in a country as the emissions attributable to the activities of the actors in that country. Hence, PBA emissions are the emissions that are emitted in Ireland. Specifically, this entails emissions due to production activities within Ireland and emissions from fuel consumption of households and the government.

CBA is defined as the sum of emissions due to production activities undertaken to meet domestic demand plus the emissions due to domestic consumption of fuels. As such, the difference between PBA emissions and CBA emissions is the emissions embedded in both imported and exported commodities.

The calculations in this analysis have been performed using the GTAP 11 database (Aguiar et al., 2022). This database is one of the most established multi-country databases with production, international trade and emissions data at a production sector level. Although input-output model-based calculations are often applied for PBA and CBA calculations, the GTAP 11 database does not include an MRIO structure that enables such calculations.

As such, our calculations rely on understanding the production process and the flow of commodities across economies. Figure 1 visually represents the modelling framework. Here, the supply of commodities in an economy originates from either domestic production or the rest of the world in the form of imports.

PBA emissions are defined as the emissions due to production within Ireland and the consumption of fuels. The consumed fuels are delivered through domestic production or imports. Regarding production, three emission sources are considered for each production sector: combustion, production processes, and endowments. Combustion refers to the combustion of fossil fuels during production. Production process-related emissions are emissions that are related to production processes themselves and not combustion, e.g., calcination during cement production. Finally, endowments refer to the factors of production used during the production process. An example would be the cattle used in agricultural production, which results in methane emissions.

We have made three adjustments to the GTAP database concerning electricity, agriculture, and aviation emissions. These adjustments are detailed in Sections 3.2.1, 3.2.2 and 3.3.3.

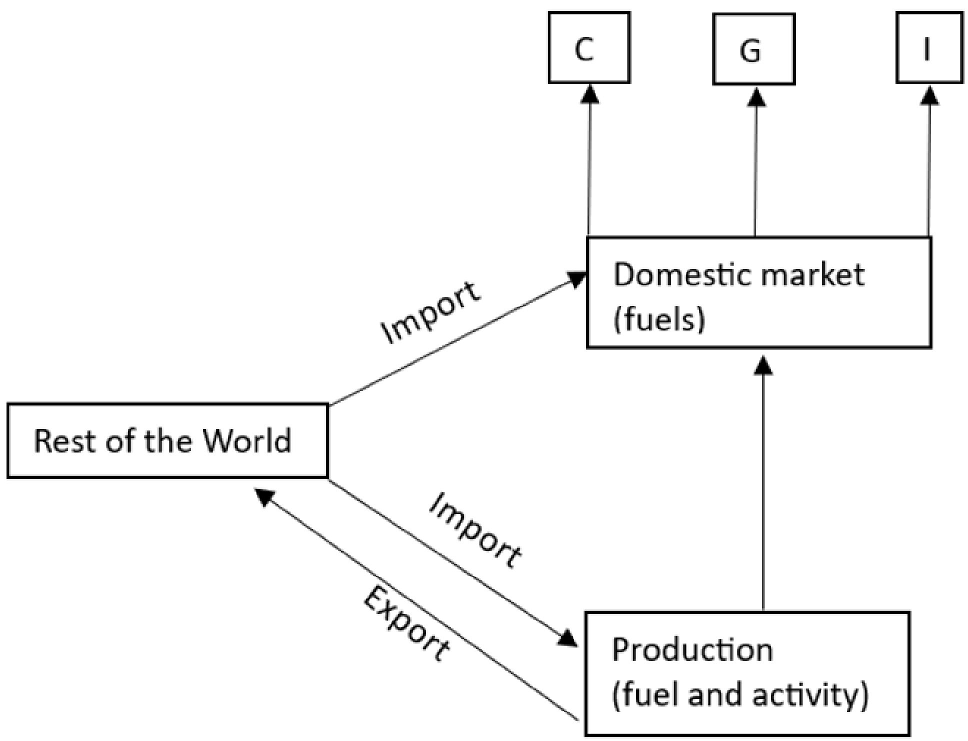

Figure 1: Production and commodity flows

3.2 Production emissions

Production-related emissions in any country or region r and production sector a are calculated as follows:[8]

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

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 greenhouse gasses 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 greenhouse gas e due to the use of factor endowments in production activity a in region r.
- $EMI\_QO_{e,a,r}$ refers to production process emissions, i.e., emissions not resulting from combustion but resulting from the production of final goods.
- $EMI\_IO_{e,c,a,r}$ 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.

It would be insightful to consider the last four items in more detail. Consider first the emissions due to endowments, $EMI\_ENDW_{e,a,r}$. 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% of endowment emissions for Ireland. In the simplest terms, this refers to emissions

[8] The expressions in the equations follow the syntax of the variables in the GTAP 11 database for ease of reference.

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.[9]

Consider next the production process emissions, $EMI\_QO_{e,a,r}$. 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.

The non-CO_2 emissions linked to fossil fuel combustion, $EMI\_IO_{e,c,a,r}$, are closely related to the first items $MDF_{f,a,r}$ and $MMF_{f,a,r}$, on this list. The first items account for CO_2 emissions, whereas this item contains data on non-CO_2 emissions. The last item, $EMI\_IOP_{e,c,a,r}$, refers to process emissions related to input use. 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.

3.2.1 Electricity embedded emissions

In the GTAP database, emissions related to electricity generation in a country are attributed to the electricity production sector. If a good is produced using electricity, the associated electricity generation emissions will not be included in the GTAP emissions calculations for that good. Hence, if a good is exported from, say, the United Kingdom to Ireland, the associated emissions from electricity use would be ignored. To account for this and include emissions resulting from electricity use in the production of goods, we adjust the GTAP database.

To better assess the importance of this, consider the example of the services sector. The production of a service does not necessarily generate high levels of emissions. But it will use electricity which, in turn, could be used for relatively emission-intensive fuel inputs. Therefore, when considering emissions from the service sector, it is important to realise that the emissions embedded in electricity production are not accounted for even though electricity is used to produce the services. If Ireland is importing services from the United Kingdom, we need to

[9] In GTAP 11 the cattle variable includes bovine cattle, sheep, goats and horses.

consider the emissions embedded in electricity used in the United Kingdom to produce the services imported by Ireland. To account for this, for each country in the database, the emissions related to electricity production are assigned to all other production sectors that use electricity. This is done by applying a sector's relative electricity usage as a weight. In other words, if a production sector in Ireland uses 20% of total electricity generated in Ireland, that sector will be allocated 20% of electricity generation emissions. To this end, let the total domestic use of the electricity commodity ($\overline{Q}^{d}_{ELY,r}$) be the following:

$$\overline{Q}^{d}_{ELY,r} = \sum_{a} INT^{d}_{ELY,a,r} + CON^{d}_{ELY,r} + INV^{d}_{ELY,r} + GOV^{d}_{ELY,r} + EXP^{d}_{ELY,r} \tag{2}$$

where $INT_{ELY,r}$ 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:

$$shareELY_{a,r} = \frac{INT_{ELY,a,r}}{\overline{Q}^{d}_{ELY,r}} \tag{3}$$

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

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

where $EMISS^{prod}_{ELY,r}$ is the emissions embedded in the electricity commodity.[10] It should be noted that this term isolates the emissions embedded in the electricity commodity to reallocate it to activities. Hence, production activity emissions are restated as follows.

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

[10] 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.

3.2.2 Animal products emissions

Ruminant livestock emissions (methane) are assigned to cattle, other animal products, and the raw milk sector. In the GTAP 11 database, the share of exports in production is 17% for the cattle sector, 22% for other animal products sector and 0.02% for the raw milk sector. However, the Meat Supply Balance by the Central Statistics Office for the year 2017 shows that of a gross indigenous production of 1.183 thousand tonnes of meat, 1.019 thousand tonnes were exported, resulting in an export rate of 86%.

The reason for the differences between the CSO and GTAP estimates of exports has a simple explanation: meat from cattle is not exported directly; instead, it is first processed to some degree and then packaged. Then, it is exported. From a data-keeping point of view, cattle are a part of the agricultural sector. But once it is processed, it becomes a manufactured good. For data-gathering purposes, it is now part of the manufacturing sector. Specifically, it falls under the FBT (food, beverage and tobacco) sector. And once it is exported, the export is recorded under manufactured goods exports rather than under agricultural exports.

GTAP's data-keeping practices further complicate the issue. From the point of view of the GTAP database, cattle are a capital good in the agricultural sector. Thus, cattle-related emissions, especially methane, are recorded as agricultural emissions. If cattle meat is exported after being processed, the emissions embedded in the exported cattle meat are not accounted for in the manufacturing sector because they were initially recorded as agricultural emissions.

To understand the issue and the proposed remedy, consider a cattle farm and a meat packaging plant. The cattle farm is in the agriculture sector; the farm owns the cattle and is accountable for the methane emissions related to the cattle. Then, the cattle are slaughtered, and the meat is taken to the packaging plant, packaged and sold abroad. Cattle meat is now exported, but not from the farm. It is exported from the packaging plant. Therefore, the manufacturing industry is the exporter. However, the methane emitter is the farm in the agriculture sector. As such, the emissions were from the cattle when they were alive, and they are accounted for in the agriculture sector. However, these emissions need to be transferred to the food manufacturing sector so that the emissions from exported goods are realistic.

Therefore, emissions related to slaughtered cattle are reallocated to the FBT sector. In the case of Ireland, bovine meat products (CMT) and meat products not classified elsewhere (OMT) use cattle as inputs for their products. Because of this, emissions from cattle that were recorded in the agriculture sector are reallocated to these commodities. The reallocation follows the same logic as the reallocation of electricity emissions. The total domestic use of cattle ($Q_{CTL,r}$) is the following:

$$\overline{Q}_{CTL,r} = \sum_{a} INT^{d}_{CTL,a,r} + CON^{d}_{CTL,r} + INV^{d}_{CTL,r} + GOV^{d}_{CTL,r} + EXP^{d}_{CTL,r} \tag{6}$$

The shares are:

$$shareCTL_{a,r} = \frac{INT_{CTL,a,r}}{\overline{Q}^{d}_{CTL,r}} \tag{7}$$

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

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

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:

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

3.3 Production and consumption-based accounting of 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 are calculated. This requires the calculation of emission coefficients that show emissions per monetary unit of output of commodity c in region r:

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

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

$$\begin{aligned} EMISS^{exp}_{c,r} &= \sum_{dst} \varepsilon_{c,r} EXP_{c,r,dst} \\ EMISS^{imp}_{c,r} &= \sum_{src} \varepsilon_{c,src} IMP_{c,src,r} \end{aligned} \tag{11}$$

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.

CBA emissions are calculated by adding imported emissions to PBA emissions and then subtracting the exported emissions. We account for two additional concerns regarding the emissions embedded in international trade. Firstly, some of the imported commodities are used domestically for the production of export goods. Hence, we define re-exported emissions as emissions embedded in imported goods that are used as inputs to the production of goods that are exported to a different country. Since these imported goods and the goods made from them are not consumed in the importing country, the imported emissions should be deducted from the calculation of CBA emissions.

The second issue is the need to account for indirectly imported emissions. Consider Ireland's imports from Country A. In order to produce the goods sold to Ireland, Country A will need to import input commodities from another country, called Country B. That is, exports of country A include some re-exports originating from country B. These re-exports of country A originate from country B and eventually arrive in Ireland. Hence, Ireland indirectly imports these goods and the emissions from country B. These need to be added to Ireland's CBA. We next consider these two items.

3.3.1 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 $EMISS_{c,r}^{imp}$ in Equation 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 $\sum_a INT\_IMP_{c,a,r}$. 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 $\sum_{src} IMP_{c,src,r}$. Given these, the share of imported intermediate inputs in aggregate imports is:

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

We know the imported emissions $EMISS_{c,r}^{imp}$ 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 $shr\_import_{c,r} EMISS_{c,r}^{imp}$.

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., $\sum_{dst} EXP_{c,r,dst}$. 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:

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

Now that we have these shares, we can calculate the re-exported emissions for country r.[11] As noted above, the emissions embedded in imported intermediate commodities is $shr\_import_{c,r} EMISS_{c,r}^{imp}$. To see how much of these imported intermediate emissions are exported, we will multiply it with the export share, $shr\_export_{c,r}$:

$$REXP\_EMISS_{c,r} = shr\_export_{c,r} \left[shr\_import_{c,r} \; EMISS_{c,r}^{imp} \right] \quad (12)$$

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

3.3.2 Indirectly imported emissions

Consider the example above, 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.

[11] 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.

The aggregate exports of the source country is these exports aggregated over destination countries, i.e., $\sum_{dst} EXP_{c,src,dst}$. Then, the share of each destination country in the total exports of an exporting country would be:

$$exp\_dst_{c,src,dst} = \frac{EXP_{c,src,dst}}{\sum\limits_{dst} EXP_{c,src,dst}} \tag{13}$$

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:

$$IND\_IMP\_EMISS_{c,dst} = \sum_{src} exp\_dst_{c,src,dst} REXP\_EMISS_{c,src} \tag{14}$$

3.3.3 Aviation emissions

We need to differentiate between domestic and international emissions from the air transport sector (ATP). This is because of the way international aviation emissions are allocated in the GTAP 11 database. Typically, aviation and maritime-related emissions are recorded in international bunkers (IPCC, 2008). However, the GTAP 11 database is related to a computable general equilibrium (CGE) model, where the concept of an international bunker does not exist. Hence, bunker emissions data is allocated to countries with respect to their international trade data (Chepeliev, 2020a, p. 13). This generates very high emissions associated with the ATP sector in Ireland. Thus, the exported emissions for the ATP sector $EMISS^{exp}_{ATP,r}$ are deducted when PBA emissions are calculated to align with the IPCC's methodology (IPCC, 2008). 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 emission calculation, the exported emissions for the ATP sector would be deducted twice.

3.3.4 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 to production emissions as defined in Section 3.1. Fuel consumption emissions, $EMISS^{con}S_{c,r}$, are defined in the GTAP 11 database as the emissions associated with the households' (consumers') use of fuels, 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:

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

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:

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

The calculations performed within the context of the presented equations imply three varieties of results. The first case uses the GTAP data as it is and no emission redistribution is done across sectors. The second case reallocates the emissions embedded in electricity, per Equation 5. In the third case, both electricity and cattle-related emissions are reallocated, per Equations 5 and 9. Thus three sets of results are presented here:

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

Also, an aggregation of results has been undertaken. The GTAP 11 database includes 65 commodities and related production activities. With three cases and 65 commodities, the amount of data produced is too large to comprehensively examine. Hence, a sector aggregation is adopted. The key to the sector aggregation is presented in Table A.1.

4 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 Table 1. In total, the PBA emissions are 73.60 $MtCO_2eq$ in the case of no redistribution. The total emissions are 69.39 $MtCO_2eq$ under each of the redistribution cases.

Table 1: Production Based Account Emissions, $MtCO_2eq$

	No redistribution	ELY redistribution	ELY&CTL redistribution
Agriculture, plant	2.89	2.98	2.98
Agriculture, animal	22.42	22.75	22.75
Other extraction	0.16	0.49	0.49
Fuels	12.48	12.51	12.51
Food, beverage, tobacco	0.70	1.44	1.44
Chemical products	0.25	0.90	0.90
Basic pharmaceuticals	0.20	0.40	0.40
Metal and mineral products	4.17	5.00	5.00
Machinery manufacturing	0.50	1.24	1.24
Other manufacturing	0.11	0.58	0.58
Electricity	12.23	0.42	0.42
Water and waste management	0.94	1.28	1.28
Construction	0.32	0.37	0.37
Air transport	2.82	2.83	2.83
Other transport	11.26	11.33	11.33
Other services	2.15	4.86	4.86
SUM	73.60	69.39	69.39

A review of the values in Table 1 raises two issues. Firstly, the values under the ELY redistribution and the ELY&CTL redistribution cases are the same. The only difference between these two cases is the redistribution of the cattle-related emissions in the last case. As implied by Equation 9, cattle-related redistribution transfers the emissions from the cattle commodity and allocates them to the meat-related food manufacturing commodities, i.e., bovine meat products (CMT) and the meat products not elsewhere classified (OMT) of the GTAP 11 database. Per the sector aggregation implied by Table A.1, this reallocation keeps the emissions within the agriculture sector. Hence, the two columns have the same values. As discussed below, this reallocation will have an impact on emissions embedded in international trade but will not impact PBA emissions.

The second issue is the reduction in PBA emissions after the reallocation of electricity emissions. PBA emissions fall from 73.60 $MtCO_2eq$ to 69.39 $MtCO_2eq$.

The reallocation of the emissions embedded in the electricity sector is based on the coefficients shown in Equation 3. These shares are based on intermediate uses in all the domestic uses, $\overline{Q}^{d}_{ELY,r}$, both final and intermediate. The redistribution isolates the emissions embedded in the electricity that is used as an intermediate good. However, the relevant shares account for final demand items as well. Therefore, some of the emissions embedded in electricity are assigned to the final uses and are not redistributed to non-electricity sectors with respect to intermediate electricity use.

For all sectors, emissions increase; however, a reduction in electricity emissions from 12.23 MtCO_2eq to 0.42 MtCO_2eq is observed due to the differences in intermediate and final usage 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 was a fall in the PBA emissions.

Without any reallocation, the sectors with the highest PBA emissions are the animal agriculture sector (22.42 MtCO_2eq), fuels sector (12.48 MtCO_2eq), electricity sector (12.23 MtCO_2eq), other transport sector (11.26 MtCO_2eq) and the metal and mineral products sector (4.17 MtCO_2eq). These account for approximately 85% of the PBA emissions.

The emissions from animal-related agriculture are mostly methane emissions due to cattle, i.e., 17.79 MtCO_2eq. Regarding fuels, this accounts for the emissions from households' consumption of fuels. Most of the fuel-related emissions are from the consumption of petroleum and coal products. From the metal and mineral products sector, 3.25 MtCO_2eq is accounted for by the mineral products not elsewhere classified sector. This sector corresponds to sector 23 under the ISIC Revision 4 classification, which includes cement production.[12]

Electricity redistribution does not change the relative importance of these sectors. The main change is the fall in the electricity-related PBA emissions, an expected outcome of the adopted emission 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 11, 12 and 14 and the obtained data is presented in Table 2. Before proceeding, it should be

[12] For a concordance between GTAP and ISIC Revision 4 sector, https://www.gtap.agecon.purdue.edu/databases/contribute/concordinfo.asp.

noted that the air transport (ATP) related emissions in Table 2 are not processed other than what the relevant equations imply, i.e., the air transport sector (ATP) related interventions to PBA and CBA emissions as in Equations 15 and 16 have not been done.

Under the assumption of no redistribution of emissions, the largest amount of emissions embedded in direct and indirect imports is observed for the fuel (7.49 MtCO_2eq), chemical products (3.48 MtCO_2eq) and animal agriculture (2.05 MtCO_2eq) sectors. Regarding fuel-related imported emissions, the largest item is the directly imported emissions from petroleum and coal products (3.12 MtCO_2eq). The second largest item is the indirectly imported emissions due to gas (2.21 MtCO_2eq), and the third largest item is the indirectly imported emissions embedded in petroleum and coal products (1.10 MtCO_2eq). Regarding animal-related agriculture trade, the emissions are embedded in the directly imported emissions from cattle (1.79 MtCO_2eq).

The sector with the largest amount of emissions in exports is the ATP (air transport) sector with 15.30 MtCO_2eq emissions.[13] The next largest is the exports from the animal agriculture sector (3.64 MtCO_2eq), with cattle accounting for most of this figure (3.07 MtCO_2eq). Finally, the chemical products sector, with 1.59 MtCO_2eq, takes third place in terms of exported emissions.

The presented values paint Ireland as a net exporter of emissions; a net amount of 5.88 MtCO_2eq emissions are exported. This is due to the export of air transport-related emissions. However, if air transport emissions are excluded, Ireland is a net importer of emissions. Such an exclusion of international aviation emissions from the national account of emissions is standard procedure. The methodology of recording emission inventories is from the Intergovernmental Panel on Climate Change (IPCC, 2008). The methodology allocates international aviation emissions due to flights originating from one country and arriving in a different country to international bunkers. Thus, in practice, the emissions from these flights are not assigned to the national emissions inventories of countries.

[13] It should be kept in mind that this number includes data on international aviation bunkers, allocated to Ireland; for details see (Chepeliev, 2020a, p. 13).

Table 2: Emissions embedded in Ireland's international trade

	No redistribution			ELY redistribution			ELY&CTL redistribution		
	Imported (direct and indirect)	Exported and reexported	Net imported	Imported (direct and indirect)	Exported and reexported	Net imported	Imported (direct and indirect)	Exported and reexported	Net imported
Agriculture, plant	1.23	0.86	0.37	1.39	0.90	0.48	1.39	0.90	0.48
Agriculture, animal	2.05	3.64	-1.59	2.12	3.86	-1.74	1.45	8.86	-7.41
Other extraction	0.05	0.03	0.02	0.07	0.08	-0.01	0.07	0.08	-0.01
Fuels	7.49	0.66	6.83	8.00	0.70	7.30	8.00	0.70	7.30
Food, beverage, tobacco	0.35	0.70	-0.35	0.58	1.35	-0.78	0.58	1.35	-0.78
Chemical products	3.48	1.59	1.89	4.60	2.65	1.95	4.60	2.65	1.95
Basic pharmaceuticals	0.20	0.28	-0.08	0.61	0.66	-0.05	0.61	0.66	-0.05
Metal and mineral products	1.88	0.93	0.95	2.63	1.36	1.27	2.63	1.36	1.27
Machinery manufacturing	0.37	0.54	-0.16	1.21	1.39	-0.18	1.21	1.39	-0.18
Other manufacturing	0.47	0.17	0.29	1.26	0.53	0.74	1.26	0.53	0.74
Electricity	0.22	0.57	-0.35	0.01	0.02	-0.01	0.01	0.02	-0.01
Water and waste management	0.01	0.00	0.01	0.01	0.00	0.01	0.01	0.00	0.01
Construction	0.01	0.00	0.01	0.01	0.00	0.01	0.01	0.00	0.01
Air transport	1.67	15.30	-13.63	1.68	15.37	-13.69	1.68	15.37	-13.69
Other transport	0.66	1.08	-0.41	0.68	1.09	-0.41	0.68	1.09	-0.41
Other services	1.32	0.98	0.34	3.96	2.34	1.62	3.96	2.34	1.62
SUM	21.46	27.34	-5.88	28.82	32.30	-3.48	28.15	37.29	-9.14

Note: Imported emission refers to $EMISS_{c,r}^{imp}$, Equation 11. Indirect imported emission refers to $IND\_IMP\_EMISS_{c,r}$, Equation 14. Exported emission refers to $EMISS_{c,r}^{exp}$, Equation 11. Re-exported emission refers to $REXP\_EMISS_{c,r}$, Equation 12. Net imported emission is calculated as $[EMISS_{c,r}^{imp} + IND\_IMP\_EMISS_{c,r}] - [EMISS_{c,r}^{exp} + REXP\_EMISS_{c,r}]$.

There is a positive amount of net imported emissions from fuel commodities with a net import value of 6.83 MtCO_2eq. Petroleum and coal are the dominant goods for fuels. Finally, the chemical products sector is a relatively large net importer of emissions with 1.89 MtCO_2eq.

The reallocation of electricity emissions does not change the substantial amount of emission imports due to fuels, with petrol and coal products and gas having the largest shares in fuel-related imported emissions. The second largest amount of emissions is from the chemical products sector, and the third largest now is the other services sector (3.96 MtCO_2eq), with business services not elsewhere classified taking up the largest share. This jump in the ranking of business services is an expected outcome of the electricity emission 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 2.63 MtCO_2eq. Though very detailed data is not available, this sector includes cement production, which is a likely candidate driving the high emissions.

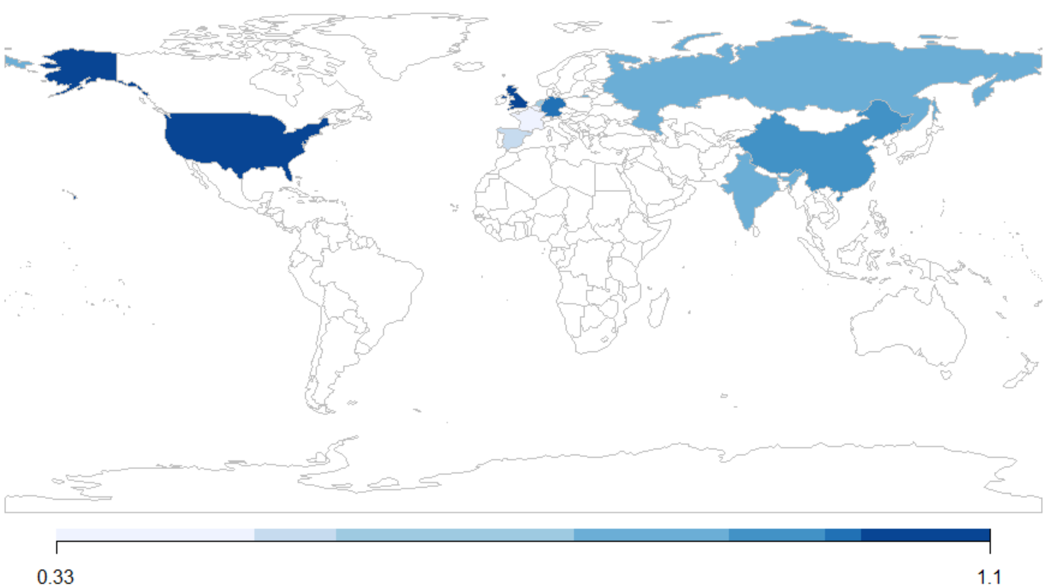

Figure 2: Sources of imported emissions

Note: The figure is based on data with electricity and cattle emissions redistributed. The underlying data is MtCO_2eq. White-shaded countries have been excluded from the figure to maintain exposition clarity.

In terms of exported emissions, the largest value is for air transport services. Next is the animal agriculture commodities with 3.86 MtCO_2eq. Third is the chemical products sector (2.65 $MtCO_2eq$), and the fourth place is held by other services (2.34 $MtCO_2eq$). When air transport is omitted, Ireland is once more a net importer of emissions by 10.21 $MtCO_2eq$. Most of these can be accounted for by fuels (7.30 $MtCO_2eq$), especially petroleum and coal products.

The reallocation of cattle-related emissions within the animal agriculture sector, in addition to electricity emission redistribution, will impact only the international trade-embedded emissions of the animal agriculture sector. The imported emissions of Ireland for this sector fall to 1.45 $MtCO_2eq$ and the exported emissions increase to 8.86 $MtCO_2eq$. The sector becomes a net exporter of 7.41 $MtCO_2eq$ emissions. This reduces the net emission imports of Ireland from 10.21 $MtCO_2eq$ to 4.54 $MtCO_2eq$, excluding air transport-related emissions.

4.3 Geographical sources of imported emissions

Identifying the countries from which Ireland imports emissions is valuable. To delve into the details of this, Figure 2 is presented. The figure shows the geographical distribution of directly imported emissions, with redistributed electricity and cattle-related emissions.

Two countries account for a large portion of the directly imported emissions. Of the 20.08 $MtCO_2eq$ of directly imported emissions, 5.86 $MtCO_2eq$ (29.16% of the total) originate from the United Kingdom and 3.08 $MtCO_2eq$ (15.35% of the total) originate from the United States of America (USA). Also with high shares in imported emissions are Germany (0.98 $MtCO_2eq$, 4.87% of total), China (0.95 $MtCO_2eq$ 4.75% of total), Russia (0.87 $MtCO_2eq$ 4.35% of total), the Netherlands (0.65 $MtCO_2eq$ 3.04% of total) and India (0.78 $MtCO_2eq$ 3.89% of total).

A further detailing of imported emissions is presented in Table 3, where imported emissions are 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 USA, Russia and the Netherlands. The second sector is the chemical products sector, where emissions mainly come from the United Kingdom, the USA 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 originate from the United Kingdom, the USA 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. Lastly is the animal agriculture product sector, where the emissions mainly come from the United Kingdom.

Table 3: Sector and country details of imported emissions, $MtCO_2eq$

	UK	USA	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 manufacturing	0.344	0.107	0.185	0.106	0.035	0.021	0.018
Other manufacturing	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

Note: The data is for the case under which both electricity and cattle emissions are reallocated.

4.4 PBA vs CBA emissions

Finally, let us compare the PBA emissions with the CBA emissions as presented in Table 4. The table shows that 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% higher than the total of PBA emissions. With electricity redistribution, emissions embedded in imported commodities increase, as seen in Table 2. Hence, upon the redistribution of electricity emissions, the total amount of CBA emissions becomes 16% higher than the total PBA emissions. With cattle-related emissions redistributed, the emissions embedded in animal agriculture exports increase, and the excess of CBA over PBA decreases to 8%.

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 $MtCO_2$. [14] The CBA emissions are 27% more than the PBA emissions. EORA-based re-

[14] https://ourworldindata.org/co2-and-greenhouse-gas-emissions#explore-data-on-co2-and-greenhouse-gas-emissions. Note that the reported data is only CO_2 and not CO_2 equivalent.

Table 4: PBA vs CBA emissions of Ireland

	No redistribution		ELY redistribution		ELY and CTL redistribution	
	PBA	CBA	PBA	CBA	PBA	CBA
Agriculture, plant	2.89	3.26	2.98	3.47	2.98	3.47
Agriculture, animal	22.42	20.82	22.75	21.00	22.75	15.34
Other extraction	0.16	0.18	0.49	0.49	0.49	0.49
Fuels	12.48	19.31	12.51	19.82	12.51	19.82
Food, beverage, tobacco	0.70	0.35	1.44	0.66	1.44	0.66
Chemical products	0.25	2.13	0.90	2.85	0.90	2.85
Basic pharmaceuticals	0.20	0.12	0.40	0.35	0.40	0.35
Metal and mineral products	4.17	5.12	5.00	6.27	5.00	6.27
Machinery manufacturing	0.50	0.34	1.24	1.07	1.24	1.07
Other manufacturing	0.11	0.40	0.58	1.32	0.58	1.32
Electricity	12.23	11.88	0.42	0.41	0.42	0.41
Water and waste management	0.94	0.95	1.28	1.29	1.28	1.29
Construction	0.32	0.32	0.37	0.37	0.37	0.37
Air transport	2.82	3.77	2.83	3.79	2.83	3.79
Other transport	11.26	10.84	11.33	10.92	11.33	10.92
Other services	2.15	2.49	4.86	6.48	4.86	6.48
SUM	73.60	82.30	69.39	80.55	69.39	74.89
CBA/PBA ratio	1.12		1.16		1.08	

sults show territorial emissions of 59.7 $MtCO_2eq$ and CBA of 72.1 $MtCO_2eq$ for Ireland in 2017, an excess of 21%.[15] Davis & 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%. 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%. 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%. With a slightly different calculation approach and using the EXIOBASE database augmented by other data sources, Bruin & Yakut (2022) calculate the PBA as 61 $MtCO_2eq$ and CBA as 106 $MtCO_2eq$; CBA is 74% more than PBA year 2019.

Our estimates are in line with the estimates found in the literature. Deviations can be attributed to the way data is composed in the GTAP 11 database. A

[15] https://www.worldmrio.com/footprints/carbon/

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 overstates 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 and can be examined through Table 2. Furthermore, one should note that this study considers multiple GHGs and reports CO_2 equivalent emissions, whereas most studies referred to here present only CO_2 emissions.

5 CONCLUSION

This study presents the PBA and CBA emissions of Ireland in 2017 calculated using the GTAP 11 database. Calculations show that PBA emissions of Ireland are concentrated in animal agriculture, fuels, electricity and other transport sectors, including land transportation. CBA emissions are obtained from PBA emissions by correcting for international trade. We find that most of the imported emissions are embedded in the fuel, chemical products and animal agriculture sectors. Exported emissions are concentrated in air transport and animal agriculture.

A further examination of the imported emissions by source revealed that these originate from Ireland's major trade partners. Imported fuel-embedded emissions originate from the United Kingdom, the USA, Russia and the Netherlands. The imported emissions embedded in the chemical products sector are mostly from the United Kingdom, the USA and Germany. The imported emissions from the animal agricultural products sector are imported from the United Kingdom and are a considerable amount. The calculated CBA emissions are 8% to 16% larger than the PBA emissions, depending on the adopted emission redistribution method. A likely driver of the limited number of studies determining PBA and CBA emissions in the literature is the complexity of performing such calculations. Additionally, because of the number of adjustments needed to use GTAP 11 data, it is unsurprising that MRIOs are often used instead to calculate PBA and CBA emissions.

The calculated values need to be approached carefully as two data-related issues are concerning. Firstly, although GTAP 11 is one of the more reliable databases covering multiple countries, it is subject to data gathering and rearrangement practices. Consider, for example, the way international trade is handled. A given trade flow is reported by both the destination country (importer) and the source country (exporter). In some cases, the value of the trade flow reported by the exporter and the importer may not match. This is not acceptable, for the GTAP 11 database is gathered as a database for the GTAP computable general equilibrium model where the mathematical structure of the model necessitates a single numerical value for a given trade flow. To reconcile bilateral trade data, the reliability of the reported trade data is assessed, and in some instances, trade data reported by some countries may be completely ignored (Gehlhar, 1996). Such practices are necessary and may cast doubt on the reliability of the calculated PBA and CBA values.

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 is 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 the GTAP database and may also be the case in other databases.

The case in favour of the GTAP 11 database is its extensive coverage across countries and sectors. This is a key advantage of the database. Further work on this topic will involve an international comparison of CBA emissions for a number of countries. The GTAP 11 database contains more than 160 countries. The calculations applied here can be replicated for the other countries within the GTAP 11 database. A comparison of similar countries would enable a deeper understanding of the position of Ireland in terms of their contributions to global emissions.

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Appendix A

Table A.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 fibers
		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
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 defense
		EDU	Education
		HHT	Human health and social work activities
		DWE	Dwellings