2024 Data Release of Consumption-based Accounts for the UK: Summary of Methods

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1 What are Consumption-based emission accounts?

Greenhouse gas (GHG) emissions can be allocated to a country in different ways: (I) territorial-based, (II) production-based, and (III) consumption-based emission reporting.

1.1 Territorial Emissions

The United Nations Framework Convention on Climate Change (UNFCCC) requires (Annex I and/or national governments that are Parties to the UNFCCC and/or the Kyoto Protocol) countries to submit annual National Emission Inventories. These inventories are used to assess the progress made by individual countries in reducing GHG emissions. The UNFCCC follows the Intergovernmental Panel on Climate Change's (IPCC) Guidelines for National GHG Inventories which is, "emissions and removals taking place within national (including administered) territories and offshore areas over which the country has jurisdiction" (IPCC, 2007). According to this definition, however, GHG emissions emitted in international territory, international aviation and shipping, are only reported as a memo and not allocated to individual countries. In the UK, the department for Business, Energy and Industrial Strategy (BEIS) reports these emissions as the UK's Greenhouse Gas Inventory and they form the basis for reporting on progress towards our domestic and international emissions reduction targets. In this report, we call this account "**territorial-based emission inventories**".

1.2 Production Emissions

In official reporting to Eurostat[1], GHG emissions are allocated in a consistent manner to the system boundary for economic activities such as the Gross Domestic Product (GDP) used in the System of National Accounts (SNA). This boundary reporting is known as the residence principle. In the SNA, international aviation and shipping are typically allocated to countries based on the operator of the vessel. Particularly in Europe (Eurostat), these inventories are often known as "National Accounting Matrices including Environmental Accounts (NAMEAs)". In the UK, the Office for National Statistics (ONS) publishes this account as part of the UK Environmental Accounts. The figures represent emissions caused by UK residents and industry whether in the UK or abroad but exclude emissions within the UK which can be attributed to overseas residents and businesses and those emissions from Land use, Land Use Change and Forestry. In this report, we call these "**production-based emission inventories**".

[1] The statistical office of the European Union

1.3 Consumption Emissions

Consumption-based emissions allocate emissions to the consumers in each country, usually based on final consumption as in the SNA but also as trade-adjusted emissions (Peters, 2008). Conceptually, consumption-based inventories can be thought of as consumption equals production minus exports plus imports (see Figure 1). Consumption-based emissions do not have to be reported officially by any country, but they are increasingly estimated by researchers (see review by Wiedmann 2009). In the UK, the Department for Environment, Food and Rural Affairs (Defra) publishes the consumption-based emissions calculated by the University of Leeds. In this report, we call these "**consumption-based emission inventories**" or "the Carbon Footprint".

Table 1 provides a simplified view of what is included and excluded in each emissions account.

Table 1: Types of emissions inventory included in UK territorial, production and consumption accounts. Green indicated inclusion and red indicates exclusion. RoW = rest of world

Emissions from…	UK Territorial (UNFCCC)	UK Production (Env Accounts)	UK Consumption
industries owned by UK, located in UK making products consumed by UK	Y	Y	Y
industries owned by UK, located in UK making products consumed by RoW	Y	Y	N
industries owned by RoW, located in UK making products consumed by UK	Y	N	Y
industries owned by RoW, located in UK making products consumed by RoW	Y	N	N
industries owned by UK, located in RoW making products consumed by UK	N	Y	Y
industries owned by UK, located in RoW making products consumed by RoW	N	Y	N
industries owned by RoW, located in RoW making products consumed by UK	N	N	Y
industries owned by RoW, located in RoW making products consumed by RoW	N	N	N
bunker aviation & shipping owned by UK and used by UK residents	N	Y	Y
bunker aviation & shipping owned by RoW and used by UK residents	N	N	Y
bunker aviation & shipping owned by UK and used by RoW residents	N	Y	N
bunker aviation & shipping owned by RoW and used by RoW residents	N	N	N
UK citizens' activities within UK territory	Y	Y	Y
RoW citizens' activities within UK territory	Y	N	N
UK citizens' activities within RoW territory	N	Y	Y
RoW citizens' activities within RoW territory	N	N	N
Land use, land use change and forestry	Y	N	N

There is a marked difference in end results depending on the chosen emissions accounting system (Barrett et al. 2013). Due to issues of national sovereignty, binding agreements on emissions may focus primarily on territorial or production-based emission estimates.

Figure 1 demonstrates the relative sizes of the UK territorial, production and consumption emissions accounts. In this example we use data for 2020. The additional flows that are included in the production account (the Environmental Accounts) include: bunker fuels from aviation and shipping; emissions from renewables and waste derived fuels (biomass); the net emissions from the inclusion of overseas emissions from UK residents and the removal of domestic emissions from non-residents; and the removal of emissions from crown dependencies, overseas territories (the Channel Islands and Gibraltar) and Land Use Change, Land Use and Forestry (LULUCF). The figure also reveals the portion of UK consumption emissions that originate abroad (the emissions embodied in imports) and those UK production emissions which are exported. It is clear that there is a marked difference in end results depending on the chosen emissions accounting system (Barrett et al. 2013). Due to issues of national sovereignty, binding agreements on emissions may focus primarily on territorial-based emission estimates meaning that no targets are set for emissions associated with bunker fuels and imported products.

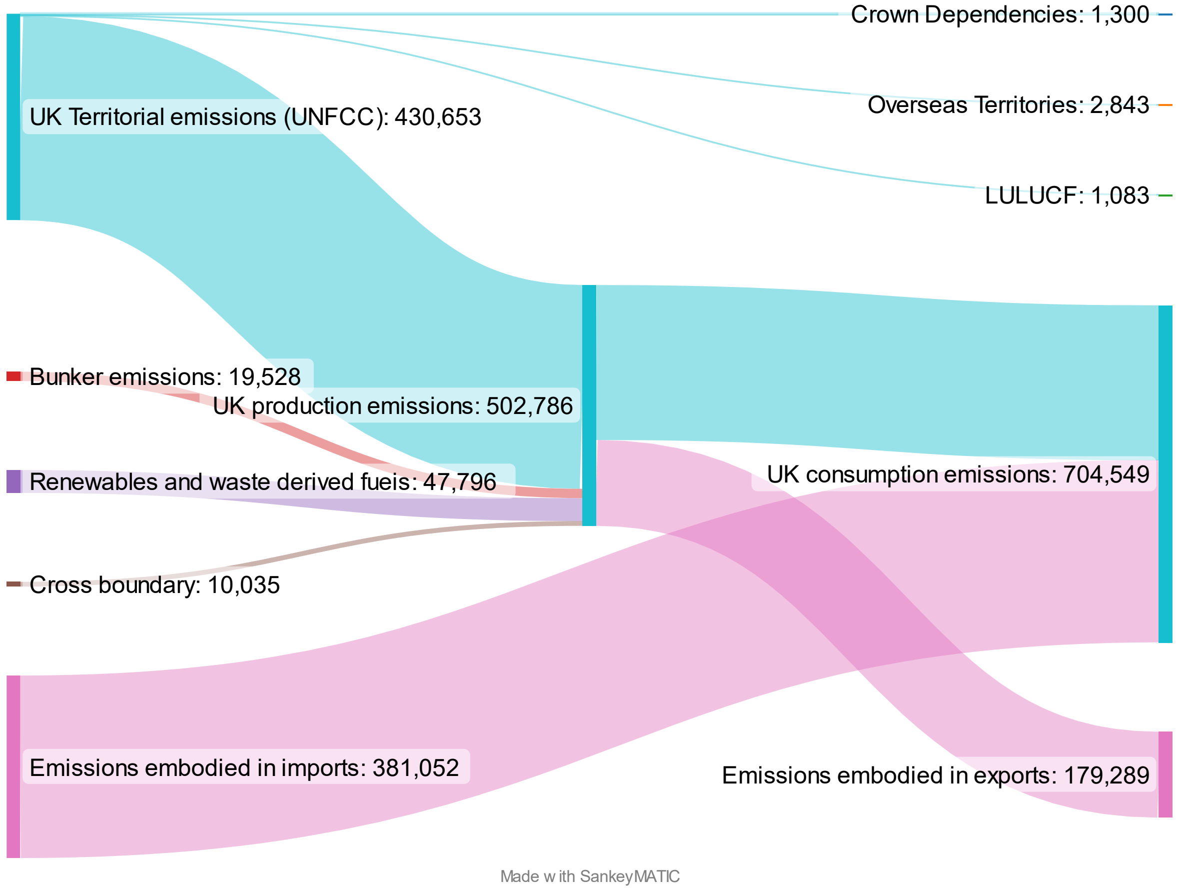

Figure 1: UK emissions from territorial, production and consumption in 2020. Measured in $KtCO_2e$ (https://www.ons.gov.uk/economy/environmentalaccounts/datasets/ukenvironmentalaccountsatmosphericemissionsbridgingtables)

1.4 What Greenhouse Gasses are included in the consumption-based emissions account

For the 2024 release of the UK consumption-based account we include the full suite of GHGs as reported to the UNFCCC. These are:

- Carbon dioxide (CO_2)
- Methane (CH_4)
- Nitrous oxide (N_2O)
- Hydro-flourocarbons (HFC)
- Perflurocarbons (PFC)
- Nitrogen trifluoride (NF_3)
- Sulphur hexafluoride (SF_6) all measured in kilotonnes CO_2e.

Non-CO_2 gasses are converted to CO_2e using the Global Warming Potential values from the IPCC Fifth Assessment Report[2] (AR5).

[2] https://www.ghgprotocol.org/sites/default/files/ghgp/Global-Warming-Potential-Values%20%28Feb%2016%202016%29_1.pdf

2 MRIO Methodology

2.1 Input-output methods.

Input-output models (IOM) have been adopted by environmental economists due to their ability to make the link between the environmental impacts associated with production techniques and the consumers of products. The Leontief Input-Output (IO) model is constructed from observed economic data and shows the interrelationships between industries that both produce goods (outputs) and consume goods (inputs) from other industries in the process of making their own product (Miller and Blair 2009).

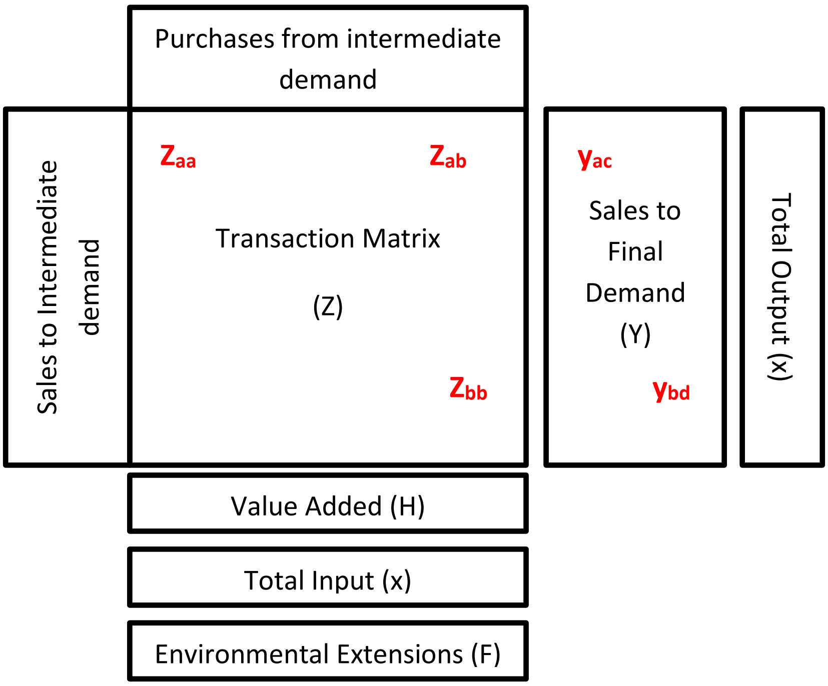

Figure 2: Basic structure of a Leontief Input-Output Model

Consider the transaction matrix $\mathbf{Z}$; reading across a row reveals which industries a single industry sells to and reading down a column reveals who a single industry buys from. A single element, $\mathbf{z}_{ij}$, within $\mathbf{Z}$, represents the contributions from the ith sector to the jth industry or sector in an economy. For example, $\mathbf{z_{aa}}$ represents the ferrous metal contribution in making ferrous metal products, $\mathbf{z_{ab}}$, the ferrous metal contribution to car products and $\mathbf{z_{bb}}$ the car production used in making cars. Final demand is the spend on finished goods. For example, $\mathbf{y_{ac}}$ is the spend on ferrous metal products by households as final consumers whereas $\mathbf{y_{bd}}$ is the spend on car products by government as final consumers.

The total output ($\mathbf{x}_i$) of a particular sector can be expressed as:

$$\mathbf{x_{i}} = \mathbf{z_{i1}} + \mathbf{z_{i2}} + \cdots + \mathbf{z_{ij}} + \mathbf{y_i} \qquad (1)$$

where $\mathbf{y}_i$ is the final demand for that product produced by the particular sector. If each element, $\mathbf{z}_{ij}$, along row i is divided by the output $\mathbf{x}_i$, associated with the corresponding column j it is found in, then each element in $\mathbf{Z}$ can be replaced with:

$$\mathbf{a_{ij}} = \frac{\mathbf{z_{ij}}}{\mathbf{x_j}} \qquad (2)$$

to form a new matrix $\mathbf{A}$.

Substituting for (2) in equation (1) forms:

$$\mathbf{x_{i=}a_{i1}x_1 + a_{i2}x_2 + \cdots + a_{ij}x_i + y_i} \qquad (3)$$

Which, if written in matrix notation is $= \mathbf{Ax} + \mathbf{y}$ *.* Solving for $\mathbf{y}$ gives:

$$\mathbf{x} = (\mathbf{I} - \mathbf{A})^{-1}\mathbf{y} \qquad (4)$$

where $\mathbf{x}$ and $\mathbf{y}$ are vectors of total output and final demand, respectively, $\mathbf{I}$ is the identity matrix, and $\mathbf{A}$ is the technical coefficient matrix, which shows the inter-industry requirements. $(\mathbf{I} - \mathbf{A})^{-1}$ is known as the Leontief inverse (further identified as $\mathbf{L}$). It indicates the inter-industry requirements of the i^{th} sector to deliver a unit of output to final demand. Since the 1960s, the IO framework has been extended to account for increases in the pollution associated with industrial production due to a change in final demand (Miller & Blair, 2009).

Consider, a row vector $\mathbf{f}$ of annual CO_2 emissions generated by each industrial sector

$$\mathbf{e} = \mathbf{f}\hat{\mathbf{x}}^{-1} \qquad (5)$$

is the coefficient vector representing emissions per unit of output[3]. Multiplying both sides of (4) by $\mathbf{e}'$ gives

$$\mathbf{e}'\mathbf{x} = \mathbf{e}'\mathbf{L}\mathbf{y} \qquad (6)$$

and simplifies to

$$\mathbf{F} = \mathbf{e}'\mathbf{L}\mathbf{y} \qquad (7)$$

where $\mathbf{F}$ is the CO_2 emissions in matrix form allowing consumption-based emissions to be determined. $\mathbf{F}$ is calculated by pre-multiplying $\mathbf{L}$ by emissions per unit of output and post-multiplying by final demand. This calculation shows how a unit change in final demand $\mathbf{y}$, increases the emissions by all industries to satisfy this change.

This system can be expanded to the global scale by considering trade flows between every industrial in the world rather than within a single country. This type of system requires a multi-regional input – output (MRIO) table. The latest audits of the main global MRIO initiatives (Peters et al. 2011; Inomata and Owen 2014) describe six systems of which three (WIOD, Eora and EXIOBASE) were released in 2012. The other MRIO systems available are GTAP, FIGARO and the OECD-ICIO tables.

[3] $\hat{\square}$ denotes matrix diagonalisation and $'$ denotes matrix transposition

2.2 Construction of the MRIO database

A UK carbon footprint model needs to be able to measure the impact of UK consumption of products considering domestic and foreign supply chains involved in production. This means the MRIO table needs to have information about flows of products from abroad to both UK intermediate and final demand. Production efficiencies vary between different producers meaning that the impact per pound spent may be larger for a product from country A than from country B.

The most accurate representation of the UK consumption-based account would measure the flow of products from every country and understand the emissions intensities associated with each industry in every country. However, when we consider how the model may be used and practicalities such as model size, data storage capacity and model run times, aggregating trade partner countries is preferable.

The UKMRIO database contains 15 regions: the UK, Brazil, Russia, India, China, South Africa, the USA, Japan, the rest of the EU, the rest of Europe, the rest of the OECD, the rest of Africa, the rest of Americas, the rest of Asia and Oceania and the Middle East. We chose these regions because they represent important trade partners.

2.2.1 MRIO table structure

The ideal MRIO data table structure requires an MRIO table with all other nations' data at the 112-sector level. Each table in the MRIO database will be structured as shown in Figure 3. Blank cells are zero.

		UK supply table at 112 sectors			
			Other nations' supply tables at 112 sectors		
UK domestic use table at 112 sectors	Other nations' intermediate demand of UK products			UK final demand of UK products	Other nations' final demand of UK products
UK intermediate demand of other nations' products	Other nations' domestic use table at 112 sectors			UK final demand of other nations' products	Other nations' final demand of other nations' products
UK value added	Other nations' value added				

Figure 3: Table structure for the the UKMRIO database

2.2.2 UK data from the ONS

UK Supply and Use tables (SUTs) are currently produced by the Office of National Statistics (ONS) at the 112-sector level for the years 1997-2021 and the 123-sector level for the years 1992-1996. All SUT tables follow the structure shown in Figure 4.

	Industries	Products			
industries		industry by product supply table			Sum of industrial output in basic prices
products	Combined use table measured in purchaser's prices. Sum of domestic intermediate use, imports to UK intermediate demand and margins and taxes and products		Combined final demand for products (UK and foreign) by households, NPISH, national & local government, gross fixed capital valuables, changes in inventories	Exports of UK products	Sum of products in purchasers prices
	Value added – wages and tax on production				
	Sum of industrial output in purchasers prices	Sum of products in basic prices	Sum of final demand in purchasers prices		

Figure 4: The UK supply and use table structure

We are unable to use the SUTs in their original form because (i) the Use table is a combination of domestic and imports and (ii) the Combined Use table is in purchaser's prices, meaning that we must also strip out margins and taxes on products. In order to adjust the SUTs so that the Use table is split by domestic use and imported use and to transform the data into basic prices, we make use of the Analytical tables.

Detailed analytical tables are available for 1990, 1995, 2005, 2010, 2013-2015. Less detailed analytical tables are available for 2016-2019 (see Figure 5). Analytical tables split the combined use table into a domestic use matrix and rows for imports, product tax and further value-added components. The 1990-2005 tables are at the older 123 sector classification. A mapping showing how to convert from 123 sectors to 112 sectors is available on the ONS website[4]. This data has been used to make a 112 by 123 weighted concordance matrix and all tables at 123 sectors are converted to 112 using this. Both the Domestic and Combined Use tables are available for 1995, 2005, 2010 and 2013-2015. For 2016-2019, only the Domestic Use table is supplied. For 2016-2019 we generate

4 https://www.ons.gov.uk/economy/nationalaccounts/supplyandusetables/adhocs/12553mappingfromio123tocpa2008productgroups

a version of the Combined Use table using tax rates from 2016 and the Imports Use table for the year in question.

Domestic use table in basic prices (112x112 or 123x123)	Domestic final demand	Domestic exports from UK
Imports row (1x112 or 1x123)	Imported final demand	

Combined use table in basic prices (112x112 or 123x123)	Combined final demand	Combined exports from UK
Total row (1x112 or 1x123)	Total final demand	

Figure 5: UK Analytical table structures (Domestic Use and Combined Use for 1995, 2005, 2010 and 2013-2015 and Domestic Use only for 2016-2019)

Proportion of Use that is domestic (112x112)	Proportion of final demand that is domestic (112x7)	Proportion of exports that is domestic by 112 products
Proportion of Use that is imported (by 112 industry)	Proportion of final demand that is imported by 7 final demand categories	

Figure 6: Domestic proportion table

The ONS also disaggregates UK production emissions to sectors in the economy and reports on these emissions as Environmental Accounts. Since the revision of the national Environmental Accounts in 2011, emissions data map to this 112-sector classification system.

2.2.3 Rest of world data from EXIOBASE v3.8.2

EXIOBASE v3.8.2, produced by the NTNU, TNO, SERI, Universiteit Leiden, WU and 2.-0 LCA Consultants (Tukker et al. 2013; Wood et al. 2015), is an MRIO database encompassing data for 49 regions for the years 1995-2021. The database is available in a Supply and Use Table structure with a homogenous sectoral classification comprising 163 industries and 200 products. From EXIOBASE we extract the following:

- Exports from the UK to other nations' intermediate demand
- Exports from the UK to other nations' final demand
- Imports to UK intermediate demand from other nations
- Imports to UK final demand from other nations
- Trade between other nations' intermediate demand

- Final demand of other nations from other nations

Before the data can be used in the UK MRIO, it needs to be manipulated to the correct structure. We transform EXIOBASE so that the number of sectors is 112 and the regions are Brazil, Russia, India, China, South Africa, the USA, Japan, the rest of the EU, the rest of Europe, the rest of the OECD, the rest of Africa, the rest of Americas, the rest of Asia and Oceania and the Middle East (see Table 2). In addition, the data must be transformed from Euros to GBP.

Table 2: EXIOBASE regions aggregated to UKMRIO regions.

UKMRIO database region	Regions from EXIOBASE
UK	UK
Brazil	Brazil
Russia	Russia
India	India
China	China
South Africa	South Africa
USA	USA
Japan	Japan
Rest of the European Union	Austria Belgium Bulgaria Croatia Cyprus Czech Republic Germany Denmark Estonia Spain Finland France Greece Hungary Ireland Italy Latvia Luxembourg Lithuania Malta Netherlands Poland Portugal Romania Sweden Slovakia Slovenia
Rest of Europe	Switzerland Norway Rest of Europe
Rest of the OECD (Non-Europe)	Canada Korea Mexico Australia Turkey

Rest of Africa	Rest of Africa
Rest of the Americas	Rest of the Americas
Rest of Asia and Oceania	Taiwan Indonesia Rest of Asia and Oceania
Rest of the Middle East	Rest of the Middle East

2.2.4 Filling in the data gaps

We are aiming to produce annual tables in the format shown below. The following explains the steps taken to produce each element in the table.

		UK supply table at 112 sectors			
			Other nations' supply tables at 112 sectors		
UK domestic use table at 112 sectors	Other nations' intermediate demand of UK products			UK final demand of UK products	Other nations' final demand of UK products
UK intermediate demand of other nations' products	Other nations' domestic use table at 112 sectors			UK final demand of other nations' products	Other nations' final demand of other nations' products
UK value added	Other nations' value added				

Figure 7: Ideal structure for UKMRIO

2.2.4.1 Domestic supply table

UK supply table at 112 sectors	=	UK supply table at 112 sectors

The ONS supply tables can be directly placed into a UKMRIO table

2.2.4.2 Domestic use table

UK domestic use table at 112 sectors	=	UK combined use table at 112 sectors	x	Proportion of Use that is domestic

The domestic use tables are formed by taking the combined use tables and using the domestic proportions table to extract only the domestic industrial spends

2.2.4.3 Domestic final demand of domestic sourced products

UK final demand of UK products	=	UK final demand of all products	x	Proportion of Final demand that is domestic

The domestic final demand tables are formed by taking the combined final demand tables and using the final demand domestic proportions tables to extract only the domestic final demand spends

2.2.4.4 Rest of World supply tables

Other nations' supply tables at 112 sectors	=	Other nations' supply tables at 112 sectors	Taken directly EXIOBASE, converted to 112 sectors, 14 regions and into GBP

The supply tables for other regions are taken from EXIOBASE after being converted to the UK 112 sector 15 region format and converted to GBP.

2.2.4.5 Rest of World use tables

Other nations' use tables at 112 sectors	=	Other nations' use tables at 112 sectors	Taken directly EXIOBASE, converted to 112 sectors, 14 regions and into GBP

The supply tables for other regions are taken from EXIOBASE after being converted to the UK 112 sector 15 region format and converted to GBP.

2.2.4.6 Rest of World final demand of Rest of World sourced products

Other nations' final demand of other nations products	=	Other nations' final demand of other nations products	Taken directly EXIOBASE, converted to 112 sectors, 14 regions and into GBP

The final demand tables for other regions are taken from EXIOBASE after being converted to the UK 112 sector 15 region format and converted to GBP.

2.2.4.7 Imports to domestic use tables

Imports to intermediate row total	=	Sum of industrial output in basic prices	-	Sum of UK domestic use by industry	-	UK value added

UK intermediate demand of other nations' products	=	Imports to intermediate row total repeated 112 x 15 times	x	Proportion of imports to UK intermediate demand by industry & region from EXIOBASE

To construct the UK imports to intermediate demand section, first a row vector of total imports to intermediate is constructed. We know that this amount must be equal to the total output in basic prices minus the domestic use table minus value added. This row vector is now disaggregated by source region and industry using proportions taken from EXIOBASE.

2.2.4.8 Imports to domestic final demand

Imports to final demand row total	=	Sum of final demand in purchasers' prices	x	Proportion of final demand that is imported
UK final demand of other nations' products	=	Imports to final demand row total repeated 112 x 15 times	x	Proportion of imports to UK final demand by industry & region from EXIOBASE

To construct the UK imports to final demand section, first a row vector of total imports to intermediate is constructed. This is the total final demand multiplied by the proportion of final demand that is imported. This row vector is now disaggregated by source region and industry using proportions taken from EXIOBASE.

2.2.4.9 Exports from to domestic use

UK exports column total	=	Exports of UK products	x	Proportion of exports that is domestic
UK exports	=	exports to intermediate and final demand column repeated 112 x 15 +1 times	x	Proportion of UK exports to all destinations from EXIOBASE

To construct the UK exports to both other nations' intermediate and other nations' final demand section, first a row vector of total exports is constructed. This is the total exports multiplied by the proportion of exports that is domestic (takes out foreign exports). This column vector is now disaggregated by source region, industry, and destination (intermediate or final demand) using proportions taken from EXIOBASE.

2.2.4.10 Domestic value added

UK value added	=	UK value added

The value added tables for the UK are taken directly from the SUTs.

2.2.4.11 Rest of World Value added

Other nations' value added	=	Other nations' value added	Taken directly EXIOBASE, converted to 112 sectors, 15 regions and into GBP

The value added tables for other regions are taken from EXIOBASE after being converted to the UK 112 sector 15 region format and converted to GBP.

2.3 Modelling and data issues and solutions

This section aims to describe the nature of any data or modelling issue, how a solution was developed and applied and discuss any assumptions or uncertainties that arise due to the steps taken.

2.3.1 Negative numbers, zeros and blanks in the UK data

Before working with the SUTs, any negative numbers in the final demand columns are zeroed and this number is added to the corresponding value-added cell to ensure that the tables still balance. Any further negative numbers are removed and replaced with $1x10^{-9}$. This is because some of the balancing techniques applied later do not work with negative values. Many of the data manipulations required to format the data into the correct structure involve a division. Division by zero is not possible, so any zeros or blanks are also replaced with $1x10^{-9}$.

2.3.2 Missing analytical data

Analytical tables (AT), which indicate the proportion of product to industry flow that is satisfied by *domestic* production are available for the years 1990, 1995, 2005, 2010, 2013-2015 and for 2016-2019. Using these tables we can calculate the proportion of all intermediate flows to UK industry that are domestic (by industry). We need a proportioning matrix for each of the years 1990 to 2020. For 2020-2021 we use the 2019 matrix. For the years between 1990 and 1995; 1995 and 2005; 2005 and 2010; and 2010 and 2013, we make linearly interpolated matrices bridging the known matrices as shown. Due to lack of data we are making assumptions about the exact proportions of products supplied to intermediate demand from domestic industry for the years 1991-1994, 1996-2004, 2006-2009, 2011-2012 and 2020-2021.

2.3.3 Reconciling the EXIOBASE data to the UKMRIO structure

Now that we have data on the total imports to UK intermediate demand, we need to disaggregate this row by industrial sectors from Brazil, Russia, India, China, South Africa, the USA, Japan, the rest of the EU, the rest of Europe, the rest of the OECD, the rest of Africa, the rest of Americas, the rest of Asia and Oceania and the Middle East to show the source of imports. This data is taken from EXIOBASE but as discussed above, EXIOBASE needs to be transformed to the UKMRIOT structure. We transform the whole of the EXIOBASE MRIOT because we will be using sections elsewhere.

- First, we transform the 163 industries and 200 products to 112 sectors. This can mean aggregating some sectors together and also splitting some sectors into two or more parts. We use the UK's industrial output breakdown as weights to disaggregate other region's Use table columns and the UK's product output breakdown to disaggregate other region's Supply table columns. Using the UK data as weights for disaggregation is an assumption. Final Demand, value added and environmental extension data are similarly aggregated and disaggregated

- Secondly, we aggregate the regions to form the 16 traded regions used in the UKMRIO.
- Finally, the data is converted to GBP from Euros using currency conversion factors from the appropriate year. We use a 12-month average conversion rate

Some of the EXIOBASE data, such as the portion representing trade between non-UK regions, is slotted straight into the UK model. Other data, such as the imports to UK intermediate demand and the Exports from UK intermediate demand are used as proportions to help disaggregated information that we already know from the ONS UK tables.

2.3.4 Imports to UK intermediate demand

The first data requirement is a matrix showing the proportion of each intermediate flow to UK industry that is from Brazil, Russia, India, China, South Africa, the USA, Japan, the rest of the EU, the rest of Europe, the rest of the OECD, the rest of Africa, the rest of Americas, the rest of Asia and Oceania and the Middle East products. This is a 14x112 by 112 rectangular matrix with column sum equal to one. The 1,568 rows are flows from foreign sectors. Because this is a matrix of proportions, we need not convert the matrix to GBP from Euros, and currency exchange rate issues are avoided.

The 'imports from' row (calculated from the UK Combined Use tables) is then multiplied down this proportional matrix to give the full intermediate flows to UK industry table.

2.3.5 Exports from UK to intermediate demand

The next use of the EXIOBASE data set is to fill in the rows showing where UK products are intermediate demands to Brazil, Russia, India, China, South Africa, the USA, Japan, the rest of the EU, the rest of Europe, the rest of the OECD, the rest of Africa, the rest of Americas, the rest of Asia and Oceania and the Middle East industry and final demand. EXIOBASE is used to make a proportional matrix of the use of UK products in RoW intermediate and final demand. As described above, the trade block data from the full Eora model is used and manipulated to make 15 matrices of 112x112. However, at this stage we do *not* use the 'exports from' column from the UK combined use tables as the exports total. Instead we know that the sum of the 'exports from' is equal to the sum of the imports to UK intermediate demand plus the different in the UK's value added and the final demand for UK products from both domestic and foreign consumers. This total is multiplied by the proportional matrix where the total of the whole matrix is one (rather than the total of the rows or the total of the columns).

Final demand from the UK tables includes the final demand of imported goods so we need to use the analytical tables again to make a domestic proportion table. Final demand of UK products by the RoW is taken from the UK trade blocks of the **full EXIOBASE** database and multiplied by an exchange rate currency conversion factor to get the data in the right unit[5].

2.3.6 Balancing the whole table

The table now needs to be balanced to ensure that total imports equal total output – in other words the row and column sums should be the same. The technique known as RAS iteratively re-proportions the table making adjustments to ensure first that the column sums are correct then the column. The process is repeated until a desired level of accuracy is acquired.

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[5] Clearly this introduces some uncertainty into the model because we use the same conversion factor for each region and sector, when in reality it is likely that the conversion factors should be sector and country- specific

To determine the true row and column sum vectors we use the fact that there are certain row and column totals that are set because the sum of the supply tables are fixed.

Figure 8 below explains how the row and column sums are determined.

		UK supply table				**A**
			supply table			**B**
UK domestic use table	int demand from UK			UK Final demand of UK	All RoW Final demand of UK	**C'**
UK int demand from	UK domestic table			UK Final demand of EU	All RoW Final Demand of EU	**D'**
UK Value Added	Value added					
A'	**B'**	**C**	**D**			

Figure 8: Pre-balanced MRIO table

To balance the table, we know that:

- A' = A (the row sum of the UK supply table)
- B' = B (the row sum of the RoW supply table)
- C' = C (the column sum of the UK supply table)
- D' = D (the row sum of the RoW supply table)

The RAS balancing procedure is then used to re-proportion this section to ensure that the MRIO table balances.

3 Accuracy, uncertainty, effects of methodological changes and comparisons with other databases

3.1 The UK consumption-based account 1990-2021

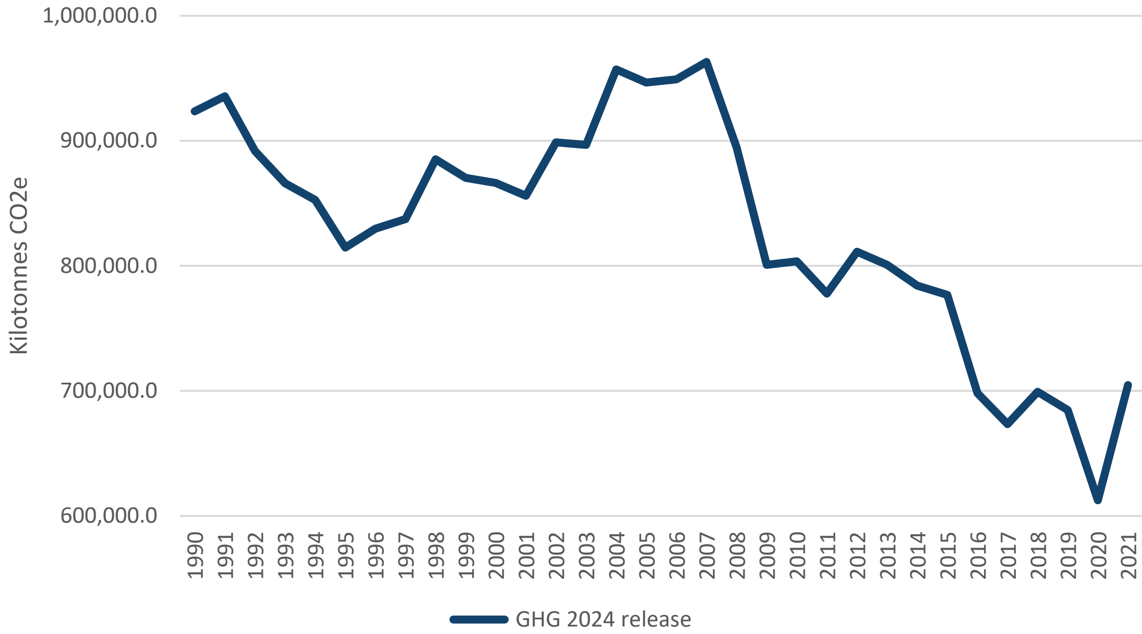

Figure 9: UK MRIO carbon footprint (all GHGs) results 1990-2021

Figure 9 shows that the UK's consumption-based account for GHGs decreased by 12% between 1990 and 1995, before climbing to a minimum of 963 Mtonnes CO2e in 2007 (an increase of 18%). The financial crisis saw a reduction of 17% to 2009, followed by a further 15% reduction between the years 2009 and 2019. The COVID-19 pandemic in 2020 saw a reduction of 11% in a single year, followed by a final increase of 15% between 2020 and 2021.

Between 2020 and 2021, the GHG emissions associated with UK consumption increased by 92 Mtonnes CO2e. Of this 92 Mtonnes CO2e, increases in household spend on electricity, gas and water, personal transport and hotels and restaurants contributed 12, 10 and 7 Mtonnes, respectively). Increased expenditure on Gross fixed capital and by Central Government contributed 13 and 12 Mtonnes respectively.

3.2 The evolution of the UK consumption-based account

Calculating consumption-based accounts, which accurately cover emissions, energy, materials and water embodied in imports, has only been possible in the last decade and the datasets and techniques are continually improving. Figure 10 shows the evolution of the UK's carbon footprint measured in $KtCO_2e$ as calculated by the UKMRIO database. The overall pattern is very similar throughout the model versions. The new 2024 release estimates very similar footprints compared to the 2023 release with a slight increase to the post-2016 results. The reasons for these small differences are due to an improvement in the way we calculate the imports proportion. These methodological improvements are explained further in section 3.5.

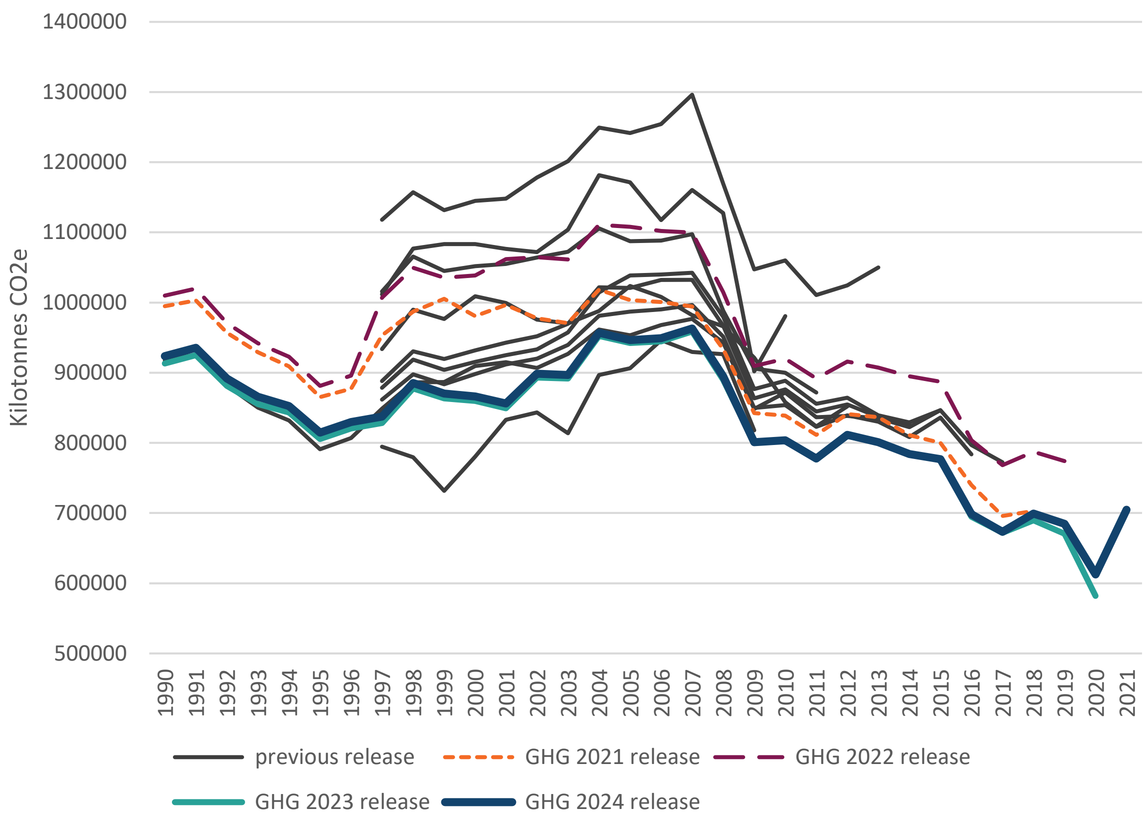

Figure 10: UK MRIO carbon footprint (all GHGs) results from 2011 release to 2024 release

3.3 Comparing UK consumption-based account with results from other MRIO databases

Prior macro-level analyses of the UK consumption-based account are available using various global MRIO databases. Examples include Steen-Olsen et al. (2012), Moran and Wood (2014), Tukker et al. (2014), Hertwich and Peters (200), Wood et al. (2018), and Barrett et al. (2013). Other studies have employed other UKMRIO models (e.g. Wiedmann et al. 2010; Druckman and Jackson 2009). Figure 11summarises the UK CO_2 footprint data provided by the most commonly used global MRIO databases communicated in the reviewed studies. Please note that the data is carbon dioxide only to allow for comparison with models where the additional greenhouse gas data is unavailable. The UKMRIO model (shown in dark blue) estimates slightly lower than other models to 2007 but post 2007, the results are strikingly similar to the newer systems Global Carbon Atlas and OECD. We believe this to be important evidence that our changed methodology is producing results that are more accurate and more in-line with other work.

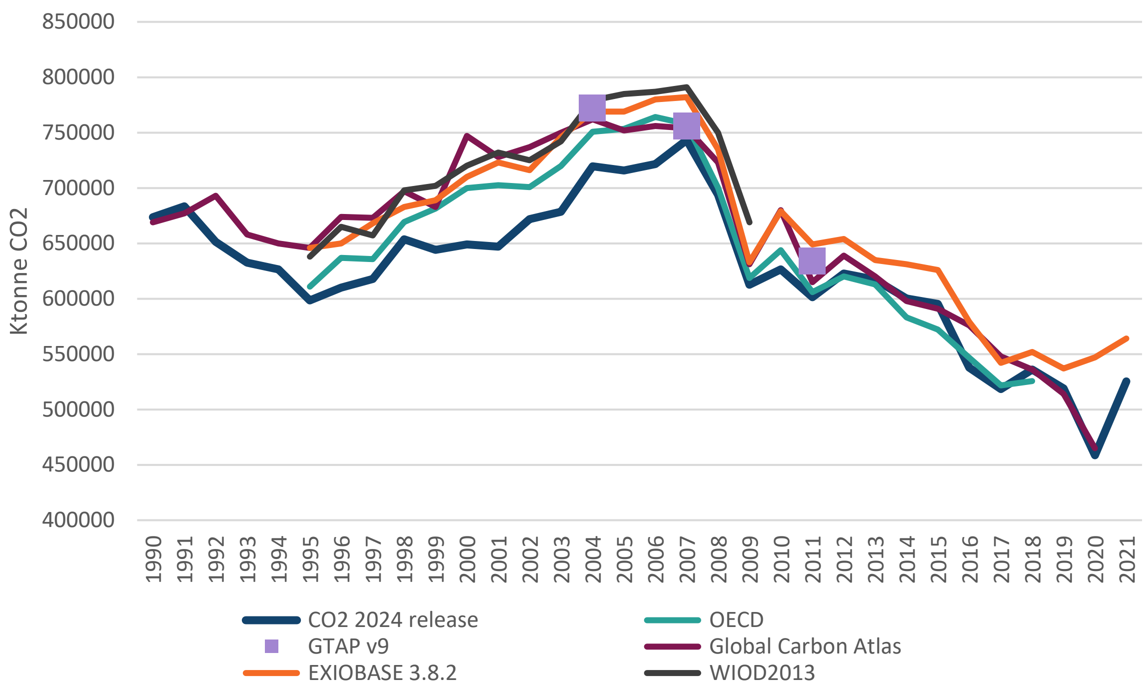

Figure 11: UK carbon footprint calculated by the UKMRIO database and the six other global MRIO databases

We have concerns, however, about the accuracy of EXIOBASE in 2020 and 2021. EXIOBASE v3.8.2 was finalised in the year before the COVID19 pandemic and its estimates for 2020 and 2021 are 'nowcasted' based on trend data and some global totals. We know that Global emissions reduced in 2020 but this is not evident in the EXIOBASE data. We are therefore considering options to improve the methods used to estimate emissions embodied in imports the UK and have funding from ESCoE to do this.

3.4 Uncertainties involved in extending the database back to 1990

For the past five updates we have used data from the National Archives to extend the dataset back to 1990. This involves using data that is not consistent with the UKMRIO database used to calculate the consumption-based account. Sometimes the data uses a different classification system for the sectors and has to be transformed to the 112 sectors used in the national accounts. In other cases, data does not exist for a particular year and assumptions have to be made using proxy data – for example using data from a different year and adjusting the totals to match known changes in GDP.

The most accurate footprint estimates will be for the years 2010 and 2013-2015. For the newly estimated years, 1995-1996 are reasonable estimates of the footprint. 1992-1994 do not have accurate information on the character of trade into the UK. 1990-1991 are the least accurate estimates and use previous years tables as a large part of the model construction.

3.5 Effects of methodological and data changes for the 2024 release

There is one methodological change for the 2024 release compared to the 2023 release:

- Introduce data from less detailed analytical tables from 2016-2019 to estimate imports proportions from 2016-2021 rather than taking the 2015 proportion for all years.

In previous versions of the method used to construct the UK MRIO database, the Detailed Analytical tables from 1990, 1995, 2005, 2010, 2013-2015 are used to calculate the proportion of Combined Use table that was domestic. We then used proportions to calculate the total imported use by industry as a row. For the 2024 release we introduced data from the Analytical tables for the years 2016-2019 to gain a better understanding of imports for these years. For 2020 and 2021 we then used the 2019 imports proportions. The Analytic tables differ from the Detailed Analytic tables in that they only include domestic and imports in basic prices. They do not include a combined use table in purchaser’s prices. To calculate the import share, we need the combined use table. For the years 2016-2019, we calculated an estimate of the combined use table using tax rates calculated for 2015.

In addition, we took out the 1990 data since it was seen as unreliable, meaning that 1995 imports shares are then allocated to the years 1990-1994. The previous method over-estimated the value of imports because we were not basing them on this basic price total.

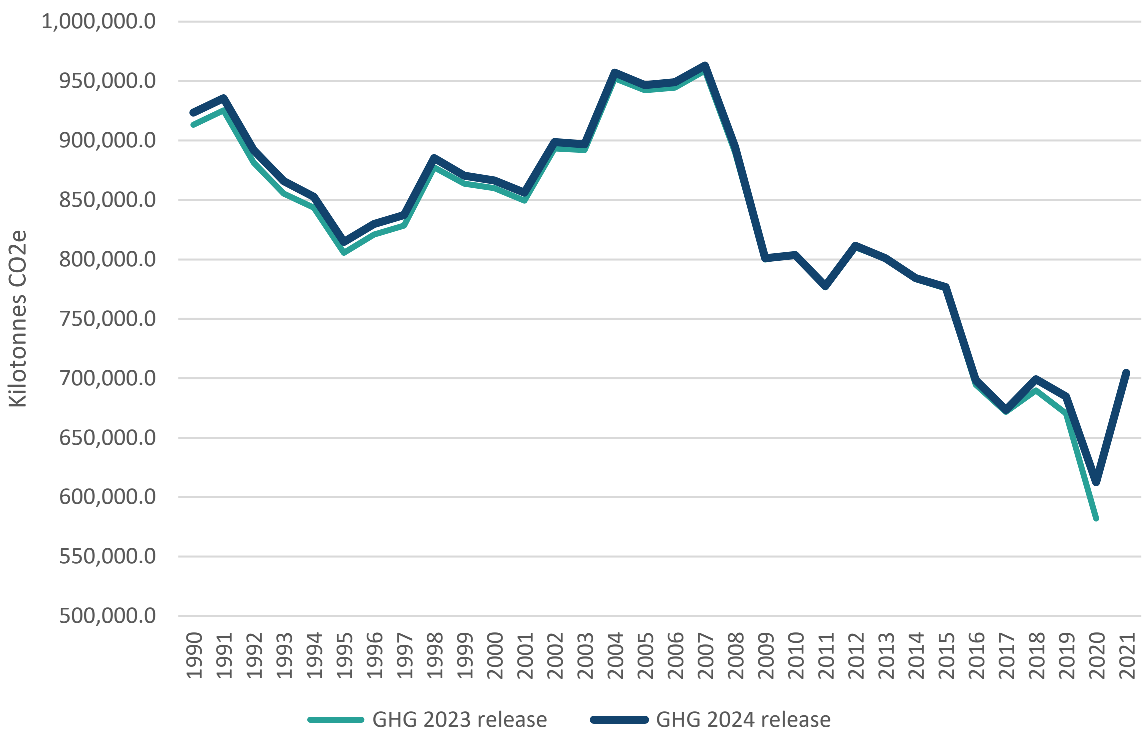

Figure 12: Comparison of the 2023 release and the 2024 release.

4 Results for the devolved regions

In 2024's release we are also able to report the consumption-based account for the devolved regions: England, Northern Ireland, Scotland and Wales.

We use a hierarchical hybrid methodology for estimating final consumption of each of the devolved regions (Minx et al, 2013). Essentially, we need to calculate what proportion of the total UK spend is each of the devolved regions is responsible for, for each consumption item contained in the database. For example, if England spends 85% of the total UK spend on Clothing, it receives 85% of the total UK footprint associated with clothing demand. To understand the portion of UK spend attributed to England, for example, we would either need to know total consumption of each good or service for each of England, Scotland, Northern Ireland and Wales or we would need an average expenditure profile for the devolved region and multiply this up by the number of residents.

For domestic consumption of gas and electricity we use the 'Regional and local authority consumption statistics' produced by BEIS which give estimates of gas and electricity consumption at the regional (NUTS1) and Local Authority levels for Great Britain for the years 2005-2021. Separate data is available for Northern Ireland, but the time series is shorter. We convert the data into proportions and use trend projections to project the data back to 2001 for all regions.

We use estimates of household spend profiles from the Living Costs and Food Survey (LCFS) for all other spends on goods and services. Since 1957, the Office for National Statistics (ONS) has annually surveyed UK households on their weekly expenditure (UK Data Service 2019). In 2008 this survey became known as the Living Costs and Food Survey; prior to this it was known as the Expenditure and Food Survey. The LCFS achieves a sample of around 6,000 UK households and is used to provide information on retail price indices, National Account estimates of household expenditure, the effect of taxes and benefits, and trends in nutrition. In addition to providing information on household spend on over 300 different product types (coded by the European Standard Classification of Individual Consumption by Purpose (COICOP)). Additional information is collected such as the age, sex and occupation of members of the household, the total household income, taxes paid, and the location, tenure, dwelling type. The characteristics of each sampled households can then be compared to the characteristics of all UK households using the UK census. The survey strives to produce a representative sample of the 28 million UK households. For each of the 5000+ household surveys in the 2020 release, a weight is supplied to indicate the proportion of UK households that are represented by this profile. For example, the 1st household in the 2021 survey has a weight of 2,990 and the sum of every weight is 28,198,240. In all calculations for this study, we use the weights to convert the sample into a set of data that is representative of all 28 million households in the UK.

The LCFS is available in a format that is comparable for the years 2001-2021. This means that our results for the devolved regions start at 2001 rather than 1990.

The UK is unusual because the Supply and Use tables constructed by the Office for National Statistics include final demand by UK households that is split by both product sectors in the IO structure and 42 aggregated sectors found in the LCFS. This means that we can be confident in linking these datasets and exploring household energy footprints by groupings formed from the household survey. The UK is unique in providing this bridge table between the two formats of recording spend by products. In other studies much work has gone into the construction and evaluation of these bridge tables (Steen-Olsen et al. 2016; Min and Rao 2017) but because the LCFS is an input to the national accounts, the ONS can supply this mapping at an aggregate scale.

3	Household final consumption expenditure 2016				
Contents					
		01.1	01.2	02.1	02.2
	Product	Food	Non-alcoholic beverages	Alcoholic beverages	Tobacco
01	Products of agriculture, hunting and related services	15 808	-	-	-
02	Products of forestry, logging and related services	-	-	-	-
03	Fish and other fishing products; aquaculture products; support services to fisl	699	-	-	-
05	Coal and lignite	-	-	-	-
06 & 07	Extraction Of Crude Petroleum And Natural Gas & Mining Of Metal Ores	-	-	-	-
08	Other mining and quarrying products	-	-	-	-
09	Mining support services	-	-	-	-
10.1	Preserved meat and meat products	19 190	-	-	-
10.2-3	Processed and preserved fish, crustaceans, molluscs, fruit and vegetables	12 200	1 908	-	-
10.4	Vegetable and animal oils and fats	1 193	-	-	-
10.5	Dairy products	11 772	-	-	-
10.6	Grain mill products, starches and starch products	2 926	-	-	-
10.7	Bakery and farinaceous products	8 719	-	-	-
10.8	Other food products	14 527	3 144	-	-
10.9	Prepared animal feeds	-	-	-	-
11.01-6 & 12	Alcoholic beverages & Tobacco products	-	-	18 520	19 640
11.07	Soft drinks	-	6 731	-	-
13	Textiles	-	-	-	-

The LCFS collects information on the Government Office Region that each surveyed household is found in. We construct an average spend profile for households in each of the four devolved regions, multiply this by the households in the regions and calculate the portion of spend by each product that each region is responsible for in order to disaggregate the total UK footprint. This method ensures that the sum of the regions equals the total footprint.

4.1 Accuracy of devolved region results.

This method assumes that each region consumes domestic and imported products in the same proportions. For example, we assume that households in England consume the same proportion of Brazilian beef products as households in Wales. This is because we assume the same production structure for products regardless of where the household is located. For many products, this is a reasonable assumption. However, we are unable to demonstrate the fact that electricity generation in Scotland may be made up of a greater proportion of renewable fuel compared to the rest of the country.

The ideal approach would necessitate the construction of a multiregional input-output model where England, Northern Ireland, Scotland and Wales are individual regions, each with their own use tables detailing their unique production recipes. However, this type of data is not currently collected and the approach we use with the four estimated final demand vectors is the best available.

Obviously, the final demand vectors generated for each of the devolved regions are built on survey data. Even though the LCFS surveys over 5,000 households each year, these are not equally distributed by region. Table 3 shows that the number of households surveyed in Wales in 2021 was just 229. It is possible that one household with particularly unusual spend in the week surveyed could skew the results when small numbers of surveyed homes are used and where this happens, those surveyed results are smoothed.

Table 3: Number of surveyed households in the 2021 LCFS

Devolved Region	Number of Surveys in the LCFS 2021
England	4261
Scotland	815
Wales	229
Northern Ireland	327

4.2 Scotland data

Please note that the Scottish Government publishes their own estimates for the carbon footprint of Scotland which takes the final demand vector from Scottish specific IO tables and uses this with the UKMRIO. The data can be found here: https://www.gov.scot/publications/scotlands-carbon-footprint-1998-2019

This result differs slightly to the estimate using the LCFS.

5 References

Barrett, J., G.P. Peters, T. Wiedmann, K. Scott, M. Lenzen, K. Roelich, and C. Le Quéré. 2013. Consumption-Based GHG Emission Accounting: A UK Case Study. Climate Policy 13 (4): 451–470. http://www.tandfonline.com/doi/abs/10.1080/14693062.2013.788858.

Druckman, A., and T. Jackson. 2009. The Carbon Footprint of UK Households 1990–2004: A Socio-Economically Disaggregated, Quasi-Multi-Regional Input–Output Model. Ecological Economics 68 (7): 2066–2077. http://linkinghub.elsevier.com/retrieve/pii/S0921800909000366.

Hertwich, E., and G. Peters. 2009. Carbon Footprint of Nations: A Global, Trade-Linked Analysis. Environmental Science & Technology 43 (16): 6414–6420.

Inomata, S., and A. Owen. 2014. Comparative Evaluation of MRIO Databases. Economic Systems Research 26 (3): 239–244. http://www.tandfonline.com/doi/abs/10.1080/09535314.2014.940856.

Miller, R.E., and P.D. Blair. 2009. Input-Output Analysis: Foundations and Extensions. Cambridge University Press.

Min, J., and N.D. Rao. 2017. Estimating Uncertainty in Household Energy Footprints. Journal of Industrial Ecology 00 (0): 1–11.

Moran, D., and R. Wood. 2014. CONVERGENCE BETWEEN THE EORA, WIOD, EXIOBASE, AND OPENEU'S CONSUMPTION-BASED CARBON ACCOUNTS CONVERGENCE BETWEEN THE EORA, WIOD, EXIOBASE, AND OPENEU'S CONSUMPTION-BASED CARBON ACCOUNTS. Economic Systems Research 26 (3): 245–261.

ONS. 2018. Supply and Use Tables. https://www.ons.gov.uk/economy/nationalaccounts/supplyandusetables/datasets/inputoutputsupplyandusetables.

Owen, A., P. Brockway, L.I. Brand-Correa, L. Bunse, M. Sakai, and J. Barrett. 2017. Energy Consumption-Based Accounts: A Comparison of Results Using Different Energy Extension Vectors. Applied Energy 190: 464–473. http://linkinghub.elsevier.com/retrieve/pii/S030626191631858X.

Peters, G.P., R. Andrew, and J. Lennox. 2011. Constructing an Environmentally-Extended Multi-Regional Input–Output Table Using the Gtap Database. Economic Systems Research 23 (2): 131–152. http://www.tandfonline.com/doi/abs/10.1080/09535314.2011.563234.

Steen-Olsen, K., J. Weinzettel, G. Cranston, E. Ercin, and E.G. Hertwich. 2012. Carbon, Land, and Water Footprint Accounts for the European Union: Consumption, Production, and Displacements through International Trade. Environmental Science and Technology 46 (20): 10883–10891.

Steen-Olsen, K., R. Wood, and E.G. Hertwich. 2016. The Carbon Footprint of Norwegian Household Consumption 1999-2012. Journal of Industrial Ecology 20 (3).

Tukker, A., T. Bulavskaya, S. Giljum, A. De Koning, S. Lutter, M. Simas, K. Stadler, and R. Wood. 2014. The Global Resource Footprint of Nations: Carbon, Water, Land and Materials Embodied in Trade and Final Consumption.

Tukker, A., A. de Koning, R. Wood, T.R. Hawkins, S. Lutter, J. Acosta-Fernández, J.M. Rueda-Cantuche, et al. 2013. Exiopol – Development and Illustrative Analyses of a Detailed Global MR EE SUT/IOT. Economic Systems Research 25 (1): 50–70. http://www.tandfonline.com/doi/abs/10.1080/09535314.2012.761952.

UK Data Service. 2019. Living Costs and Food Survey.

Wiedmann, T. 2009. A Review of Recent Multi-Region Input–Output Models Used for Consumption-Based Emission and Resource Accounting. Ecological Economics 69 (2): 211–222. http://linkinghub.elsevier.com/retrieve/pii/S0921800909003577.

Wiedmann, T., R. Wood, J. Minx, M. Lenzen, D. Guan, and R. Harris. 2010. A Carbon Footprint Time Series of the UK – Results From a Multi-Region Input–Output Model. Economic Systems Research 22 (1): 19–42. http://www.tandfonline.com/doi/abs/10.1080/09535311003612591.

Wood, R., K. Stadler, T. Bulavskaya, S. Lutter, S. Giljum, A. De Koning, J. Kuenen, et al. 2015. Global Sustainability Accounting—Developing EXIOBASE for Multi-Regional Footprint Analysis. Sustainability 7: 138–163.

Wood, R., K. Stadler, M. Simas, T. Bulavskaya, S. Giljum, S. Lutter, and A. Tukker. 2018. Growth in Environmental Footprints and Environmental Impacts Embodied in Trade: Resource Efficiency Indicators from EXIOBASE3. Journal of Industrial Ecology 22 (3): 553–564.