Carbon 'hot-spots' in global supply chains: an inter-regional input-output analysis.

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Abstract

Input-Output (IO) frameworks have been extensively used to study anthropogenic CO_2 emissions within single economies or globally. This is usually done through the calculation of headline figures like the Production and Consumption Accounting Principles (PAP and CAP), which in turn leads to a lack of transparency on the structure of emissions and limits the information available on the drivers of those emissions. To overcome these limitations, we decompose the standard Environmental Inter-Regional Input-Output (EIRIO) headline calculations, drawing on the OECD Inter-Country IO tables. We show how this facilitates consideration of downstream demands driving the production and associated CO_2 emissions at specific industrial 'hot-spots' outside the borders of individual regions/territories under study. The results for a UK study reveal how domestic final demand can drive the generation of emissions outside the UK's territorial boundaries (despite the fact that the majority of emissions are generated within its borders). The combined Chinese 'Electricity, Gas and Water Supply' sector is identified as a major direct emitter of CO_2 in the global supply chain of other industries (including UK-based ones) serving UK final demands. Furthermore, the UK 'Health and Social Work' sector is revealed to have the second largest CO_2 footprint driven by UK final demand, amongst all production sectors in all countries. However, it is found to have numerous CO_2 'hot-spots' in its international upstream supply chain, highlighting the impact of UK's 'Health and Social Work' sector on generation of emissions in the UK's trading partners.

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1. Introduction

Over the last two decades the Input Output (IO) framework has become a widely used tool in studies related to the environmental impact of economic activities. One of the most commonly studied fields is the structure of CO_2 emissions under different accounting principles. The prevailing policy approach internationally for mitigating climate change, adopted by UNFCCC, assigns responsibility to the participating members only for the emissions generated within their territory (United Nations, 1992). This Production Accounting Principle (PAP) has been met with scepticism by numerous researchers (e.g. Wyckoff and Roop, 1994; Munksgaard and Pedersen, 2001) mainly due to the issue of emissions embodied in international trade, which may be overlooked by an approach that focuses on a single country. Furthermore, as Arrow et al (1995) discuss, developed countries can achieve their emissions reduction by moving their high emissions generating activities abroad, i.e. the phenomenon identified as carbon leakage.

The fact that emissions-intensive goods are often produced for exports led to the suggestion that a Consumption Accounting Principle (CAP) would be a better way of assigning responsibility for the generated emissions. Under CAP the ultimate responsibility is assigned to the consumer of any given product or service, assuming that demand for production is the driver for any emissions, and therefore alleviating any responsibility from the producer. However, the policy focus in the UNFCCC COP21/CMP11 (in Paris, November 2015) remained the same, meaning that territorial PAP will be the approach used to calculate emissions and assign responsibility for action, at least in the medium term. Additionally, policy makers, in the UK for example, have raised a number of issues associated with the implementation of consumption-based measures. As reflected in a report from the House of Commons Energy and Climate Change Committee (2012a), the (now part of the Department for Business, Energy & Industrial Strategy) Department of Energy and Climate Change (DECC) has highlighted the lack of robust and transparent data on international trade that would be crucial in designing consumption-based measures. Furthermore, the UK government, responding to the aforementioned report, has also brought forward the existence of practical complications due to the product-specific nature of the consumption-based emissions (House of Commons Energy and Climate Change Committee, 2012b).

These by no means suggest that CAP should be disregarded, especially since there have been steps towards the direction of resolving the lack of robust data by publishing detailed Inter-Regional Input Output (IRIO) tables like the World Input Output Database (Timmer et al, 2015) and the OECD Inter-Country Input Output database (OECD, 2015). In fact, in the same report by the UK House of Commons Energy and Climate Change Committee (2012a), it is highlighted what the potential benefits are from implementing consumption-based policies. However, it seems preferable to find a way to gather information and develop techniques to consider insights from both PAP and CAP measures to make more informed policy decisions. Moreover, demand is not the sole driver of emissions and more often than not consumers do not have any direct control of the production methods used. In this sense, CAP analysis may be regarded more as a useful approach in understanding the main economic pressure points that drive the emissions generated by producing sectors rather than a responsibility ‘principle’ as such.

In this paper, we propose that a ‘hot-spot’ approach, which studies the emissions from the perspective of both the producer and the consumer, offers a better understanding on the drivers and the structure of emissions. Given the globalised nature of modern economies, supply chains are not restricted within the borders of a country. It is necessary then to apply the methodology in a more global framework. IRIO provides such an accounting framework. Analysing the data available in the OECD Inter-Country Input-Output (ICIO) Database[1] (OECD, 2015)[2] it is possible to identify CO_2 emissions 'hot-spots' in global supply chains, varying from direct emitters and industrial outputs with large overall footprints (in serving final demands) to specific points in sectors' supply chains that embody significant volumes and/or intensity of emissions. IRIO ensures that emissions embedded in international trade will be accounted for during the analysis. Therefore, it enables the decomposition of emissions embodied in downstream and upstream flow of goods for any given sector. The next section provides a review of the existing relevant literature. Section 3 expands on the methodology and the data used while in Section 4 some key results are presented and discussed. The final section concludes and offers suggestions for further research.

2. Literature background

2.1 Inter-Regional Input Output in environmental studies

Early CAP and PAP studies used Single Region Input Output (SRIO) (e.g. Munksgaard and Pedersen, 2001; Machado et al, 2001). A SRIO can be created by using national IO tables (generally part of national statistics) along with necessary 'satellite' data for the environmental extension (e.g. emissions per industrial sector, which may or may not be provided through national accounting or other official published data sources). SRIO data provided through national statistics tend to have a greater level of sectoral detail than the Multi-Region IO (MRIO) or IRIO data provided by bodies such as OECD, the WIOD project or GTAP, and often also offer more break down of domestic final

[1] Other published IRIO datasets include WIOD and GTAP. More details are provided in the following section.

[2] In this study, an earlier, pilot, version of the database is used. We are thankful to the OECD Directorate for Science, Technology and Innovation for providing access to the database and also for all the support in terms of collaboration and exchange of ideas and additional data. Their contribution has been invaluable.

consumers (e.g. breaking out tourist demand from household consumption). The downside of SRIO – with imports and exports reported in an aggregate row and column respectively - is the lack of information on the emissions impact of international trade. Even where an underlying 'use matrix' is available to identify both domestic and imported goods and services imported to each production sector and final consumer by output or commodity type, this is likely to be aggregated at 'Rest of World' (ROW) category with no information on pollution technologies of the industries located in different countries. This way any analysis on emissions impacts attributed to final demand in SRIO tends to be conducted under the 'domestic technology assumption' that the imported goods have been produced using the same technology as the examined economy (see Turner et al, 2011). In a globalised economy, this could lead to reduced accuracy and credibility of any findings.

In an effort to capture the environmental impacts of international trade, there were efforts to produce MRIO frameworks (see Wiedmann et al, 2007; Wiedmann, 2009 for detailed reviews of SRIOs and MRIOs). MRIO and IRIO differ in terms of the detail incorporated in matrices recording inter-country transactions. However, the common feature of MRIO and IRIO is that they include inter-country transactions explicitly for every country in the framework, without having the imports and exports in aggregated categories (columns/rows) as in SRIO. Therefore, an approach based on MRIO or IRIO provides a fuller insight on the pollutants emitted to produce goods that will be used either as intermediate or final goods outside the territory of each directly emitting country. In one of the studies using MRIO, Lenzen et al (2004) expanded the work of Munksgaard and Pedersen (2001) to include Denmark and some of its major trading partners (Sweden, Norway and Germany) as well as ROW. Among their findings, Lenzen et al (2004) demonstrated that as they moved towards a scenario where country-level data on production (and polluting) technologies were incorporated, the emissions attributed to each country differed significantly. Denmark, for instance, was proven to be an emissions importer instead of an exporter as calculated in the SRIO analysis of Munksgaard and Pedersen (2001). These findings suggest that, in order to improve the accuracy of our findings, it is of key importance to use frameworks as detailed as possible when it comes to the production technology and trade relationships of the countries included. In fact, the work by Shui and Harriss (2006) on the impact of trade between China and USA demonstrates that trade relations between very large and open economies may have a significant effect on global emissions.

In general, MRIO/IRIO have been used for a variety of types of analyses, including estimation of a range of different types of footprints (ecological, carbon and water footprint), as well as materials use embodied in international trade (e.g. Munoz and Steininger, 2010; Serrano and Dietzenbacher, 2010; Bruckner et al, 2012; Ewing et al, 2012). The progress and beneficial characteristics of MRIO/IRIO over the last years has been discussed by Wiedmann et al (2011). This review also provides an insight on what might be the requirements from future researchers who opt to use MRIO/IRIO analyses in determining the environmental impact of human activities. MRIO tends to be used where there are limitations on inter-regional trade data. Therefore, we hereon refer to the full IRIO approach.

A common research interest amongst the studies using both SRIO and IRIO has been the allocation of responsibility for the emissions generated and investigating the differences between PAP and CAP findings for given countries under study. However, focusing on the differences in allocated emissions under different accounting principles does not necessarily offer a better understanding on the structure of the emissions. Turner et al (2007) moved towards the direction of a more in-depth study of the IRIO underlying matrices by using the IRIO theory to establish a method that can capture both the direct and indirect effects of human economic activities. Their method calculates the ecological footprint; however, by substituting the resource-use matrix with emission intensities matrix then the model can be used in the carbon footprint framework. In fact, McGregor et al (2008) used this approach to calculate the CO_2 trade balance between Scotland and the rest of UK. A similar approach has been suggested when studying the concept of shared responsibility (e.g. Lenzen et al, 2007; Cadarso et al, 2012) where, due to the need to allocate responsibility to different points along supply chains, it was necessary to decompose the total emissions/footprint figures. One of the most recent IRIO is the Global Resource Accounting Model (GRAM) introduced by Wiebe et al (2012), who use the OECD Inter-Country Input-Output (ICIO) accounts to calculate the emissions embodied in international trade originating from energy use. The method used by Wiebe et al (2012) shares significant similarities to the approach discussed by Turner et al (2007).

The papers by Turner et al (2007) and McGregor et al (2008) also highlight a number of issues that need to be addressed in order to generate credible results. The most significant one is the requirement for highly detailed datasets that meet specific characteristics such as: (a) all the transactions between the countries included reported in IO format with (b) common sector classifications and (c) inclusion of direct imports of final goods and detailed imports of intermediate goods. Therefore, IRIO tables are difficult and resource intensive to produce, providing one reason why IRIO has not been extensively used until recently. Amongst the existing IRIO datasets, one of the most extensively used ones is the World Input Output Database (WIOD) (Timmer et al, 2015). The WIOD dataset includes 40 countries plus Rest of the World (ROW) with 35 production sectors in each. The data have been harmonized in a way that the table of every country included has the same sector classification and the transactions are reported in US dollars (USD) across the board. Additionally, an array of social and environmental satellite accounts is included to facilitate the use of WIOD in a variety of fields. However, in this paper the OECD ICIO database is used as it benefits from a larger number of countries (57 plus ROW) and less aggregated sectors in each country (37 sectors rather than 35 in WIOD). The fact that the sectors are grouped differently compared to WIOD also meant that it was necessary to create a 'satellite' emissions account for use in the environmental IRIO, rather than using the one published as part of the WIOD project.

2.2 'Hot-spots' and key sectors

Even though Input-Output frameworks have been extensively used in environmental studies, the concept of 'hot-spots' has received limited attention, especially when studying CO_2 emissions. There are examples of studies identifying 'hot-spots' but either focus on specific commodities or use different economic tools or even study different types of environmental effects. For instance, Acquaye et al (2011) focus specifically on the 'hot-spots' along the biodiesel supply chain, while Turner et al (2012) determined 'hot-spots' in metal manufacture within the Welsh economy (in performing a CGE analysis) and Court et al (2015) field of interest is hazardous waste in domestic supply chains for a range of different types of production and consumption.

However, methodologies to help distinguish which sectors and coefficients in an IO framework are the most important in an economy have been developed for many years and there exist studies that discuss on methods to identify those sectors and coefficients. The methods identifying important sectors are usually referred to as key sector analysis and they are applicable at inter-regional, national and sub-national level. Rasmussen (1957), Chenery and Watanabe (1958), Hirschman (1958), Dietzenbacher (1992), Sonis et al (2000), Miller and Lahr (2001), Midmore et al (2006) are only some examples of studies that present and discuss on methodologies to identify key sectors. All of them provide different approaches that can be used to identify sectors which have strong forward and/or backward linkages. Our methodology builds primarily on the more classic methods (Rasmussen, 1957; Chenery and Watanabe, 1958; Hirschman, 1958) rather than the eigenvector method (Dietzenbacher, 1992; Midmore et al, 2006). The classic key sector analysis uses the Type I output multiplier as an indicator of a sector's backward linkages. In a similar way, we examine each sector's Type I emissions multiplier against its final demand to gauge whether the sector is heavily dependent on polluting inputs or it is the volume of final demand that mainly drives that sector's footprint. In essence, our approach considers the backward linkages of each sector but introduces measurement of emissions to the calculation so that the backward linkages are examined from the perspective of the environmental impact. However, our proposed methodology moves forward by disaggregating the supply chains, and therefore the forward and backward linkages, in order to study which of their components are the most polluting.

In that sense, our methodology shares a somewhat similar reasoning to what is referred to as 'important coefficient' analysis. Perhaps the most straightforward approach was implemented by Okamoto (2005) who used the value of the average transaction on the 2000 China Multi-Regional IO data (CMRIO) to distinguish the important transactions. However, as Miller and Blair (2009, pp567-570) describe, there are a number of developed methodologies that identify coefficients in the Input Output coefficients matrix that if they undergo changes they lead to significant changes in the Leontief inverse[3]. Even though our approach is different in that we apply our analysis after the calculation of the Leontief inverse, still the two methods have a common motivation; to highlight those elements, of the Emissions multipliers matrix and the CO_2 emissions matrix in our method or the Input Output coefficients matrix in 'important coefficient' analysis, which have a more significant role to play in meeting our different goals set.

3. Methodology and data

3.1 Inter-Regional Input Output

As has already been discussed, in order to study the generated emissions due to international trade it is necessary to use an IO framework that includes multiple regions, or countries as in this study. The basic IO equation of a framework with 2 regions, a simpler version of the framework used in this paper, is the following.

[3] More details on the Leontief inverse, as well as all the other matrices mentioned in this section, are presented in the next section

$$\begin{bmatrix} X^{11} & X^{12} \\ X^{21} & X^{22} \end{bmatrix} = (\begin{bmatrix} I^1 & 0 \\ 0 & I^2 \end{bmatrix} - \begin{bmatrix} A^{11} & A^{12} \\ A^{21} & A^{22} \end{bmatrix})^{-1} \begin{bmatrix} Y^{11} & Y^{12} \\ Y^{21} & Y^{22} \end{bmatrix} \quad (1)$$

X^{11} is a $N \times 1$ vector of output of every sector $i = 1, \dots, N$ produced and supported by final consumption demand originating in region 1, while X^{12} is the output produced in region 1 and supported by final consumption demand originating in region 2 (via export demands Y^{12}). In the same way X^{21} is the output produced in region 2 and supported by export demand from region 1 while X^{22} is the output supported by domestic final consumption demand in region 2. Each $N \times N$ matrix A is called an input-output coefficients matrix. For example each element a_{ij}^{12} of matrix A^{12} shows the intermediate purchase of input from sector i in region 1 as a share of total input in sector j output in region 2 ($i, j = 1, \dots, N$). The key point to note, relative to SRIO, is that the elements of A^{12} and A^{21} are part of (endogenous) intermediate matrix rather than (exogenous) final demand (exports) and primary input (imports). In the framework used in this study the output of each sector is reported in monetary value, in millions of US dollars (USD millions).

Finally, Y^{11} is a $N \times Z$ vector of final demand for output from the sectors in region 1 by final consumers in region 1, while Y^{12} is the final demand for output from the sectors in region 1 that is exported to final consumers in region 2. Similarly, Y^{21} is the final demand for output of sectors in region 2 exported to final consumers in region 1 while Y^{22} is the domestic final demand for output from the sectors in region 2. Each element y_{jz}^{12} of Y^{12} represents the type z, $z = 1, \dots, Z$, final demand for output of sector j in region 1 exported to of final consumers in region 2. Types of final demand include public and private (household and government) final consumption or capital formation. In this way, it is possible to identify the output in regions 1 and 2 supported by specific types of final demand in either region (the partitioned X matrix)

Moving forward, we subtract the partitioned input-output coefficients matrix from the identity matrix I, which is partitioned with zero matrices on the interregional elements, and invert. This gives us the partitioned interregional Leontief inverse L:

$$L_{IRIO} = (\begin{bmatrix} I^1 & 0 \\ 0 & I^2 \end{bmatrix} - \begin{bmatrix} A^{11} & A^{12} \\ A^{21} & A^{22} \end{bmatrix})^{-1} \quad (2a)$$

For the general case where there are multiple regions $r, s = 1, \dots T$, the Leontief inverse is reported as:

$$L_{IRIO} = \begin{bmatrix} l_{ij}^{11} & \cdots & l_{ij}^{1s} & \cdots & l_{iN}^{1T} \\ \vdots & \ddots & \vdots & \ddots & \vdots \\ l_{ij}^{r1} & \cdots & l_{ij}^{rs} & \cdots & l_{iN}^{rT} \\ \vdots & \ddots & \vdots & \ddots & \vdots \\ l_{Nj}^{T1} & \cdots & l_{Nj}^{Ts} & \cdots & l_{NN}^{TT} \end{bmatrix} \quad (2b)$$

Each element l_{ij}^{rs} of the Leontief inverse indicates the output required from sector i in region r to meet one monetary unit worth of sector j final demand in region s. The column totals give us the interregional output multipliers of each sector j. When $r = s$ then the sectors are within the same country and the sum of column entries in this sub-matrix give us own-country output multiplier effects. However, note that even though A^{rr} will be the same as the input-output coefficients matrix of region r in an SRIO, this does not mean that L_{IRIO}^{rr} is necessarily the same as the single region Leontief inverse of region r. This is due to the fact that IRIO also captures interregional feedback effects: that is, intermediate goods produced in region r that are exported to intermediate consumption to another region s before the outputs of region s sectors are imported as inputs by region r sectors.

When there are more than two regions, the final demand matrix for total final demand for the output of each sector j in each region s (row totals of vector Y) is the following:

$$DY_{IRIO} = \begin{bmatrix} Y^s & & 0 \\ & \ddots & \\ 0 & & Y^T \end{bmatrix} = \begin{bmatrix} y_j^s & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & \ddots & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & y_N^s & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & \ddots & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & y_j^T & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & \ddots & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & y_N^T \end{bmatrix} \quad (3a)$$

However, it is also possible to focus on any one specific source of final demand for output by the final consumers in one specific region. In that case the final demand matrix is the following:

$$DY^s_{z\ IRIO} = \begin{bmatrix} Y_z^{rs} & & 0 \\ & \ddots & \\ 0 & & Y_z^{Ts} \end{bmatrix} = \begin{bmatrix} y_{jz}^{rs} & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & \ddots & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & y_{Nz}^{rs} & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & \ddots & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & y_{jz}^{Ts} & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & \ddots & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & y_{Nz}^{Ts} \end{bmatrix} \quad (3b)$$

Each element y_{jz}^{rs} of $DY^s_{z\ IRIO}$ in $(3b)$ represents the final demand for the output of sector j in region r that is generated by consumer z in region s. Therefore, the matrix as a whole reflects the demand of final consumers z in region s for output from all the sectors in all the regions included in the IRIO.

It is also possible to express the final demand diagonal matrix in a way that it shows the total final demand for the output of sector j in region r that is generated by total final consumption in a given region s (e.g. UK final consumption). In that case the final demand diagonal matrix will be the following:

$$DY^s_{IRIO} = \begin{bmatrix} Y^{rs} & & 0 \\ & \ddots & \\ 0 & & Y^{Ts} \end{bmatrix} = \begin{bmatrix} y_j^{rs} & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & \ddots & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & y_N^{rs} & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & \ddots & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & y_j^{Ts} & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & \ddots & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & y_N^{Ts} \end{bmatrix} \quad (3c)$$

For the elements of $(3c)$ we have that $y_j^{rs} = \sum_{z=1}^{Z} y_{jz}^{rs}$.

By post-multiplying the diagonal matrix of total final demand $(3a)$ by the Leontief inverse the result is the following matrix:

$$L_{IRIO}DY_{IRIO} = \begin{bmatrix} l_{ij}^{11}y_j^1 & \cdots & l_{ij}^{1s}y_j^s & \cdots & l_{iN}^{1T}y_N^T \\ \vdots & \ddots & \vdots & \ddots & \vdots \\ l_{ij}^{r1}y_j^1 & \cdots & l_{ij}^{rs}y_j^s & \cdots & l_{iN}^{rT}y_N^T \\ \vdots & \ddots & \vdots & \ddots & \vdots \\ l_{Nj}^{T1}y_j^1 & \cdots & l_{Nj}^{Ts}y_j^s & \cdots & l_{NN}^{TT}y_N^T \end{bmatrix} \quad (4)$$

Studying the elements of (4) – which could also be calculated by using subsets of final demand from $(3b)$ and $(3c)$ - it is possible to identify how the total production in each sector is ultimately supported or driven by demands for the outputs of different sectors located in different regions. Moreover, (4) allows us to consider these demands in terms of total or any given sub-type of final demand (where sub-elements of the total y_j^s are applied). Each element $l_{ij}^{rs}y_j^s$ of (4) represents the production required from sector i in region r to meet the final demand for output of sector *j* in region *s*. Examining the elements along each row of (4) - the row totals of which correspond to total output of sector i in region r - it is possible to consider output supported at different points of each sector's downstream supply chain. This is the production in each sector required to support the final demand for output produced in others, both within the same country and others. Similarly, the elements down a column of (4) – the sum of which is the total output across the global economy ultimately driven by final demand for output in the sector in question - detail a sector's direct plus indirect upstream supply chain requirements, extending beyond the limits of the country where that sector is located.

It is important to note that, in constructing this system as a full IRIO, it is necessary that the elements outside the main diagonal, where $r \neq s$, have been derived from actual data, not estimates[4]. The amount of detailed data required to produce IRIO tables is rather large, but in applications like 'hot-spot' detection and analysis, the increased accuracy provided by IRIO is of paramount importance.

[4] In MRIO the elements outside the main diagonal, A^{r1} for instance, are estimated by pre-multiplying A^{11} with a coefficients matrix, the elements of which represent the portion of the monetary flow from region *r* to region 1 over the total monetary flow to region 1, for each of the industry sectors (see Miller and Blair, 2009, pp 91-93).

3.2 Environmental IRIO

IRIO can be expanded to report the emissions embodied in transactions between industrial sectors of different regions. The first step is to create an E matrix which includes CO_2 emissions coefficients for industries in all included regions. To do so, it is required to have satellite emissions data reported at sector level, for every sector of every country included in the IRIO.

$$E_{IRIO} = \begin{bmatrix} E^r & & 0 \\ & \ddots & \\ 0 & & E^T \end{bmatrix} = \begin{bmatrix} e_i^r & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & \ddots & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & e_N^r & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & \ddots & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & e_i^T & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & \ddots & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & e_N^T \end{bmatrix} \quad (5)$$

Each element e_i^r represents the CO_2 emissions coefficient (or carbon intensity) of sector i in region r, i.e. the emissions (in physical units – million tonnes (Mt) of CO_2 in this paper) generated by sector i in region r per monetary unit worth of output. The emissions coefficients are obtained by dividing the total direct emissions of each sector by the sector's total output. By pre-multiplying E_{IRIO} to the Leontief inverse, each emissions coefficient is matched to the appropriate element of the Leontief inverse. The resulting matrix shall be called Emissions multipliers matrix:

$$Emm_{IRIO} = E_{IRIO} L_{IRIO} = \begin{bmatrix} e_i^1 l_{ij}^{11} & \cdots & e_i^1 l_{ij}^{1s} & \cdots & e_i^1 l_{iN}^{1T} \\ \vdots & \ddots & \vdots & \ddots & \vdots \\ e_i^r l_{ij}^{r1} & \cdots & e_i^r l_{ij}^{rs} & \cdots & e_i^r l_{iN}^{rT} \\ \vdots & \ddots & \vdots & \ddots & \vdots \\ e_N^T l_{Nj}^{T1} & \cdots & e_N^T l_{Nj}^{Ts} & \cdots & e_N^T l_{NN}^{TT} \end{bmatrix} \quad (6)$$

The column totals of (6) for each sector j correspond to the output-emissions multiplier of each sector. However, with the decomposition approach adopted here, (6) allows us to consider the sectoral and spatial composition of these multipliers. Each element $e_i^r l_{ij}^{rs}$ shows the emissions generated by sector i in region r to meet one monetary unit worth of final demand for the output of sector j in region s. Post-multiplying then with the diagonal (total) final demand matrix (3a), the result is the EIRIO CO_2 emissions matrix Cem_{IRIO}:

$$Cem_{IRIO} = Emm_{IRIO} DY_{IRIO} = \begin{bmatrix} e_i^1 l_{ij}^{11} y_j^1 & \cdots & e_i^1 l_{ij}^{1s} y_j^s & \cdots & e_i^1 l_{iN}^{1T} y_N^T \\ \vdots & \ddots & \vdots & \ddots & \vdots \\ e_i^r l_{ij}^{r1} y_j^1 & \cdots & e_i^r l_{ij}^{rs} y_j^s & \cdots & e_i^r l_{iN}^{rT} y_N^T \\ \vdots & \ddots & \vdots & \ddots & \vdots \\ e_N^T l_{Nj}^{T1} y_j^1 & \cdots & e_N^T l_{Nj}^{Ts} y_j^s & \cdots & e_N^T l_{NN}^{TT} y_N^T \end{bmatrix} \quad (7)$$

Cem_{IRIO} is the core matrix of the method used in this paper and the 'hot-spot' analysis will be conducted on its elements and the version based on (3c) for total UK final demand. The elements of the Cem_{IRIO} demonstrate (for the accounting year in question) the spatial and industrial distribution of emissions embedded in the supply chain of the total domestic final consumption in any one consuming region. Each element $e_i^r l_{ij}^{rs} y_j^s$ tells us the emissions generated by sector i in region r to meet the total final demand requirements for output of sector j in region s. As with output in equation (4) in the previous sub-section, the elements along each row of (7) show how the generation of emissions in each producing sector i can be distributed among all the sectors j, in all T regions in terms of supporting their final demand, i.e. the downstream supply chain. That is, the elements of (7) report emissions embodied in output to meet final demands of each sector j that are actually generated by sector i. The sum of each row in (7) is the total emissions directly generated by each sector i in each region r as would be recorded under a standard PAP measurement. On the other hand, the elements down each column of (7) show the embodied emissions in each point of each sector j's upstream supply chain, regardless of the region where that point is located. Thus, the sum of each column shows the global CO_2 footprint of production to support final consumption (regardless of the location of that final consumption) of each sector j.

However, if the focus is to calculate the emissions attributed to a particular country under CAP, it is necessary to: (a) limit the y elements used in calculating (7) to total domestic final consumption generated from within the country in question (but which will involve positive entries in all regions that there are direct imports from); and (b) add the emissions directly generated by those final consumers (generally limited to households with direct emissions generated; in public sector activity recorded in government production rather than consumption activities). Here we focus our attention on the composition of industrial emissions so we limit our attention to (7), whether for total final consumption demands or different types and/or locations of demand therein (i.e. we abstract from emissions directly generated by final consumers).

The advantage of the decomposed approach detailed above is that it enables to study the structure of industrial emissions and also the identification of those elements of (7) that make the most significant contribution in terms of CO_2 emitted. Moreover, as shown in the previous chapter, quite often the majority of the CO_2 emissions required by a sector (directly or indirectly) are located within a small number of components of its supply chain.

3.3 Emissions 'hot-spots'

The different categories of 'hot-spots' identified in this paper have already been described briefly in the first section. This section presents the methodology developed to identify the different types of 'hot-spots'. For the purposes of this study as a 'hot-spot' is considered:

(a) A sector that in producing output directly generates significantly more emissions compared to other sectors in an economy either to support total final consumption demand or components thereof (e.g. in our 'hot-spot' analysis focusing on the global supply chain serving a particular type or location – e.g. UK below - of consumer(s)); i.e. has a larger sum of its row in (7).

(b) A sector where the output produced to meet final demand for its output (again, either in total or components thereof), directly and/or indirectly, has a larger footprint, i.e. larger sum down its column in (7), compared to other sectors in an economy

(c) A point in a sector's downstream or upstream supply chain, an element within (7) that embodies emissions above a set threshold level in serving all or particular type(s) of final consumption demand.

Table 1 is a simple illustrative example for two regions, A and B, with 3 industrial sectors in each. Examining the data of Table 1 will aid in understanding the methodology used to identify 'hot-spots'.

Table 1: Example of 'hot-spot' detection

		Region A			Region B			
		Sector 1	Sector 2	Sector 3	Sector 1	Sector 2	Sector 3	Total Direct Emissions
Region A	Sector 1	28	1	5	4	11	4	53
	Sector 2	3	16	2	3	27	2	53
	Sector 3	8	19	32	1	3	0	63
Region B	Sector 1	10	36	0	50	28	4	128
	Sector 2	5	10	12	2	21	9	59
	Sector 3	9	11	3	1	5	10	39
	Total Emissions (footprint)	63	93	54	61	95	29	

Row maximum
28
27
32
50
21
11

To identify Type (a) 'hot-spots' all that is required is to sum the elements along the row of each sector to calculate the total direct emissions generated by each sector. In Table 1 the sector with the largest volume of direct emissions is Sector 1 of Region B, which can be identified as a Type (a) 'hot-spot'.

Similarly, to identify Type (b) 'hot-spots' it is necessary to sum the elements down the column of each sector, calculating the emissions generated throughout the upstream global supply chain to meet each sector's final demand, i.e. the CO_2 footprint of each sector's production to meet final consumption demand. It can be seen in Table 1 that the sector with the largest footprint is Sector 2 of Region B, however Sector 2 of Region A has a similar footprint. Therefore, both sectors can be identified as Type (b) 'hot-spots'.

To identify the last type of 'hot-spots' it is necessary to define a threshold of emissions. As an illustrative example of a 'hot-spot' threshold, we may identify Type (c) 'hot-spots' by first identifying the row maximums for each row in (7). Then, if we take the average of row maximums, every element of (7) above this average may considered a Type (c) 'hot-spot'. Using averages as a criterion to identify important cells in IO data is not an uncommon approach as it was used for instance by Okamoto (2005) on the 2000 China Multi- Regional IO data (CMRIO) to distinguish the important transactions. In Table 1 such points are the production of Region A Sectors 1 and 3 and Region B Sector 1 for their own final demand, the production of Region B Sector 1 required by Region A Sector 2 and Region B Sector 2, as well as the output of Sector 2 in Region A required by Sector 2 in Region B. As can be seen in Table 1, Type (c) 'hot-spots' either have the major share of a sector's direct emissions or contribute the majority of emissions to a sector's footprint.

In practice, there may be some more specific and policy-motivated means of specifying thresholds (in the context of emissions targets etc.). For example, 'hot-spot' thresholds can be set in accordance with environmental research outcomes and/or derived from the goals set for each country under international climate change agreements. Under the recent multinational agreements like the UNFCCC agreements and the Europe 2020 strategy, participating nations are required to reduce their greenhouse gas emissions by a set percentage (different for each party) compared to 1990, which is set as a baseline year. Using the CO_2 emissions inventory for 1990, adjusted for the goal of each country that we are interested in, it is possible to calculate the average embodied emissions in each of the transactions within this country. Setting that as the threshold level on the latest IO data would then identify the intersectoral transactions that require policy attention in order to meet the set goals. Unfortunately, not every country faces the same challenges, participates and ratifies the international agreements or has the same agenda in terms of the relationship between economic expansion and environmental protection. Under those constraints, the flexibility of this method in determining the 'hot-spot' threshold level is useful. For the purposes of this paper the threshold is assumed to be the same across every country, however, it is possible to assign a different threshold for each country. In this way, the 'hot-spots' identified are examined under the prism of the obligations of the country where they are located, hence facilitating multilateral co-operation.

However, the core objective of deriving the method here is to help understand the structure of emissions serving all or particular types/locations of final demand. Focusing on aggregate figures for CAP and/or PAP deprives us from important information on where the majority of emissions to support any given component of county level or total global consumption demand are located and to consider this in the context of understanding domestic and global supply chain relationships. For instance, in Table 1, most of the emissions in the upstream supply chain of Sector 2 in Region 2 are located in the two Type (c) 'hot-spots'. However, to have an even fuller understanding of the emissions it is necessary to apply the 'hot-spot' methodology on the Emissions multipliers matrix (6). Assuming everything else remains constant, identifying 'hot-spots' on (6) - i.e. based on the direct and indirect emissions intensity per average unit of output required at a particular point in an industry's supply chain - enables to locate potential 'hot-spots' in absolute numbers in the event that associated final demand increases (though it is important to note that this involves assuming that average multiplier relationships given by the accounting framework for particular point in time will apply in terms of marginal impacts). Furthermore, studying the underlying multipliers of the 'hot-spots' identified in CO_2 emissions matrix (7), allows for a distinction between those 'hot-spots' that were mainly driven by the multipliers (intensity) and those that the main driver is scale of economic activity.

3.4 Data

For this study the IRIO account used is the pilot OECD Inter-Country Input-Output Database focusing on the most recent data of 2009. The database consists of:

- 57 countries, both OECD and non-OECD members, plus the Rest of the World (see Appendix A for a full list of countries);
- Industrial sectors have been grouped into 37 sectors following ISIC v3.1 (see Appendix B for complete list of sector grouping).

Apart from the intermediate goods/inputs the database also includes:

- Taxes less subsidies on products
- Cost, insurance and freight price/free on board price adjustments on exports
- Direct purchases abroad by residents (imports to final consumption)
- Purchases on the domestic territory by non-residents
- Value-added at basic prices
- International transport margins.

Final demand is aggregated into five categories:

- Private (Household) Consumption
- Non-Profit Institutions Serving Households
- Government Final Consumption
- Gross Fixed Capital Formation
- Inventory (changes in stocks).

A key point is that this dataset meets the requirements described by Turner et al (2007) as necessary for a global Inter Regional Input Output (IRIO) table that can be used for multiplier-based CAP and PAP analyses. The database includes direct imports of final goods as well as detailed data on the import of intermediate goods. The data have been harmonised in terms of making consistent data from a range of different sources (in particular, building up interregional elements from data on bi-lateral trade flows) and follow the same classification throughout the dataset. The final result is an IRIO table that demonstrates all the transactions between the countries included in IO format. However, since the database is at a pilot stage, it is constantly evolving. This means that there could be inaccuracies, which as the project develops are being reduced in an effort to create a more solid dataset. Nonetheless, the OECD database is preferred in this study over other widely used datasets e.g. WIOD. The most significant advantage of the OECD database is the greater degree of sectoral detail, 37 sectors instead of 35, which according to Wyckoff and Roop (1994) enhances the accuracy of the final results.

Moving forward, to create the 'satellite' emissions account it was necessary to explore the emissions directly associated with industrial outputs in the IO table. The account that was built for the purposes of this paper includes the emissions generated by fuel combustion either during production or by auto-producing heat and electricity, fugitive gases during coal and oil extraction and emissions by industrial processes. Appendix C provides details on how the account was created. The data sources used are IEA fuel combustion data and UNFCCC. The creation of an emissions account was necessary as the number of countries included is larger than any existing dataset and in addition a wider variety of pollution origins has been included to increase accuracy.

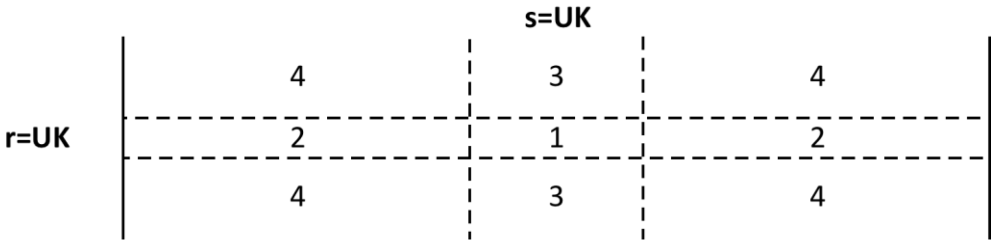
4. Results

4.1 General overview

Examining the data when we calculate (7) using $(3a)$ for total final consumption demand across all countries reveals some rather interesting findings. Over 85% of the total emissions are located on the main diagonal of sub-matrices of the CO_2 emissions matrix (7), where $r = s$. This means that 85% of the total global emissions are generated by industries producing to meet their own final demand, or in supporting production to meet final demand in industries operating within the same country (although that final demand may in some cases be largely located outside the country). This is true for developed and developing countries alike. In major OECD economies of Germany, UK and USA the respective percentages are 79.4%, 85.9% and 92.4%, whereas in the developing economies of China (excluding Hong Kong which is reported as a separate country) and India the figures stand at 89.5% and 88.8% respectively. If the focus of study is the impact of economic activities within a single country, then IRIO is not necessary as SRIO can provide the necessary information and often with an increased level of detail. The benefit of using an IRIO is that it allows the study of the off-diagonal sub-matrices of the CO_2 emissions matrix (7). It provides us with the opportunity to identify 'hot-spots' located on the international part of any sector's downstream and upstream supply chains, even if the overall impact of these may be small relative to own-country effects on the diagonal of $r = s$ sub-matrices in (7). It also allows us to capture any inter-regional feedback effects, where production sectors in region r export to intermediate sectors in region s with outputs of the latter then imported back to the production sectors in the first region.

To demonstrate the ability to study the off-diagonal sub-matrices of (7), here we focus on the UK as a case study. To calculate the CO_2 emissions matrix (7), the diagonal matrix of final demand $(3c)$ was used for $s =$UK. This means that $(3c)$ shows the output of every sector in every country required by all UK final consumers (i.e. all individual types z=1,…, Z across UK households, government, capital formation etc.; or all five groups listed in Section 3.4). Therefore, in this case (7) shows the emissions generated globally but ultimately driven by UK total final demand. Data show that UK total domestic final demand was the driver of just over 1,167 Mt of CO_2 in the accounting year of 2009, i.e. the sum of all elements in (7). This equates to a UK carbon footprint in terms of global industrial emissions (i.e. excluding direct emissions by UK consumers) of 1,167 Mt of CO_2, which compares to UK industrial PAP emissions (i.e. the sum of the rows of (7) for $r =$UK, when calculated using $(3a)$) of 913.92 Mt of CO_2. The following chart is a rough representation of the interpretation of different elements of (7), under the assumption that the focus is still UK's total final demand (see Appendix A for list of countries where the UK – abbreviated by OECD to GBR although representing whole of UK - appears around half way down the list so that we represent in a corresponding position in Chart 1).

Chart 1: The different 'areas' of the Cem matrix (7)



Of the 1,167 Mt total amount of emissions in (7) for UK final consumption, 714 Mt of CO_2 or 61% was directly generated by UK production sectors, i.e. rows totals of (7) where r =UK, areas 1 and 2 in Chart 1. This includes 1.89 Mt of CO_2 emissions embodied in exported intermediate goods produced by UK sectors, which in terms of elements of (7), these are the elements located on the rows where r =UK but s ≠UK, i.e. the areas labeled 2 on Chart 1. These are emissions generated in the UK to support the production of goods and services in sectors outside the UK that are imported by UK final consumers. Data show then that the majority of direct emissions by UK sectors, 712.15 Mt of CO_2, were generated to support the final demand of UK sectors, i.e. $r = s$ =UK in (7) or area 1 on Chart 1.

Areas 3 and 1 in Chart 1 are where s =UK and represent the footprint of UK sectors serving UK final demand. The footprint of UK sectors is 838.31 Mt of CO_2. As shown above 79.3% of these emissions are generated by UK sectors, i.e. area 1 in Chart 1 where $r = s$ =UK. The remaining 20.7% of emissions (186.15 Mt of CO_2) are generated by non-UK sectors to support the UK total final demand of UK sectors. These sectors are located in areas labelled 3 in Chart 1 and they are the elements of (7) with r ≠UK and s =UK. Finally the sectors in areas 4 of Chart 1 represent emissions by non-UK sectors that produce output to support the UK total final (direct import) demand for output from non-UK sectors, i.e. sectors with r, s ≠UK in (7). The total emissions of these sectors are 266.99 Mt of CO_2, which is a 22.9% share of the total emissions driven globally by UK total final demand.

The first points of focus in this section are the sectors outside areas 1 and 2 in Chart 1 – i.e. non-UK emissions required by UK final demand. By examining the sum or each sector's row we identify the Type (a) 'hot-spots' located outside the UK. Analysis of results for (7) shows that China's 'Electricity, Gas and Water Supply' (i.e. where $r =$China and $i =$'Electricity, Gas and Water Supply') is the largest Type (a) 'hot-spot' outside the UK in terms of emissions driven by UK total final demand. Focusing then on this specific sector we are moving forward by investigating Type (c) 'hot-spots' on China's 'Electricity, Gas and Water Supply' international downstream supply chain, i.e. the elements of (7) located where $r =$China, $i =$ 'Electricity, Gas and Water Supply' and $s \neq$China. The reason for this focus is that an analysis of the Chinese 'Electricity, Gas and Water Supply' domestic downstream supply chain, i.e. where $s =$China, can also be conducted using a SRIO.

Furthermore, analysing the elements of (7) we can rank the different sectors in different locations in terms of the composition of the footprint of serving UK final consumption demand – i.e. the sum of each sector's column in (7) - regardless whether they are located within the UK ($s =$UK) or outside the UK ($s \neq$UK). Analysis of the results of (7) shows that the largest Type (b) 'hot-spots' driven by UK total final demand are UK-based sectors. Amongst them, global emissions to support UK final demand for the UK's 'Health and Social Work' is the second largest Type (b) 'hot-spot' behind UK's 'Electricity, Gas and Water Supply'. UK's 'Health and Social Work' is a rather interesting case though, due to the number of Type (c) 'hot-spots' on its international upstream supply chain, i.e. elements of (7) where $s =$UK and $j =$ 'Health and Social Work' but $r \neq UK$. Therefore, we focus our investigation for Type (c) 'hot-spots' on UK's 'Health and Social Work' international upstream supply chain.

As shown above, emissions generated by UK production sectors are the major contributors to UK sectors' footprint driven by UK total final demand. However, there are UK sectors where each monetary unit worth of final demand has a larger impact on the non-UK side of their upstream supply chain. That means that the sum of the elements down the sector's column in (7) and the underlying emissions multiplier matrix (6) are larger on the non-UK rows rather than the rows of UK sectors. Such examples are UK's 'Motor Vehicles, Trailers and Semi-trailers' and 'Office, Accounting and Computing Machinery'.

In general, it is important to note (particularly in terms of useful policy analysis tools that could be extracted from the IRIO framework) the total footprint of serving UK final consumption demand for each sector j in each region s could also be calculated by multiplying that sector's Type I emissions multiplier (column total from equation (6)) with the sector's total UK final demand. Sub-totals for elements of the multiplier located in different countries could be used similarly. This builds on the familiar use of multiplier values to assess particular types of impact in particular areas whenever there is a change in economic activity. However, using the adopted methodology of this paper, post-multiplying $(3c)$ to (6), enables us to study and analyse the structure of the footprint in detail. In practice, what this approach essentially involves is multiplying the total final demand in question (with our focus here on the total of UK final demand across all five types identified in Section 3.4) for each production sector in each region with every element down the sector's emissions multiplier column in (6). However, we do present examples of results, for example in Table 2 below, where users of the research output can conduct simpler multiplier calculations.

4.2 Type (a) and downstream Type (c) 'hot-spots' outside the UK driven by UK total final demand

As already discussed in the previous sub-section, the first focus point of this study is to locate Type (a) 'hot-spots' outside the UK. In total the non-UK sectors generate 455.04 Mt of CO_2 (row totals of (7) excluding r =UK). Table 2 shows the 'Top 10' sectors in terms of direct emissions associated with UK total final demand that are located outside the UK.

In Table 2 the 'Direct Emissions' column (first column of results) refers to the sum of the elements along each sector's row in (7), while the next column shows these emissions as a percentage share of the total emissions generated driven by UK total final demand. The third column indicates the share of the sector's total direct emissions (full PAP) that are the UK-driven entries in the first column. The 'CO2 Intensity' and 'UK Total Final Demand' columns refer respectively to the sector's elements on E matrix (5) - i.e. the direct CO_2 intensity e_i^r of each sector - and on final demand matrix $(3c)$ respectively, i.e. the final demand from UK element for y_j^{rs} of each sector. Please note that the CO_2 intensity is in Mt/\$m of output. The unit used might make the figures of that column seem rather small, however, they represent significant volumes of emissions that should not be neglected. The final column refers to the monetary value of the output of each sector that is ultimately supported/driven by UK total final demand. This is the sum of each sector's row in (4) when calculated using $(3c)$. If we multiply this against the direct CO_2 intensity of the sector, we have another means of generating the result in the first column (but one that is embedded in calculation of (7), that is considering the supported output multiplier effect rather than moving straight to the emissions multiplier). The difference between the figures of columns 5 and 6 in Table 2 indicates whether each sector mainly produces final goods for UK final consumers or intermediate goods to support other sectors' UK total final demand.

As reported in the discussion in the previous section (and also reported at the bottom of Table 2) the total direct (PAP) emissions generated globally driven by UK's total final demand are 1,167.2 Mt of CO_2. Of these emissions 453.2 Mt of CO_2 are generated outside the UK, i.e. 38.8% of the total direct emissions driven by UK total final demand. The sectors listed in Table 2 account for 37% of the emissions driven by UK total final demand and generated outside the UK. The vast majority of the sectors listed on Table 2 – most notably 'Electricity, Gas and Water Supply' in different countries - have minimal amounts of UK total final demand compared to their output associated with UK total final demand. This implies that the output of the $i =$ 'Electricity, Gas and Water Supply' (hereafter

EGWS) sectors in the countries shown on Table 2 is used as input by other sectors in these countries (assuming a low level of trade in EGWS itself, though gas exports may be important) that either export final goods to the UK, or produce outputs to intermediate demands entering supply chains that ultimately (but indirectly) serve UK final demand. That is, there may be many rounds of multiplier effects involved. This is what our Type (c) 'hot-spots' allow us to consider.

Table 2: Top 10 Direct emitters driven by UK Total Final Demand outside the UK

Rank	Country	OECD Sector Code	Sector	Direct Emissions (Mt of CO2)	% share of Total Direct Emissions (UK Total Final Demand)	% share of sector's Direct Emissions (Total Final Demand)	CO2 Intensity (Mt CO2/$m output)	UK Total Final Demand ($m)	Total Output for UK Final Demand ($m)
1	China	C40T41	Electricity, Gas and Water Supply	51.50	4.41%	0.76%	0.0143	7.16	3,598.53
2	USA	C60T63	Transport and Storage	29.11	2.49%	1.53%	0.0030	4,086.64	9,792.30
3	China	C27	Basic Metals	19.74	1.69%	0.86%	0.0022	0.07	8,823.19
4	Russia	C40T41	Electricity, Gas and Water Supply	13.30	1.14%	1.13%	0.0106	40.05	1,258.99
5	Russia	C27	Basic Metals	10.64	0.91%	2.78%	0.0045	0.97	2,355.74
6	USA	C40T41	Electricity, Gas and Water Supply	10.34	0.89%	0.23%	0.0136	12.80	759.60
7	Germany	C40T41	Electricity, Gas and Water Supply	8.73	0.75%	1.45%	0.0032	67.05	2,722.22
8	India	C40T41	Electricity, Gas and Water Supply	8.58	0.73%	0.56%	0.0260	0.01	329.53
9	China	C24	Chemicals and Chemical Products	8.57	0.73%	1.18%	0.0010	956.85	8,971.83
10	South Afric	C40T41	Electricity, Gas and Water Supply	7.14	0.61%	1.65%	0.0416	35.17	171.85
			All UK Sectors	714.04	61.18%				
			All other non-UK Sectors	285.50	24.46%				
			Total Direct Emissions driven by UK Total Final Demand	1,167.20	100.00%				

Before we turn our attention to downstream Type (c) 'hot-spots', let us consider the importance of direct CO_2 intensities. Of the ten sectors in Table 2 the ones that directly generate the most significant amount of CO_2 emissions, i.e. sum of sector's row in CO_2 emissions matrix (7), are the Chinese EGWS, the USA's 'Transport and Storage', the Chinese 'Basic Metals' and the Russian EGWS. They have the most significant shares of the total direct emissions driven by UK total final demand and can therefore be considered as Type (a) 'hot-spots' in the global supply chain serving UK consumption. The largest Type (a) 'hot-spot' of Table 2 is China's EGWS sector. Figures in Table 2 show that the main driver of the emissions generated by the sector is the CO_2 emissions intensity. China's EGWS CO_2 emissions intensity is the 24th highest amongst all 2146 sectors (with 37 industries in 58 regions/countries including ROW) included in the OECD ICIO framework used. Even though the sector's output associated with UK total final demand (the figure on the 'Total Output for UK Final Demand' column on Table 2) is ranked only 100th amongst all 2146 sectors included in the framework, still, due to the relatively high emissions intensity, the direct emissions of China's EGWS driven by UK total final demand are the largest outside the UK. In fact, the Chinese EGWS sector is ranked 4th in direct emissions driven by UK total final demand amongst all 2146 sectors. However, the results reported in Table 2 suggest that it is rather common for EGWS sectors to be relatively CO_2 intensive. In fact, the only exception is the German EGWS sector, which in 2009 had a mixture of production technologies that allowed for a rather low CO_2 emissions intensity, lower than the other relevant sectors of Table 2. The reason why Chinese EGWS tops Table 2 is that at the same time it has the second largest direct emissions intensity and the largest output associated with UK total final demand amongst all the EGWS sector of Table 2.

Focusing on the top direct emitter of Table 2, Chinese EGWS, the significant difference between the sector's UK total final demand and the output produced due to UK total final demand indicates that the majority of the sector's direct emissions is distributed along the sector's downstream supply chain. Quite possibly then, there could be important Type (c) 'hot-spots' on China's EGWS downstream supply chain. Here, for an element of the CO_2 emissions matrix (7) to be considered as a Type (c) 'hot-spot', when UK total final demand is used, we take a simple threshold level as the average of row maximums, which works out at 0.29 Mt of CO_2. Table 3 shows the Type (c) 'hot-spots' on China's 'Electricity, Gas and Water Supply' downstream supply chain to support UK final consumption that are located outside the Chinese borders, i.e. $r =$China, $i =$ 'Electricity, Gas and Water Supply' and $s \neq$China. These 'hot-spots' are elements of (7) that were summed to calculate the China's EGWS direct emissions presented in Table 2. Apart from excluding the 'hot-spots' located in the domestic downstream supply chain of the Chinese EGWS, there are no other restrictions as to where the 'hot-spots' might be located. Therefore, the Type (c) 'hot-spots' presented in Table 3 are in fact the only ones in the international part of China's EGWS downstream supply chain.

Table 3: 'Hot-spots' on China's 'Electricity, Gas and Water Supply' downstream supply chain outside China

Country	OECD Sector Code	Sector	Embodied Emissions (Mt of CO2)	% share of China's'Electricity, Gas and Water Supply' Total Direct Emissions	Emissions Multiplier (Mt of CO2/$m of FD)	Total UK Final Demand ($m)
United Kingdom	C85	Health and Social Work	2.63	5.10%	0.000009	278,391
	C45	Construction	1.98	3.85%	0.000011	182,564
	C75	Public Admin. and Defence; Compulsory Social Security	1.63	3.16%	0.000009	176,865
	C50t52	Wholesale and Retail Trade; Repairs	1.06	2.05%	0.000004	245,224
	C34	Motor Vehicles, Trailers and Semi-trailers	0.68	1.33%	0.000030	23,208
	C55	Hotels and Restaurants	0.50	0.96%	0.000004	116,762
	C90t93	Other Community, Social and Personal Services	0.48	0.92%	0.000004	112,778
	C70	Real Estate Activities	0.40	0.78%	0.000002	200,776
	C64	Post and Telecommunications	0.39	0.75%	0.000011	34,589
	C27	Basic Metals	0.38	0.74%	0.000034	11,376
	C65t67	Finance and Insurance	0.38	0.73%	0.000003	136,449
	C80	Education	0.35	0.68%	0.000003	123,696
	C29	Machinery and Equipment n.e.c	0.32	0.63%	0.000029	11,299
	C15t16	Food Products, Beverages and Tobacco	0.32	0.62%	0.000009	35,177
		All others	40.01	77.69%		
		Total Direct Emissions	51.50	100.00%		

The first results column in Table 3 shows the element of the respective sector on the row of Chinese EGWS in (7), which corresponds to a specific point in Chinese EGWS downstream supply chain, while the second column shows these elements as a percentage share of the total direct emissions of China's 'Electricity, Gas and Water Supply'. The third column is the element of each sector listed in Table 3 on the row of Chinese EGWS in (6) whereas the fourth column shows the y_j^{rs} in final demand matrix $(3c)$ for each of the sectors listed in Table 3, i.e. the UK final demand for each of the sectors in Table 3.

Interestingly enough, all the Type (c) 'hot-spots' on the Chinese EGWS sector row of (7) that are associated with UK total final demand and located outside China, are found within the UK. In total, they have just over a 22% share of the total Chinese EGWS emissions that are attributable to UK final consumption. It can be seen that the top 4 Type (c) 'hot-spots' of Table 3 have a more significant share (14.16%) of Chinese EGWS direct emissions, compared to the other Type (c) 'hot-spots' of Table 3. Examining the figures of Table 3 reveals that the emissions embodied in the top 4 Type (c) 'hot-spots' are driven by the volume of consuming sector's total UK final demand rather than their emissions multipliers, which are well below the emissions multipliers of other sectors in Table 3. This is not surprising given that UK total final demand is mainly served by UK sectors (i.e. 87.8% of UK total final demand is expenditure in UK sectors). In fact, the top 4 sectors of Table 3, UK's 'Health and Social Work', 'Construction', 'Public Admin and Defence; Compulsory Social Security' and 'Wholesale and Retail Trade; Repairs'; are also within the top 5 sectors in terms of total UK final demand, the other one being UK's 'Real Estate Activities'.

3.4.3 Type (b) and upstream Type (c) 'hot-spots' driven by UK total final demand

As seen in a previous sub-section, UK total final demand is primarily met by the output of UK sectors. This being the case, one could argue that when looking for the sectors with the largest CO_2 footprint driven by UK total final demand, the majority of them will also be UK-based. Table 4 shows the top 10 sectors in terms of footprint, i.e. sum of each sector's column in (7), driven by UK total final demand.

Table 4: Top 10 sectors in terms of footprint driven by UK Total Final Demand

Rank	Country	OECD Sector Code	Sector	Total Emissions (Footprint) (Mt of CO2)	% share of Total Footprint (UK Total Final Demand)	% share of sector's Footprint (Total Final Demand)	Type I Emissions Multiplier (Mt of CO2/$m of Final Demand)	Sector's Total UK Final Demand ($m)
1	United Kingdom	C40t41	Electricity,Gas and Water Supply	230.36	19.74%	99.63%	0.0040	57,660.64
2		C85	Health and Social Work	95.09	8.15%	99.89%	0.0003	278,390.77
3		C50t52	Wholesale and Retail Trade; Repairs	88.14	7.55%	99.50%	0.0004	245,223.65
4		C45	Construction	53.31	4.57%	99.35%	0.0003	182,564.40
5		C60t63	Transport and Storage	52.01	4.46%	80.60%	0.0011	46,492.67
6		C75	Public Admin. and Defence; Compulsory Social Security	47.56	4.07%	99.25%	0.0003	176,864.64
7		C55	Hotels and Restaurants	42.11	3.61%	94.70%	0.0004	116,762.31
8		C90t93	Other Community, Social and Personal Services	28.49	2.44%	95.17%	0.0003	112,777.75
9		C65t67	Finance and Insurance	25.23	2.16%	84.84%	0.0002	136,449.48
10		C80	Education	20.03	1.72%	98.60%	0.0002	123,696.10
			All others	484.87	41.54%			
			Total Footprint	1,167.20	100.00%			

In Table 4 the first column is the sum of the elements down each sector's column in (7). The second column is the share of each sector's footprint of the total global emissions driven by UK total final demand. The third column shows the footprint of each sector driven by UK total final demand as a percentage share of the sector's footprint driven by global total final demand. Column 4 is the sum of the emissions multiplier elements down each sector's column in (6) and finally column 5 shows the y_j^{rs} in $(3c)$ for each of the listed sectors, i.e. each sector's UK final demand.

As expected, the top 10 sectors with the largest footprint driven by UK total final demand are all UK based. The non-UK sector with the largest footprint driven by UK total final demand is the Chinese 'Textile, Textile Products, Leather and Footwear', which is ranked 12th amongst all the sectors in terms of footprint driven by UK total final demand and thus not included in Table 4. Examining the sectors of Table 4 there is a common trend across the majority of them. The footprint of these sectors, driven by UK total final demand, has over a 90% share of the sectors' footprint driven by global total final demand (i.e. the column total of (7) calculated using $(3c)$ as a share of that calculated using $(3a)$). Given that the Type I emissions multiplier is constant regardless of the location of the final consumer, these figures show that the final demand requirement of the sectors in Table 4 largely originates within the UK itself.

Of all the sectors listed in Table 4, UK's 'Electricity, Gas and Water Supply' has by far the largest footprint in serving UK final consumption (and generally if we use $(3a)$ to calculate (7)). This is mainly driven by the sector's Type I emissions multiplier (i.e. the sum of the sector's column in (6)) which is the largest amongst the sectors of Table 4. On the other hand, it can be seen that there are UK sectors like 'Health and Social Work' and 'Wholesale and Retail Trade; Repairs' where the magnitude of the footprint is driven by the volume of their total UK final demand rather than the (direct plus indirect) CO_2 intensity given by the emissions multiplier. More generally, for the majority of the sectors on Table 4 the main driving factor is indeed the value of their total UK final demand rather than their Type I emissions multiplier. The policy implications of this information are that for the majority of the sectors in Table 4 it would be preferable to explore environmental policies that are associated with consumer behaviour instead of trying to de-carbonise their upstream supply chains. For example, educating the general population in making more efficient use of the services of the 'Wholesale and Retail Trade; Repairs' sector could lead in reduction of the sector's final demand. The emissions related consequence of this reduction would be reduced embodied emissions in the sector's upstream supply chain. However, the findings of this 'hot-spot' analysis do not provide an overview of all the potential impacts that would come as a result of policies introduced in the sectors of Table 4 (or any other sectors). Further analysis would be necessary to pick those sectors that any decrease in final demand, in order reduce their footprint, would have the least impact possible in value-added lost and increased unemployment.

Just as we considered Type (c) downstream 'hot-spots' linked to Type (a) PAP 'hot-spots' in the previous section, it is worth investigating the upstream supply chains of the top sectors of Table 4 to see whether there are any interesting and/or important Type (c) 'hot-spots'. This involves considering column entries of (6) and (7) for the sectors identified in Table 4. First, for the UK EGWS sector the major contributor to the sector's footprint is its own-sector emissions to meet its own total UK final demand, which embodies 219 Mt of CO_2, i.e. almost all of the emissions of the Type (b) 'hot-spot'. However, it is worth noting the level of aggregation involved in the OECD EGWS sector. Water supply tends to be electricity intensive while electricity production can be gas-intensive. Therefore, there are likely to be important inter-sectoral effects hidden in the own-sector ($i = j, r = s$) EGWS results throughout our results for both the multiplier effects in (6) and total supported emissions in (7). This is an issue that has been identified by numerous studies (e.g. Ara, 1959; Miller and Blair, 1981; de Mesnard and Dietzenbacher, 1995; Hawdon and Pearson, 1995; Lahr and Stevens, 2002) but is outside the scope of this paper to study the potential errors generated due to the over-aggregation of sectors in IRIO tables. In general, though, a single region analysis based on more sectorally disaggregated published regional or national accounts would tend to separately identify what tend to be relatively energy- and emissions-intensive utilities sectors.

On the other hand, the second largest sector of Table 4, UK's 'Health and Social Work', has a more interesting upstream supply chain as it includes several Type (c) 'hot-spots' located outside the UK territory. Table 5 shows the Type (c) 'hot-spots' in UK's 'Health and Social Work' that are driven by UK total final demand and located outside the UK. These are elements of (7) with $s =$UK, $j =$ 'Health and Social Work' and $r \neq$UK. As a reminder, our illustrative threshold level for a Type (c) 'hot-spot' is 0.29 Mt of CO_2 and all the entries in Table 5 are above this level.

Table 5: 'hot-spots' on UK's Health and Social Work upstream supply chain outside UK

Country	OECD Sector Code	Producing Sector	Embodied Emissions (Mt of CO2)	% share of UK's Health and Social Work Footprint	Output Multiplier ($m of Output/$m of FD)	CO2 Intensity (Mt of CO2/$m of Output)
China	C40t41	Electricity, Gas and Water Supply	2.63	2.76%	0.00066	0.0143
USA	C60t63	Transport and Storage	1.83	1.93%	0.00221	0.0030
USA	C24	Chemicals and Chemical Products	1.35	1.42%	0.00804	0.0006
Russia	C40t41	Electricity, Gas and Water Supply	1.27	1.33%	0.00043	0.0106
USA	C40t41	Electricity, Gas and Water Supply	1.23	1.29%	0.00032	0.0136
Netherlands	C24	Chemicals and Chemical Products	1.15	1.21%	0.00787	0.0005
Russia	C24	Chemicals and Chemical Products	1.11	1.17%	0.00047	0.0086
China	C27	Basic Metals	1.05	1.10%	0.00168	0.0022
Germany	C24	Chemicals and Chemical Products	0.87	0.91%	0.00898	0.0003
Germany	C40t41	Electricity, Gas and Water Supply	0.84	0.89%	0.00095	0.0032
India	C40t41	Electricity, Gas and Water Supply	0.70	0.74%	0.00010	0.0260
Russia	C27	Basic Metals	0.66	0.70%	0.00053	0.0045
China	C24	Chemicals and Chemical Products	0.56	0.58%	0.00209	0.0010
Canada	C24	Chemicals and Chemical Products	0.52	0.55%	0.00169	0.0011
USA	C23	Coke, Refined Petroleum Products and Nuclear Fuel	0.51	0.53%	0.00140	0.0013
Netherlands	C23	Coke, Refined Petroleum Products and Nuclear Fuel	0.45	0.47%	0.00134	0.0012
Germany	C23	Coke, Refined Petroleum Products and Nuclear Fuel	0.42	0.44%	0.00111	0.0013
Russia	C23	Coke, Refined Petroleum Products and Nuclear Fuel	0.40	0.42%	0.00074	0.0019
Saudi Arabia	C23	Coke, Refined Petroleum Products and Nuclear Fuel	0.40	0.42%	0.00032	0.0045
France	C24	Chemicals and Chemical Products	0.39	0.41%	0.00349	0.0004
Spain	C60t63	Transport and Storage	0.39	0.41%	0.00173	0.0008
China	C23	Coke, Refined Petroleum Products and Nuclear Fuel	0.38	0.40%	0.00053	0.0026
Germany	C60t63	Transport and Storage	0.38	0.40%	0.00251	0.0005
Netherlands	C40t41	Electricity, Gas and Water Supply	0.33	0.34%	0.00056	0.0021
Canada	C40t41	Electricity, Gas and Water Supply	0.32	0.34%	0.00016	0.0073
		All Others	74.97	78.84%		
		Total Footprint of UK's Health and Social Work driven by UK total final demand	95.09	100.00%		

The first column of Table 5 includes the element of each sector in Table 5 on the CO_2 emissions matrix (7) - i.e. column entries for $j =$ 'Health and Social Work' and $s =$UK when (7) is calculated using $(3c)$ - while column 2 presents them as a percentage share of UK's 'Health and Social Work' footprint in serving UK final consumption demand. Column 3 includes each sector's element on the Leontief inverse $(2b)$ while column 4 shows the e_i^r of E matrix (5) for each of the producing sectors in Table 5. The elements of $(2b)$ and (5) are presented separately and not as elements of (6). The benefit of using this approach is that we can distinguish whether the receiving sector, in this case UK's 'Health and Social Work', requires large volume of output from any one producing sector or whether it is the producing sector's emissions intensity that drives the emissions of that Type (c) 'hot-spot'. Please note that Table 5 presents the Type (c) 'hot-spots' in a different way compared to Table 3. The reason is to demonstrate the different analysis options when using an IRIO.

As can be seen from Table 5, a rather large number of Type (c) 'hot-spots' can be found on UK's 'Health and Social Work' upstream supply chain that are located outside the UK and driven by UK total final demand. Their total contribution to the sector's footprint is just over 21%[5]. Analysing the UK's 'Health and Social Work' Type I emissions multiplier it can be seen that each monetary unit of final demand has a more significant impact within the UK. 61% of the emissions embodied in the sector's footprint are generated by UK based industries and 39% abroad. The results in Table 5 encompass most of this 39%.

The results in Table 5 imply that the UK's Health and Social Work has some rather specific upstream international supply chain requirements, which will involve both direct imports and multiplier

[5] For most of UK sectors the majority of emissions generated to support their final demand are located within the UK. However, there are three sectors, 'Motor Vehicles, Trailers and Semi-trailers', 'Office, Accounting and Computing Machinery' and 'Machinery and Equipment n.e.c.' that the main body of the emissions generated to support their final demand is located outside the UK. For each of the aforementioned UK sectors the contribution to the Type I emissions multiplier from abroad is 60%, 57% and 53%. Still due to the relatively small volume of total UK final demand their footprint is rather small compared to other sectors and thus not featured in Table 5. However, assuming that everything else remains constant, an increase in the total UK final demand of UK's sectors C34, C30 and C29 would lead to a significant increase in the size of their footprint, the majority share of which would be outside UK borders.

impacts of other intermediate input (domestic and imported) requirements. Although located in several different trading partners of the UK, the CO_2-emitting outputs required come from 'Chemicals and Chemical Products', 'Coke, Refined Petroleum Products and Nuclear Fuel', 'Electricity, Gas and Water Supply', 'Transport and Storage' and 'Basic Metals' sectors in various countries around the world. The appearance of these sectors in our 'hot-spot' analysis may be expected given that their activities include the production of pharmaceuticals, diesel, gas and precious metals as well as their transportation. These are all products that are necessary for 'Health and Social Work' activity. However, they may not be the obvious focus of attention in considering how to address the carbon footprint of this type of sector.

Table 5 suggests that 'Health and Social Work' (hereafter HSW) mainly depends (directly or indirectly) on production of output in the global 'Chemicals and Chemical Products' industries (hereafter CCP). HSW sectors of the different countries in the OECD database tend to have highest output multiplier values located in CPP sectors – i.e. elements for $i =$CCP and $j =$HSW in the interregional Leontief inverse in equation (2). At the same time the direct CO_2 emissions intensity of CCP does not vary greatly from country to country. Therefore, the differences in the embodied emissions associated with CCP production in the respective Type (c) 'hot-spots' are largely associated with the output multiplier relationship with UK HSW. One exception is the requirements from German CCP. As can be seen in the third column of Table 5 the output multiplier of German CCP is larger than the output multiplier of the CCP sector in the USA. This implies that UK HSW requires larger volumes of German CCP output to support its domestic final demand. However, the USA CCP CO_2 intensity is twice as large as the one of the German CCP (data in column 4 of Table 5). As a result, the Type (c) 'hot-spot' where the producing sector is USA CCP has more embodied emissions than the one where the producing sector is German CCP.

On the other hand, there can be seen significant variations in underlying determinants that are not limited to the output multiplier effect when it comes to EGWS 'hot-spots' in the UK HSW supply chain. For instance, the third column of results in Table 5 shows that the Chinese EGWS 'hot-spot' (the largest in the table) is driven largely by this sector being more (directly) emissions intensive than any other sector in Table 5, rather than the level of output requirements. This is further illustrated by the fact that even though the UK HSW sector has somewhat similar output requirements for EGWS from China and The Netherlands (0.00066 $m per unit of output to meet final demand relative to 0.00056 in the third column), still the difference in direct emissions intensity (0.0143 Mt per $1m output relative to 0.0021) puts the Chinese Type (c) EGWS 'hot-spot' at the top of Table 5 whereas the Dutch one is second to last.

From a policy perspective, the knowledge of the structure of embodied emissions of any given sector could provide policy makers with important information to inform additional options for targeted policies in reducing the carbon footprint of that sector. However, in the case of the Type (c) 'hot-spots' of Table 5 there could be jurisdiction issues due to the fact that industries of different countries are involved. Still the knowledge acquired from 'hot-spot' analysis on an IRIO level can be used on a commercial level. For example, firms that operate within UK's 'Health and Social Work' could apply commercial pressure to their suppliers abroad, in an effort to reduce their CO_2 footprint. This information may also be of use to procurement managers in public run 'Health and Social Work' activities. It is quite often the case that purchase decisions will focus on the economic side of the purchases, looking for those imports that meet the needs and requirements at the minimum cost. However, where there is a real need and commitment to reduce the carbon footprint of public sector activities (which generally focusses on more direct sources of emissions, such as energy efficiency of buildings) having access to the type of information reported in Table 5 could help add the element of environmental impact in the decision process.

5. Conclusion and extension

The use of an IRIO enables a more accurate calculation of the emissions attributed to each sector especially under a Consumption Accounting Principle (CAP). In a SRIO, if we were to estimate the emissions embodied in the imports of any sector, it was necessary to make some generalising assumption, such as that all the trade partners of the country under examination were using the same production technology at the same point in time. As more countries are included in the IO framework, we obtain more detailed data on the environmental impact of the sectors within these countries. Therefore, the number of countries for which we need to assume that they share production technologies is gradually reduced and the results we obtain better reflect the embodied emissions in any sector's upstream supply chain. Furthermore, in IRIO imports and exports of intermediate goods are endogenous, rather than exogenous inputs and exported final demand, and as a result the multiplier effects can be calculated more accurately.

Applying the 'hot-spot' methodology to a global IRIO framework enables the identification of 'hot-spots' beyond the borders of a single country. It is possible to highlight components of the international side of the downstream and upstream supply chain of any sector and study the impact that final demand of any sector has outside the borders of the country where the sector (and/or final consumption demand for output) is based. However, the findings of 'hot-spot' analysis on an IRIO need to be reviewed with some degree of attention. Any kind of IO analysis is heavily dependent on the quality of the data used. This is even more important in IRIO, where the data come from various different sources, with different collection procedures and techniques, a point that was raised by the UK Department of Energy and Climate Change (DECC) (as reflected in the report by the House of Commons Energy and Climate Change Committee, 2012a). As such it is impossible to be absolutely sure that the quality of the data used to compile the IRIO tables is the same across the board.

For the purposes of this paper the OECD “Inter-Country Input Output” database (OECD, 2015) was used. The creators of the database in OECD had to reconcile and balance the data from all the different sources in order to create a credible dataset. However, it is rather common in large IRIO datasets like WIOD and the OECD “Inter-Country Input Output” database that the industrial sectors are highly aggregated in order to achieve a uniform classification across all regions. Over-aggregation can lead to analytical errors while at the same time masks the true nature of the Type (c) ‘hot-spots’ when these involve the production of a highly aggregated sector. For example, as it has been mentioned for EGWS throughout this paper so far, it is impossible to judge which one(s) out the sectors that are aggregated into EGWS contributes the main share of embodied emissions in any of the EGWS Type (c) ‘hot-spots’ in Table 5 (section 3.4.3). Due to this limitation, ‘hot-spot’ analysis is mostly useful in providing spatial information on ‘hot-spots’, which then would need to be further investigated using national and sub-national IO tables in order to get the maximum level of details possible. Still, the development of this type of datasets could gradually lead to the resolution of the data issue that DECC is highlighting.

The other point of required attention is the adjustment of the ‘hot-spot’ threshold level. In this paper, the average of the row maximums in the CO_2 emissions matrix is used for illustrative purposes to aid in demonstrating how the proposed methodology can be used. This is by no means the optimal way of setting the threshold. As it has been discussed, it is possible to adjust the threshold either based on environmental research or based on the emissions goals set by international agreements. Given that different countries have different agendas and interests, the latter approach seems more plausible given that participation in and ratification of an international agreement implies that the parties involved accept the goals set and the accounting methods proposed.

Generally, the way IRIO 'hot-spot' analysis can influence policies is significantly different to a potential analysis on SRIO. Whereas at the national level (which is studied using SRIO) it is possible to regulate any sector's upstream and downstream supply chains in order to reduce their footprint or their direct emissions, at the international level there are jurisdictional barriers and as such bilateral co-operation is necessary. However, having the information from IRIO 'hot-spot' analysis available can lead to indirect measures involving consideration of environmental parameters when purchasing necessary inputs for public sector activities, as discussed for the UK's 'Health and Social Work' sector. Additionally, the same results can be used as a basis for developed countries to provide funding to carbon reduction initiatives in developing countries, under the carbon finance concept. For example, in Table 2 a number of non-UK sectors are presented that generate significant emissions due to UK final demand. This information coupled with a carbon price could be considered as UK's mandatory contribution to carbon reduction funds, which in turn will be used by the countries influenced in order to develop carbon saving innovations. From a different perspective, this information enables private firms to become significant contributors in the reduction of their footprint by identifying the most polluting components of their upstream supply chains and therefore acting to enforce the use of more environmentally friendly technologies by their suppliers.

It is clear then that performing a 'hot-spot' analysis at the interregional level helps with generating additional information that could not be obtained by just focusing on the single region level. Unfortunately, as discussed above, there are specific limitations that derive from the current characteristics of the available IRIO tables. For example, the level of aggregation poses significant limitations in our understanding, especially in the case of EGWS sector which so far has been flagged multiple times as significantly polluting, but for which we cannot be sure which of the different components of this aggregated sector actually holds the largest share of emission or whether the share is evenly distributed. It is important then to identify how significant these limitations are and more importantly how much more information we could obtain by overcoming them.

A logical next step then is to apply the proposed methodology on detailed and disaggregated sub-national IO tables, published directly from the local authorities rather than derived from IRIO tables. This exercise will help understand the level of details that can be obtained by conducting a ‘hot-spot’ analysis and at the same time how restrictive and problematic is (or is not) the use of datasets with highly aggregated sectors. Furthermore, should the results from the application on disaggregated sub-national IO tables prove that there are significant errors associated with the aggregation then this will provide a strong argument in favour of the development of disaggregated national and sub-national IO tables. At the moment, as Turner (2006) points out, there are doubts on whether the investment on detailed IO datasets is worthwhile in terms of the resources required. Even in cases like Scotland where the detailed IO tables have been developed, there has been limited use of those IO tables for emissions related analyses. Applying ‘hot-spot’ analysis on disaggregated IO datasets could then act as reassurance that there are significant gains to be made by using these datasets and as a result encourage more extensive use and continued support/further development of these IO tables.

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Appendices

Appendix A; Table A.1: The countries included in the OECD Inter-Country Input Output Database

OECD Abbreviation	Country
AUS	Australia
AUT	Austria
BEL	Belgium
CAN	Canada
CHL	Chile
CZE	Czech Republic
DNK	Denmark
EST	Estonia
FIN	Finland
FRA	France
DEU	Germany
GRC	Greece
HUN	Hungary
ISL	Iceland
IRL	Ireland
ISR	Israel
ITA	Italy
JPN	Japan
KOR	Republic of Korea
LUX	Luxembourg
MEX	Mexico
NLD	Netherlands
NZL	New Zealand
NOR	Norway
POL	Poland
PRT	Portugal
SVK	Slovak Republic
SVN	Solvenia
ESP	Spain

OECD Abbreviation	Country
SWE	Sweden
CHE	Switzerland
TUR	Turkey
GBR	United Kingdom
USA	United States
ARG	Argentina
BRA	Brazil
BRN	Brunei
BGR	Bulgaria
KHM	Cambodia
CHN	China
TWN	Chinese Taipei
CYP	Cyprus
HKG	Hong Kong
IND	India
IDN	Indonesia
LVA	Latvia
LTU	Lithuania
MYS	Malaysia
MLT	Malta
PHL	Philippines
ROU	Romania
RUS	Russian Federation
SAU	Saudi Arabia
SGP	Singapore
ZAF	South Africa
THA	Thailand
VNM	Vietnam
ROW	Rest of the World

Appendix B; Table B.1: The Industry×Industry industrial sectors of the OECD Inter-Country Input Output Database

Sector Number	OECD Sector Code	Sector Name	ISIC rev3.1
1	C01t05	Agriculture, Hunting, Forestry and Fishing	01,02,05
2	C10t14	Mining and Quarrying	10,11,12,13,14
3	C15t16	Food products, Beverages and Tobacco	15,16
4	C17t19	Textiles, Textile Products, Leather and Footwear	17,18,19
5	C20	Wood and Products of Wood and Cork	20
6	C21t22	Pulp, Paper, Paper Products, Printing and Publishing	21,22
7	C23	Coke, Refined Petroleum Products and Nuclear Fuel	23
8	C24	Chemicals and Chemical Products	24
9	C25	Rubber and Plastics Products	25
10	C26	Other Non-Metallic Mineral Products	26
11	C27	Basic Metals	27
12	C28	Fabricated Metal Products except Machinery and Equipment	28
13	C29	Machinery and Equipment n.e.c	29
14	C30	Office, Accounting and Computing Machinery	30
15	C31	Electrical Machinery and Apparatus n.e.c	31
16	C32	Radio, Television and Communication Equipment	32
17	C33	Medical, Precision and Optical Instruments	33
18	C34	Motor Vehicles, Trailers and Semi-trailers	34
19	C35	Other Transport Equipment	35
20	C36t37	Manufacturing n.e.c; Recycling	36,37
21	C40t41	Electricity, Gas and Water Supply	40,41
22	C45	Construction	45
23	C50t52	Wholesale and Retail Trade; Repairs	50,51,52
24	C55	Hotels and Restaurants	55
25	C60t63	Transport and Storage	60,61,62,63
26	C64	Post and Telecommunications	64
27	C65t67	Finance and Insurance	65,66,67
28	C70	Real Estate Activities	70
29	C71	Renting of Machinery and Equipment	71
30	C72	Computer and Related Activities	72
31	C73	Research and Development	73
32	C74	Other Business Activities	74
33	C75	Public Admin. and Defence; Compulsory Social Security	75
34	C80	Education	80
35	C85	Health and Social Work	85
36	C90t93	Other Community, Social and Personal Services	90,91,92,93
37	C95	Private Households with Employed Persons	95

Appendix C: The creation of satellite emissions account

C.1 Allocation of emissions from fuel combustion

As described above the satellite emissions account is critical for conducting ‘hot-spot’ analysis. Given that existing emissions accounts are not compatible with the OECD database used in this study, the one used here had to be created from scratch. As mentioned in the main text, the data sources used are IEA fuel combustion data and UNFCCC. IEA fuel combustion data include the emissions generated by each aggregated sector, divided by fuel type. There is an issue in that the grouping used by IEA is completely different than the OECD one, with the implication that the emissions had to be allocated to the respective OECD sector. Table 2.C.1 demonstrates the allocation of the emissions to the OECD groups. The guideline was the IEA accompanying document, “CO_2 emissions from fuel combustion: Documentation for beyond 2020 files” (IEA, 2012). Please also note that IEA used ISIC rev.4 therefore the sectors mentioned in the document had to be matched to the ISIC rev3.1 used by OECD.

It can be seen that in numerous cases the same IEA group includes several OECD sectors. For example, Transport equipment in IEA refers to C34 and C35 in OECD database (see Appendix B above for sector key). To allocate the emissions, fuel purchase coefficients have been used. The inputs of each sector, regardless of country of origin, have been pooled and inputs from sectors C10t14, C23 and C90t93 have been used for the coefficients. C10t14 was used for extracted fossil fuel (coal, crude oil, natural gas etc.), C23 for the oil products (diesel, petrol, kerosene etc.) and C90t93 for waste used as fuel. Therefore, the format of the fuel purchase coefficient for C10t14 for instance would be the following:

$$Fuel\ purchase\ coef = \frac{input\ of\ sector\ from\ sector\ C10t14}{total\ inputs\ of\ group\ from\ sector\ C10t14} \quad (C.1)$$

The formula changes for the different sources of fuel. The same coefficient is used for every group that requires to be allocated to different OECD sectors. Please note that all the transport related groups, with the exception of pipeline transport which was only linked to sector C40t41 and the general transport group which is linked to C60t63, have been allocated to every sector.

C.2 Allocation of emissions associated with autoproducers

Autoproducers are generally the plants within industries that generate electricity and/or heat to meet the needs of the firm. The emissions associated with autoproducers are quite significant; therefore, it was considered important to allocate them to the respective industrial sectors. The problem is that IEA has detailed data only for the OECD countries. Thus, it was necessary to use some form of proxy to estimate the production of autoproducers in non-OECD countries. To that end the OECD regions have been used. IEA data include the autoproducer emissions for OECD Europe, Asia Oceania and America. The underlying assumption is each country has similar autoproducers technology in comparison to the others of the same continent. With that in mind it is possible to estimate the emissions generated by using the following coefficient:

$$Production\,Volume\;coef = \frac{Total\;autoproducers\;emissions\;of\;country}{Total\;autoproducers\;emissions\;of\;OECD\;region} \quad (C.2)$$

Having calculated that coefficient, it is possible to estimate the emissions by multiplying the production figures in the OECD region dataset with the production volume coefficient. Please note that in the case of South Africa, Australia has been used as proxy, as there is no OECD Africa region. The other necessary step is to calculate the emissions generated for every kwh of electricity and TJ of heat produced by autoproducers:

$$Electricity\ CO2\ coef = \frac{(0.5 * Unalloc) + (Autoprod\ electr) + (0.5 * CHP)}{Total\ Net\ Production\ (electricity)} \quad (C.3)$$

$$Heat\ CO2\ coef = \frac{(0.5 * Unalloc) + (0.5 * CHP) + (Autoprod\ heat)}{Total\ Net\ Production\ (heat)} \quad (C.4)$$

Once again coefficients have been used. Please note that the unallocated autoproducers and the autoproducer CHP (Combined Heat Power) plants have been divided equally between electricity and heat production. This might not always be the case but in fact the estimated figures are quite close to the actual reported emissions of autoproducer plants.

Once the aforementioned procedure has been completed the emissions are allocated to the respective sectors as seen on the autoproducers column of Table 2.C.1. In the cases where an autoproducer category included more than one OECD sector, the emissions were split using the total output of the sector as a criterion, assuming that the higher the production the more each industry needs to run the autoproducing plants.

C.3 Fugitive gases and industrial processes

The last emissions sources included in the emissions account were fugitive gases from fossil fuel extraction and non-fuel combustion emissions during specific industrial processes. The data source in all cases have been the UNFCCC website (UNFCCC, 2014). The issue faced was that data on non-Annex I countries were limited if not existent. Thus, it was necessary to use a proxy. Australia has been used as a proxy due to the great data availability. On top of that Australia was used by Lenzen et al (2004) to model the Rest Of the World, therefore it seems like an acceptable choice. As in previous cases a coefficient has been created to establish the size of the sector under examination compared to the respective Australian sector:

$$Production\ \&\ Technology\ coef = \frac{Country's\ sector\ emissions\ (IEA)}{Australia's\ sector\ emissions\ (IEA)} \quad (C.5)$$

This coefficient can capture the differences both in production volume and technology used. Consequently, the UNFCCC data for Australia are multiplied with the coefficient of the respective sector to produce the estimate for the non-Annex I country under examination. Finally, the emissions are allocated to each sector as seen in Table 2.C.1.

Table 2.C.1: Allocation of emissions to OECD sectors

OECD Sector	Combustable Fuels (IEA table)	Autoproducers	Transport	Manufacturing industries/non-enery use industry	Other	Industrial Processes	Extraction Emissions
C01t05	Agriculture/forestry Fishing	Agriculture Fishing			Other		
C10t14	Mining and quarrying	Mining and quarrying Coal mines Oil and gas extraction Non-specified energy industry					Fugitive gases
C15t16	Food and tobacco	Food and tobacco		Manufacturing industries/non-enery use industry		Other production	
C17t19	Textile and leather	Textile and leather		Manufacturing industries/non-enery use industry			
C20	Wood and wood products	Wood and wood products		Manufacturing industries/non-enery use industry			
C21t22	Paper, pulp and printing	Paper, pulp and printing		Manufacturing industries/non-enery use industry		Other production	
C23		Patent fuel plants Coke ovens BKB plants Gas works Blast furnaces Oil refineries Coal liquefaction plants Liquefaction (LNG) / regasification plants Gasification plants for biogases Gas-to-liquids (GTL) plants Charcoal production plants Non-specified energy industry		Manufacturing industries/non-enery use industry			
C24	Chemicals and petrochemicals	Chemicals and petrochemicals		Manufacturing industries/non-enery use industry		Chemical industry	
C25 C36t37	Non-specified industry	Non-specified industry		Manufacturing industries/non-enery use industry			
C26	Non-metallic minerals	Non-metallic minerals		Manufacturing industries/non-enery use industry		Mineral products	
C27	Iron and steel Non-ferrous metals	Iron and steel Non-ferrous metals		Manufacturing industries/non-enery use industry		Metal production	
C28 C29 C30 C31 C32 C33	Machinery	Machinery		Manufacturing industries/non-enery use industry			

OECD Sector	Combustable Fuels (IEA table)	Autoproducers	Transport	Manufacturing industries/non-enery use industry	Other	Industrial Processes	Extraction Emissions
C34 C35	Transport Equipment	Transport Equipment		Manufacturing industries/non-enery use industry			
C40t41	Main activity electricity and heat production Main activity electricity plants Main activity CHP plants Main activity heat plants Own use in electricity, CHP and heat plants	Non-specified energy industry Pipeline transport	Pipeline transport	Non-enery use industry			
C45	Construction	Construction		Manufacturing industries/non-enery use industry			
C60t63	Transport Road Domestic aviation Rail Domestic navigation Non-specified transport Non-energy use in transport	Rail Non-specified transport					
C50t52 C55 C64 C65t67 C70 C71 C72 C73 C74 C75 C80 C85 C90t93	Commercial and public services	Commercial and public service			Other		
C95	Residential	Residential			Other		