Identifying and analysing carbon ‘hot-spots’ in an Inter-Regional Input Output framework

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Thesis Abstract

Input Output frameworks have been widely used to study the emissions of industrial sectors either in specific economies or globally but usually focus on aggregated measures under production or consumption accounting principles (PAP and CAP). This leads to a lack of transparency in terms of the structure of the emissions and provides limited information on what are the main drivers of the emissions allocated to each sector under PAP and CAP. This information gap limits the options of policy makers to interventions on whole sectors, rather than the components of their supply chains that hold the major shares of the total embodied emissions. In this thesis we argue in favour of a more disaggregated, a 'hot-spot', approach that provides a better understanding of the structure of emissions under both of these headline measures. We develop a methodology to identify CO_2 'hot-spots' in downstream and upstream supply chains, both domestic and global. The methodology is applied first to a Single Region Input Output framework for China in 2005 identifying 'Electricity, Gas and Water Supply' as the Chinese sector with the highest direct emissions. Examination of the sector's domestic downstream supply chain reveals that the majority of emissions are generated to support the final demand of other domestic sectors. Of these 'Construction' is the main driver and it also is the Chinese sector that is found to have the largest domestic CO_2 footprint, with several emissions 'hot-spots' in its domestic upstream supply chain. The 'hot-spot' methodology is then extended to a global Inter-Regional Input Output framework to consider 'hot-spots' in a global supply chain context. By focusing on 2009 (the year for which appropriate data are most recently available) and UK total final demand we find that Chinese 'Electricity, Gas and Water Supply' is the non-UK sector with the largest direct emissions driven by UK total final demand. Studying this sector's downstream supply chain outside China reveals that a large share of the sector's emissions is ultimately generated to support several UK-based sectors' domestic final demand. Furthermore, the UK 'Health and Social Work' sector is identified as the UK

sector with the second largest global footprint to support domestic final demand. We identified a number of 'hot-spots' in the international part of its upstream supply chain, with a key finding being its dependence on the activity and the embodied emissions in global chemicals production. Finally, the thesis goes on to demonstrate how conducting 'hot-spot' analysis on disaggregated regional/sub-national Input Output tables can provide more detailed local level analysis of 'hot-spot' findings from the Inter-Regional Input Output framework. The key finding in this respect is the importance of introducing region specific emissions data where possible, as non-region specific data can lead in incorrect estimation of the embodied emissions in any component of the supply chains of any sectors. In general, through this research project we developed a methodology that can enhance the policy makers understanding of the structure and the drivers of the emissions generated throughout the economy. This additional information on the emissions structure, when combined with familiar IO analysis on employment and value-added for example, has the potential to lead to more targeted/focused policies, which result in significant emissions reduction with the minimum employment, resources and value-added cost.

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Chapter 1: Thesis Introduction

1.1 Policy background and relevance of thesis

Input Output (IO) analysis is a widely used tool in the research of the CO_2 emissions generated due to economic activities. Especially over the last two decades, a large number of studies have been published that calculate and study the total direct emissions[1] of each industrial sector in different countries, including among others Brazil, China, Denmark and USA. The total direct emissions reflect the emissions generated by each producing sector to support the final demand of all the other sectors, not just their own final demand. This being the case it was recognised that the final demand of all the sectors in an economy has a significant role to play in the emissions generated directly by any sector. As such researchers used IO analysis to also calculate the CO_2 footprint[2] of all the sectors in different economies. In fact, most studies calculated both the total direct emissions and the CO_2 footprint, comparing the two (see Wiedmann et al, 2007 for review). This thesis sets to address a problem that exists when focusing on the calculation of these headline figures. As can be seen by examining an IO table, each producing sector sells different value worth of output to each consuming sector and in much the same way each consuming sector requires different value of output from the different producing sectors to meet its final demand. Under the assumption that each producing sector charges a flat price of output to all consuming sectors, the differences in value of output paid actually reflect differences in volume of output required. Therefore, it can be seen that each producing sector distributes different volumes of output to each consuming sector and vice versa. The methodology proposed in this thesis disaggregates the downstream and upstream supply chains of each sector, and therefore the headline figures of total

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1 Direct emissions are the emissions generated by any sector to meet its own final demand and support the final demand of all the other sectors in an economy.

2 In this thesis the CO_2 footprint is defined as total volume of CO_2 emissions embodied in the output of all the sectors featured in the upstream supply chain of any given sector, acting as direct requirements to meet that sector's final demand.

direct emissions and CO_2 footprint, allowing the study of the structure of the supply chains and the embodied emissions in each component of the supply chains.

The development and results of IO analysis tools are closely related to policy. For instance, the recent international climate change mitigation agreements under UNFCCC (Kyoto 1997, Copenhagen 2008, Paris 2015) or Europe 2020 strategy, employ a goal setting approach where each participating party is required to reduce anthropogenic greenhouse gas (GHG) emissions below the emissions of 1990, which is set as a baseline year. Each party is held responsible for the emissions generated within its territory under a territorial Production Accounting Principle (PAP), i.e. the total direct emissions of the producing sectors in this party/country. Researchers have argued, even before the implementation of the Kyoto protocol in 1997 (see Wyckoff and Roop, 1994), that such an approach would limit the effectiveness of any international agreement as parties would be in a position to meet their emissions goals by shifting the most polluting parts of their production to developing nations without strict environmental regulations and/or emissions goals, i.e. pollution leakage (Arrow et al, 1995). An alternative approach that has been developed (see for example Munksgaard and Pedersen, 2001), involves a Consumption Accounting Principle (CAP), under which the consumer is held responsible for the emissions generated to meet its demand. The CAP emissions of any given sector include the CO_2 footprint of that sector plus the emissions generated by consuming the final goods produced by the sector under examination. Consumption oriented approaches have also been investigated by governments, including the UK, as potential ways of achieving their emissions goals. A report by the House of Commons Energy and Climate Change Committee in 2012, reflects on the potential benefits that the committee sees in adopting consumption-based approaches. However, one of the main issues that have been identified involves the lack of credible inter-regional data, which would be crucial in studying CO_2 emissions under CAP as quite often parts of the upstream supply chain of any sector are located outside the territorial limits of each country. This problem has been flagged up by the House of Commons Energy and Climate Change Committee (2012a) but the development of the World Input Output Database (Timmer et al,

2015) and the OECD Inter-Country Input Output Database (OECD, 2015), among others, are steps towards a solution of the lack of credible IO data. Still, there exists an additional issue when considering the adoption of a CAP approach. Under CAP, consumption is recognised as the main driver of emissions. It is assumed then that the consumer is aware of the environmental impact of the activities that support its consumption and has some control over the technologies used, whereas commonly consumers' decisions are driven by the cost of the goods and services either being unaware or disregarding the environmental consequences. Furthermore, consumers, more often than not, do not have any actual control or means of influencing the technology used by the producers. As such, adopting a CAP approach could lead in penalising the consumers that do not have the means to acquire information on the impact of their consumption or the financial resources to switch to 'cleaner' but more expensive substitutes to meet their needs.

Our proposed approach recognises that there is merit to both PAP and CAP. A sector that directly generates a large volume of emissions and/or has a large CO_2 footprint merits additional attention. However, the disaggregation of the supply chains allows us to investigate which components of that sector's supply chains hold the most significant share of the total direct emissions or contribute the most on the sector's footprint. Emphasising and analysing these components, that we define as Type (c) 'hot-spots'[3], identifies the role of the requirements of the consumer and the technology of the producer in driving the embodied emissions and which of them should be regarded as the main driver. From a policy perspective, the additional information on the drivers of emissions can be translated into more options for policy makers. For example, if it is found that the requirements of 'Public Administration' from the 'Electricity' sector have high volume of embodied emissions, the proposed methodology/analytical tool can show policy makers the contribution of final demand for 'Public Administration' services, requirements of 'Electricity' output to support 'Public Administration' final demand and the emissions intensity of the 'Electricity' sector (i.e. 'Electricity' production technology) in

[3] Detailed definitions of all the different types of 'hot-spots' can be found throughout the thesis starting from Chapter 2

the total volume of embodied emissions. Using this information, coupled with analyses from other IO analytical tools on the impact on employment and generated value-added, policy makers can decide where policy interventions should take place. The ultimate goal of applying our proposed methodology with other types of IO analysis is to be in a position to allocate the available resources in a more efficient way, achieving significant reduction of emissions, while minimising any potential losses in employment or generated value-added.

One of the key features of the proposed methodology is that can be applied both in single region and inter-regional frameworks. For the single region, as it will be discussed in Chapter 2, the analysis can be used in goal setting scenarios. This way the findings can be used as guidelines for policy makers in order to achieve the goals set under international climate change agreements. Of equal importance though is the applicability of the method in inter-regional frameworks. As it was mentioned above, in modern economies, the supply chains are rarely confined within a single country. This being the case, when there are policy efforts in reducing the embodied emissions in either the downstream or the upstream supply chain of any sector in a country, inevitably some components of those supply chains that hold a significant share of the total embodied emissions will be located outside the country. Due to jurisdictional issues quite often it is not possible to impose interventions on industrial sectors outside the territorial borders of a country. However, identifying those 'hot-spots' in the international part of the supply chains could facilitate the reduction of emissions by informing bilateral technology exchange agreements. Even when technology exchange/bilateral co-operation is not possible, since the year 2000 there have been several carbon initiatives promoting the adoption of cleaner technologies in developing nations. These initiatives are referred to using the umbrella term carbon finance and many of them are supported by large international organisations like the World Bank. The results of our proposed inter-regional analysis then could be used as a basis for determining the funding contribution of developed countries to these initiatives, which in turn would fund emissions-reduction projects.

1.2 Structure of thesis

As mentioned in the previous section this thesis focuses on decomposing the downstream and upstream supply chains of any sector, both in a single country and internationally. We call the findings of our analysis 'hot-spots'. 'Hot-spots' are defined in three general ways. First, they are defined in terms of sectors with more direct emissions than the others in an economy. Second, they are also defined in terms of sectors with a larger footprint than the others in an economy. Third, 'hot-spots' are identified and considered in terms of specific components of a sector's downstream and upstream supply chain (i.e. decomposing information on the first two types). As indicated throughout the previous section, in this thesis we demonstrate that by adopting a 'hot-spot' analysis approach it is possible to get a better understanding on where the emissions are generated and what are the key drivers of their volume. Therefore, the central proposition of this thesis is that 'hot-spot' analysis can lead to more informed and more targeted policy decisions than the headline PAP and CAP analyses that have become so prevalent in the academic and wider research and policy literatures.

This thesis is organised as a collection of three papers/chapters, each written as a self-contained piece including literature review and methodology along with original applied work. The second chapter focuses on how 'hot-spots' are defined and considers how standard CAP/PAP accounting methodology may be developed to identify them in an IO framework. To that end a Single Region Input Output (SRIO) framework is used, developing a Chinese case study extracting data for this country from the OECD Inter-Country Input Output database that is used throughout the thesis. The chapter provides guidance on the way that the SRIO is created and how it is extended to an Environmental SRIO (ESRIO), with a focus on CO_2 emissions. Due to what we argue is the need to have a clearer picture of the structure of emissions in and/or driven by different sectors of the economy (and different types of final consumption demand), the ESRIO in this chapter is used in a range of different ways that provide more information and a fuller analysis relative to more traditional IO-based CAP and PAP approaches. Specifically, we use the developed methodology to identify the Chinese sectors with the largest volume of direct emissions and the largest footprint, while studying their downstream and upstream supply chains respectively.

Moving forward through the thesis, the third chapter reflects the recognition that for most modern economies the supply chains of any given sector extend beyond the borders of its home country. Therefore, here we move to the development of the global Inter-Regional Input Output (IRIO) framework. Adopting a global IRIO approach facilitates the study of the impact of any one sector in any country on the activity and emissions generation in other countries. The third chapter involves an extension of IRIO to an Environmental IRIO (EIRIO). The features of the conventional EIRIO approach are presented and discussed and previous applications in the literature reviewed. However, the key contribution of this paper is to extend the 'hot-spot' identification methodology of the second chapter and apply it using EIRIO decomposition methods. In the applied analysis we focus on the impacts of UK total final demand and identify sectors outside the UK that directly generate significant emissions in serving this demand. We also study in detail the downstream supply chain of the top direct emitting sector outside the UK that produces to support the UK final demand of other sectors globally. Additionally, we identify the sectors with the largest global footprints driven by UK final demands, focusing on UK 'Health and Social Work' activity as a rather interesting example where we can pinpoint important 'hot-spots' in this sector's upstream supply chain components that are located outside the UK. Finally, but of particular importance to the applied contribution made in this thesis, the third chapter is related to an appendix detailing the development of the CO_2 'satellite' account for the OECD Inter-Country IO (ICIO) database. The author worked towards the development of this dataset in the early stages of the PhD study, during and following a research visit with the ICIO team at the OECD Directorate for Science, Technology and Innovation.

The fourth chapter goes on to focus on the implications and resolution of a commonly observed trade-off between IRIO and SRIO, where the latter is based on use of national/regional IO tables as a component of published official statistics. The nature of the trade-off is that IRIO provides crucial information in IO format on multi-lateral international trade but at the cost of industry level detail. On the other hand, SRIO analyses based on national/regional IO tables tend to benefit from a greater level of sectoral disaggregation. Where sub-national regional IO data are available, SRIO also benefits from greater spatial focus, but at the cost of (even) more information loss on intra- and inter-national trade flows. We explore how benefits of both approaches may be maximised, by considering the results of Inter-Regional 'hot-spot' analyses for the UK, focusing on sectors that we then turn our attention to at the Scottish level using more sectorally detailed regional IO data. In doing so, we demonstrate how the information acquired for the case study of UK 'hot-spots' using IRIO and the OECD Inter-Country Input Output database can be enhanced in terms of regional level details by using SRIO and Scottish regional IO tables. Specifically, we demonstrate how the combined UK 'Electricity, Gas and Water Supply' sector, identified as a 'hot-spot' at the Inter-Country database level, may be disaggregated at national and regional level, with identification of further 'hot-spot' activity therein. However, in considering the nature of UK 'hot-spots' at a Scottish level, we also demonstrate the importance of introducing region specific emissions data to give policy makers a more accurate picture of the level of emissions within Scotland. Continuing the focus on Scottish electricity generation within the wider UK sector, we then consider how our results are impacted by introducing data on emissions reported to Scottish Environment Protection Agency by Scottish firms, in place of the UK level average emissions intensity data point provided by the OECD ICIO satellite account. We find that this one impacts the magnitude and ranking of the Scottish sectors with the largest domestic CO_2 footprints. This result highlights the importance of region specific emissions data. It proves that applying generic emissions data, that were created for and initially applied to aggregated sectors at national level, fails to capture the differences in production technologies used in different regions. As a consequence of this any results that are obtained can be over or underestimated, especially in the case of sectors that a multitude of production technologies can be used to produce the same output, but with significantly different environmental impact. Therefore, when these results are used to inform policy decisions they could mislead policy makers into either implementing interventions for 'hot-spots' that in reality do not have as many embodied emissions as it was calculated or fail to identify 'hot-spots' that could be rather interesting for policy makers in terms of achieving emissions reduction with low associated costs.

The last chapter of this thesis provides a conclusion of this research project as a whole. It summarises the methodology used throughout this project, while reflecting on the strong points and highlighting the weaknesses and challenges that have been discussed in the previous chapters. At the same time, it provides a reflection on the potential future research that can originate from this project.

Chapter 2: Identifying CO_2 'hot-spots' in Input Output frameworks: A Chinese single region example.

Abstract

The chapter uses data for China in 2005 in a Single Region Input Output framework to develop a methodology to identify CO_2 'hot-spots' in domestic supply chains. It is argued that 'hot-spot' methodology can provide a better understanding of the drivers of sectoral emissions, while allowing a decomposition of the sectors' supply chains, thereby offering a clearer view on the structure of emissions. Combining the better understanding of the emissions' structure with familiar IO analyses, on employment and value-added for example, can lead to policies that are targeted on the 'hot-spots' where they can achieve significant emissions reduction with the minimum resources cost and losses in employment and value-added. Analysis of the IO data showed that a combined 'utility' sector, 'Electricity, Gas and Water Supply', is the most polluting Chinese sector in terms of direct CO_2 emissions, whereas 'Construction' has the largest domestic CO_2 footprint, which is mainly driven by Gross Fixed Capital Formation. This finding can be associated with the status of China as a developing country, building up production capacity to facilitate its economic growth. Furthermore, the 'Construction' requirements drive the emissions embodied in the largest 'hot-spot' on 'Electricity, Gas and Water Supply' downstream supply chain, while it is revealed that 'Electricity, Gas and Water Supply' emissions are mainly generated to support the production required to meet the final demand of other sectors.

2.1 Introduction

UNFCCC agreements in Kyoto (1997) and Copenhagen (2008) signify important steps in a global effort to mitigate climate change. UNFCCC adopted a territorial Production Accounting Principle (PAP) under which every member party, that ratified the agreements, is being held responsible for the emissions generated within its borders (United Nations, 1992). However, even before the implementation of the Kyoto Protocol, the effectiveness of such an approach was doubted. For example, Wyckoff and Roop (1994) suggested that, due to the amount of emissions embodied in imported goods, an approach relying exclusively on domestic emissions for any one country would be less effective in mitigating the emissions of greenhouse gases at the global level. Early indications show that the policy focus will be the same in the upcoming UNFCCC COP21/CMP11 meeting that will be held in Paris in late 2015. This means that, at least for the foreseeable future, any international climate change mitigation efforts are likely to be based on a territorial PAP approach. Under PAP a country, or region, is held responsible for the emissions of industries operating within its borders.

Numerous studies have conducted comparisons between PAP and a Consumption Accounting Principle (CAP). Under CAP a country's emissions balance includes the emissions generated within its borders in producing goods to be consumed domestically, either as intermediate or final goods, plus the emissions embodied in imports. Thus any emissions generated to produce exported goods, intermediate or final, are not allocated to the country where pollution generation actually takes place rather than where the final consumption driving them is located. The pollution generation aspect of the environmental extension of Input Output (IO) framework has been a commonly used method in studying PAP and CAP. It allows the researchers to study the contribution of different industrial sectors to the total emissions balance of any region/country. Furthermore, it is possible to focus on different types of final demand and study the effect they have on a country's emissions balance. Single Region Input Output (SRIO) has been used in earlier studies (e.g. Munksgaard and Pedersen, 2001; Machado et al, 2001). SRIO is relatively easy to apply since the data required can be extracted by national or regional statistics, which are readily available; often countries publish IO tables. Additionally, there tends to be a high level of details in terms of the types of domestic final consumers identified in regional IO tables. On the down side national IO tables generally lack in details on the use of the exported part of the production. Multi-

Regional Input Output (MRIO) has been increasingly used in more recent publications (e.g. Munoz and Steininger, 2010; Serrano and Dietzenbacher, 2010), on the grounds that it provides better understanding of the impacts of international trade. However, this often comes at the expense of details on types of final demand. The problem is that the data used for MRIO need to be harmonized, so that they are presented in a common way for all the regions included in the framework. This means that it is often necessary to aggregate industrial sectors as well as types of final consumers, which reduces the level of detail.

The common ground between PAP and CAP is that responsibility for the generated emissions is placed on one side or the other. Under PAP it is assumed that the producer is solely responsible for the emissions, which may be appropriate in terms of production technology. Under CAP on the other hand the final demand for goods and thus the end consumer is highlighted as responsible for the generated emissions of any and all industries, according to the perspective that without any demand there would not be any production and therefore any generation of emissions. The aforementioned studies (Machado et al, 2001; Munksgaard and Pedersen, 2001; Munoz and Steininger, 2010; Serrano and Dietzenbacher, 2010) mainly examine the differences in emissions balances between a PAP and a CAP approach. There has been work though, using the IO framework, on the concept of joint responsibility (e.g. Lenzen et al, 2007; Cadarso et al, 2012) essentially recognizing varying degrees of responsibility along the supply chain of each commodity. Wiedmann et al (2007) along with (Wiedmann, 2009) offer detailed reviews on the use of both SRIO and MRIO frameworks, while Wiedmann et al (2011) focus on the evolution of MRIO.

2.2 'Hot-spots' and key sectors

In this chapter, an alternative approach is considered. This is a 'hot-spot' approach that involves decomposition of PAP and CAP but which has received limited attention. In general, a 'hot-spot' can be a sector that directly generates a larger amount of emissions or one that its upstream supply chain embodies more emissions than the upstream supply chains of other sectors in a specific region, country or even globally. Alternatively, a point on a sector's downstream or upstream supply chain that embodies emissions above some acceptable level may also be considered as a 'hot-spot'. 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[4]. 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.

The goal of this chapter then is to develop a methodology of identifying CO_2 'hot-spots' in down and upstream supply chains using IO accounting frameworks. The fact that there is no focus on a specific commodity enables the analysis of the data without the need for specialised procedures like 'Life cycle analysis' as observed by Wiebe et al (2012). Moreover, by analysing the observed 'hot-spots', it is possible to distinguish between those where the absolute amount of emissions is mainly driven by the volume of production and/or those that come as a result of the emissions intensity of the production technology used. Furthermore, while IO is not a sophisticated modelling framework, analysis on the use of multipliers does permit the identification of points in supply chains and/or sectors as a whole, that have the potential to become 'hot-spots' in the event of increased final demand. Below, the third section of this chapter presents the methodology developed here for SRIO multiplier analysis to detect

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

CO_2 'hot-spots' in domestic supply chains, along with a brief summary of the data used. The fourth section then discusses some interesting results that emerge from the analysis while Section 5 concludes and offers suggestions for future research.

2.3 Methodology

In this section the adopted methodology is presented. The section starts with a brief presentation of the SRIO providing some details on the way that it has been used in this paper and how a SRIO is expanded to an Environmental SRIO. Then the 'hot-spot' identification methodology is explained through a relatively simple but illustrative example and finally information on the data used in this chapter are provided.

2.3.1 Single Region Input Output

In this chapter the methodology used is based on IO analysis as discussed by Miller and Blair (2009). The key equation of the IO framework used in this study is

$$X = (I - A)^{-1} D_Y \quad (1)$$

where $X = \begin{bmatrix} X_1 \\ \vdots \\ X_i \\ \vdots \\ X_N \end{bmatrix}$ represents the output of sectors $i = 1, \cdots$,N in a $N \times 1$ vector format, where X_i is the total output of sector i. A is a $N \times N$ matrix, whose elements a_{ij} denote Input-Output coefficients and represent the input requirements of sector j from sector $i = 1, \cdots$,N to produce one unit of x_j. Finally $D_Y = \begin{bmatrix} y_1 & 0 & 0 \\ 0 & \ddots & 0 \\ 0 & 0 & y_N \end{bmatrix}$ is the diagonal matrix of final demand. The elements of D_Y may represent total final demand for each sector, but (1) can also be studied in terms of any particular type of final demand such as private (household) consumption, gross capital formation etc. and consider the total output X, driven by that final demand source, depending on the focus of study. This approach allows for a focus on one specific type of final demand each time and, when we extend to environmental IO below, to explicitly study the emissions generated in producing output to meet this specific source of final demand. In the case of single region, final demand includes the final goods produced for domestic consumption by different types of domestic final consumers, exported final goods to be used by different types of final consumers abroad as well as exported intermediate goods. In published SRIO for a given country, all exported goods are usually aggregated into a single category including both intermediate and final goods. However, the Inter-Country Input Output (ICIO) table that is used to create the SRIO for our empirical study distinguishes exports to final and intermediate demand in different countries. It thereby, offers the benefit of being able to study the impact of producing intermediate goods in one country to be used as inputs by any sector of any other country included in the ICIO table. For example, it is possible to separately examine the impact of UK's intermediate and private and public final consumption to China by respectively using the data for UK's imports to producing sectors and final consumption sectors in turn as the elements of D_Y in (1).

In moving to the IO multiplier matrix that underlines the model in (1), $(I-A)^{-1}$ is an $N \times N$ matrix that is called Leontief inverse, L.

$$L = (I-A)^{-1} = \begin{bmatrix} l_{11} & \cdots & l_{1j} & \cdots & l_{1N} \\ \vdots & \ddots & \vdots & \ddots & \vdots \\ l_{i1} & \cdots & l_{ij} & \cdots & l_{iN} \\ \vdots & \ddots & \vdots & \ddots & \vdots \\ l_{N1} & \cdots & l_{Nj} & \cdots & l_{NN} \end{bmatrix} \quad (2)$$

The elements l_{ij} of the Leontief inverse indicate the production required from sector i to meet a unit of final demand of sector j. Post-multiplying the final demand diagonal matrix (for total or any given type of final demand) to the Leontief inverse gives us the following result:

$$LD_Y = \begin{bmatrix} l_{11}y_1 & \cdots & l_{1j}y_j & \cdots & l_{1N}y_N \\ \vdots & \ddots & \vdots & \ddots & \vdots \\ l_{i1}y_1 & \cdots & l_{ij}y_j & \cdots & l_{iN}y_N \\ \vdots & \ddots & \vdots & \ddots & \vdots \\ l_{N1}y_1 & \cdots & l_{Nj}y_j & \cdots & l_{NN}y_N \end{bmatrix} \quad (3)$$

where y_j represent the elements of D_Y along the main diagonal and therefore the final demand for output of sector j. Each element $l_{ij}y_j$ then demonstrates the production required from sector i to meet the final demand of sector j. The key difference between the approach used in this chapter and the most commonly used one lies on the presentation of the elements of (3). In most SRIOs, final demand is presented by a $N \times 1$ vector or by a $N \times Z$ matrix that includes all the different types of final demand for each sector. Both these approaches generate aggregated results. In the more general case of post-multiplying L with the $N \times Z$ final demand matrix, the result is a $N \times Z$ output matrix that shows the output of each sector that is driven by each type of final demand, i.e. the total output of sector i due to private final consumption or government consumption etc. of all sectors j. On the other hand, in (3) it is possible to examine the output of any sector i due to any selected type of final demand of any sector j, e.g. the output of sector $i =$ 'Mining and Quarrying' required to meet the demand for sector $j =$ 'Construction' gross capital formation. This process requires that each time a different type of final demand needs to be used in D_Y, but at the same time provides a better understanding of how changes in every type of final demand of each sector are spread throughout the economy.

Studying the LD_Y matrix in (3) allows us to distinguish the different components of the downstream and upstream supply chains of each sector. Each element along a row of the LD_Y matrix demonstrates the value of the output produced by producing sector i, that is directly required to meet the final demand of sector j, i.e. the downstream supply chain of sector i. In a similar way the columns of LD_Y matrix represent the upstream supply chain of each sector j, as the elements down each column are the direct requirements of sector j for output from sectors i ,so that it meets its final demand. Having this information available enables us later on to identify which of these points on each sector's downstream and upstream supply chains embody a large enough volume of CO_2 emissions to classify them as 'hot-spots'.

2.3.2 Environmental Input Output

The goal of this chapter is to create a version of the IO framework that would allow the identification of CO_2 emissions "hot-spots". As Leontief (1970) highlights, conventional statistics only report transactions that have some market value. Since environmental impact is generally a "non-market" transaction (an externality), it is usually omitted and the extent of it should be calculated indirectly. For the purposes of this chapter it is necessary to use CO_2 multipliers. The use of CO_2 multipliers in (1) leads to a transformation of the standard SRIO in a way that the output is expressed in terms of CO_2 emissions rather than monetary value.

Extension to environmental IO requires availability of satellite emissions data[5] at sector level, specifically examining total emissions per sector, aggregated at the same level as in the IO tables available. Following that, by dividing the total emissions of each industry group by its total output, the result is what is called an output-emissions coefficient e_i for each producing sector. Here we focus on a single pollutant, CO_2 emissions, therefore the output-emissions coefficient can also be called CO_2 intensity. What CO_2 intensity represents is the amount of emissions directly generated per monetary unit of output produced. By arranging the emissions coefficients along the main diagonal of a diagonal matrix, the result is the $N \times N$ matrix E

$$E = \begin{bmatrix} e_1 & 0 & \dots & 0 \\ 0 & e_2 & \dots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \cdots & e_N \end{bmatrix} \quad (4)$$

To generate output-emissions multipliers and the environmental IO, E matrix is pre-multiplied to the Leontief inverse. This gives us the basic equation for the environmental IO:

$$EX = E(I - A)^{-1} D_Y \quad (5)$$

[5] A satellite emissions account is a dataset that breaks down the emissions of each sector included in the main IO data tables by fuel type, while also listing the non-combustion emissions (e.g. fugitive gases during extraction of coal, emissions due to industrial processes etc.).

This leads to the Leontief inverse presented in (2) to be transformed as follows. The result is called Emissions multipliers matrix (Emm for short)

$$Emm = E(I-A)^{-1} = \begin{bmatrix} e_1 l_{11} & \cdots & e_1 l_{1j} & \cdots & e_1 l_{1N} \\ \vdots & \ddots & \vdots & \ddots & \vdots \\ e_i l_{i1} & \cdots & e_i l_{ij} & \cdots & e_i l_{iN} \\ \vdots & \ddots & \vdots & \ddots & \vdots \\ e_N l_{N1} & \cdots & e_N l_{Nj} & \cdots & e_N l_{NN} \end{bmatrix} \quad (6)$$

This approach has been suggested by Court et al (2015) for hazardous wastes. In essence what this process achieves is to transform the Leontief inverse in a way that each element of the matrix demonstrates the amount of CO_2 emitted by sector i so that one unit of final demand in sector j is met. The sum of the elements of (6) down a column is the CO_2 emissions Type I multiplier, commonly called output-emissions multiplier, which shows the total CO_2 emissions generated by all the sectors to meet one monetary unit worth of sector j final demand.

Following the same procedure as before, by post-multiplying (6) with the matrix of final demand D_Y, the result is the CO_2 emissions matrix (Cem). This is the core matrix of the Environmental SRIO and the 'hot-spot' analysis will be conducted primarily on Cem.

$$Cem = EmmD_Y = \begin{bmatrix} e_1 l_{11} y_1 & \cdots & e_1 l_{1j} y_j & \cdots & e_1 l_{1N} y_N \\ \vdots & \ddots & \vdots & \ddots & \vdots \\ e_i l_{i1} y_1 & \cdots & e_i l_{ij} y_j & \cdots & e_i l_{iN} y_N \\ \vdots & \ddots & \vdots & \ddots & \vdots \\ e_N l_{N1} y_1 & \cdots & e_N l_{Nj} y_j & \cdots & e_N l_{NN} y_N \end{bmatrix} \quad (7)$$

Following up from the discussion on (3) this method distinguishes itself from the commonly used Environmental SRIO. It provides a decomposed picture of the emissions generated by each sector, revealing the embodied emissions in the different components of each sector's downstream and upstream supply chain. Each element $e_i l_{ij} y_j$ represents the emissions generated by sector i in producing output to support the final demand of sector j.

As it has already been discussed the goal of this chapter is to develop a methodology to identify 'hot-spots' in domestic downstream and upstream supply chains. The different categories of 'hot-spots' identified involve sectors with a larger volume of direct emissions and/or a larger CO_2 footprint compared to the other sectors in an economy. However, it is not necessary that the emissions of each sector, direct or footprint, are evenly distributed amongst the different components of the sector's downstream and upstream supply chain. It is then important to highlight those points that have the largest share of each sector's direct emissions and/or the most significant contribution to each sector's footprint. Analysing the elements of (7) enables the identification of 'hot-spots' belonging to each one of the different categories described.

The sum of the elements of each row on (7) calculates the direct emissions of each sector i and can therefore be used to identify the largest direct emitters. Moreover, examining the elements along each row, for each sector i, reveals the emissions directly generated in producing output to meet the sector's own final demand but also to support the final demand of other sectors. By doing so is possible to highlight those components, i.e. 'hot-spots', on each sector's downstream supply chain that have the largest share of the sector's total direct emissions and therefore need most attention, rather than just focusing on the total emissions of each sector.

Furthermore, the sum down the column of each sector j is the sector's CO_2 footprint, allowing for the distinction of those sectors with larger footprint compared to the others in an economy. By focusing on the elements down the column of each sector j in (7) it becomes possible to study the emissions embodied in sector j output requirements from other sectors to meet its own final demand. Part of the arguments in favour of a CAP approach is that, quite often, industrial sectors might not generate significant emissions during their production phase while the different points on their upstream supply chain are generating significant CO_2 emissions. By adopting the suggested methodology, it is possible to identify the points on any sector's upstream supply chain that embody the most significant volume of emissions and therefore make the most significant contribution to the sector's footprint.

2.3.3 'Hot-spot' detection

The different categories of 'hot-spots' identified in this paper were discussed briefly in the previous 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 generates directly significantly more emissions compared to other sectors in an economy either to support total final consumption demand or components thereof; i.e. has a larger sum of its row in the CO_2 emissions matrix (7).

(b) A sector where the output produced to meet its final demand (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 random example of a simple illustrative single region with only 3 sectors but still rather helpful in understanding the methodology used to identify 'hot-spots'.

Table 1: Example of 'hot-spot' detection

	Agriculture	Mining	Food/Beverage	Total Direct emissions	Row maximum
Agriculture	750.00	11,900.00	1,020.00	13,670.00	11,900.00
Mining	38,000.00	490.00	54,500.00	92,990.00	54,500.00
Food/Beverage	260.00	1,050.00	500.00	1,810.00	1,050.00
Total Emissions (footprint)	39,010.00	13,440.00	56,020.00		

Identifying Type (a) 'hot-spots' is rather straightforward. By summing the elements along the row of a sector it is possible to calculate the direct emissions generated by that sector. In Table 1 such a sector is

‘Mining’. It can be seen that ‘Mining’ is by far the sector with the largest sum of its row. Therefore, ‘Mining’ can be identified as a Type (a) ‘hot-spot’.

In a similar fashion it is equally straightforward to identify Type (b) ‘hot-spots’. Summing down the column of each sector it is possible to calculate the emissions generated throughout each sector’s domestic upstream supply chain to meet each sector’s final demand, i.e. the sector’s domestic CO_2 footprint. In Table 1 ‘Food and Beverage’ is the sector with the largest footprint. This identifies ‘Food and Beverage’ as a Type (b) ‘hot-spot’ and at the same time the significant difference between the sector’s direct emissions and CO_2 footprint suggests that there must be points with large volume of embodied emissions in ‘Food and Beverage’ upstream supply chain.

Focusing solely on the total figures though is not enough. More often than not, specific components of a sector’s supply chain have the largest share of the sector’s total emissions, both in terms of direct emissions and footprint. At the same time the rest of the components have minor or even negligible embodied emissions due to the fact that the underlying supported output is low and/or the emissions intensity is low. In that sense identifying those key points aids in making more targeted policies, instead of generally trying to make specific sectors more environmentally friendly. To identify this type of ‘hot-spots’ it is necessary to establish an emissions threshold level above which every element of (7) will be considered a Type (c) ‘hot-spot’. For illustration purposes, in this chapter, that level is set to be the average of the row maximums. 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. However, there is flexibility in setting the threshold level and can be quite easily set at a level to match the suggestions that derive from research outputs in the field of environmental science and/or political decisions. Regarding the latter, the approach adopted in this chapter, and this thesis as a whole, is compatible and easily applicable in a goal setting framework. Recent multinational agreements like the UNFCCC agreements and the Europe 2020 strategy, require that the participating parties 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.

Looking at the data in Table 1 there are two points that embody more emissions than the average of the row maximums. These are the portions of 'Mining' output required to support 'Agriculture' final demand and 'Food and Beverage' final demand and they can be classified as Type (c) 'hot-spots'. In general, identifying all these different elements and important sectors, i.e. the different types of 'hot-spots', offers policy makers more options as to where interventions can be implemented. However, reviewing the data in Table 1 also reveals the importance of setting the 'hot-spot' threshold level correctly. For example, it can be seen that the output of 'Agriculture' to support the final demand of 'Mining' is not considered a Type (c) 'hot-spot' when using the row maximum average as a threshold level; even though it is the most polluting output of 'Agriculture'. Setting the threshold level lower, for example at 1,000, would then increase the number of Type (c) 'hot-spots' to 5. The scope of this thesis is not to provide a solid way of setting the threshold level rather than to develop the 'hot-spot' analysis methodology and demonstrate ways in which it could be utilised. Still this simple example of sensitivity analysis shows that when applied in real-life scenarios, careful consideration is required when setting the threshold level in order for the analysis to report those components of the supply chains that truly require increased policy attention.

Another important point to note is that the approach described here involves identifying the 'hot-spots' on absolute numbers, that is on the total amount of emissions. The main driver of these emissions is final demand. However, total emissions are directly linked to the emissions multipliers of each sector. It is worthwhile to apply ‘hot-spot’ methodology to Emissions multipliers matrix (6) as well, which is in this case is an alternative application of a simple ‘important coefficient’ approach (Miller and Blair, 2009, p 568). In doing so it is possible to identify elements that have the potential to become ‘hot-spots’ on absolute numbers if their final demand or that of a heavily dependent sector increases. Therefore, acting proactively, potential sources of significant pollution could be avoided. It is important to highlight though that since IO is not a sophisticated modelling tool, if ‘hot-spot’ analysis of (6) is employed to draw conclusions on potential sources of significant pollution then the analysis results will have the underlying assumption that the production technology remains exactly the same.

2.3.4 Data

For this study the IO table used is the 2005 Chinese component of the OECD Inter-Country Input-Output Database (OECD, 2015)[6]. The database consists of 57 countries, both OECD and non-OECD members, plus the Rest of the World. The version of the database used in this paper shares the same sector grouping as the World Input Output Database (WIOD) (Timmer et al, 2015). The industries of each country have been grouped into 35 sectors following International Standard Industrial Classification of all economic activities (ISIC) rev3.1 (see Appendix 1.A for a complete list of sector grouping). 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.

[6] This chapter uses an earlier pilot version of the database. We would like to express our gratitude to OECD Directorate for Science, Technology and Innovation for sharing the database with us and for their continuous support throughout this research project.

On the final demand side there are five types of final demand included:

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

It is important to note at this point that the data are being reported in monetary value of the goods and services traded. China has been selected for this single region study because it is generally recognised as a major emitter of CO_2 and also a major exporter.

The satellite emissions data used come from the WIOD project (Genty, 2012). Among the satellite accounts created from that project there is a detailed table with the emissions generated by each sector, derived from 26 combustible and non-combustible energy sources as well a non-energy category. The sectoral classification matches the one of the OECD database used in this chapter; therefore, there is no need to use a different sector mapping. The WIOD emissions table also includes the emissions of the households as an aggregated category. Household direct emissions are generated as a direct result of consumption of final goods, but they are not part of a sector's downstream supply chain. However, if it is required to calculate the total emissions generated due to private consumption then the household direct emissions should be included in the calculations.

2.4 Results of 'hot-spot' analysis

In this section some interesting results from the analysis are presented. The 'hot-spot' analysis was conducted on CO_2 emissions matrix (7), which was calculated using total final demand. The first sub-section focuses on the direct emissions of Chinese sectors. 'Electricity, Gas and Water Supply' is found to be the largest Type (a) 'hot-spot' and there is additional focus on its downstream supply chain to identify potential Type (c) 'hot-spots'. In the second sub-section the point of focus is the footprint of Chinese sectors. The largest Type (b) 'hot-spot', i.e. the sector with the largest footprint, is found to be 'Construction'. Almost the entire output of 'Construction' is produced to meet its final demand, which is also the largest amongst Chinese sectors, so the sector's upstream supply is examined to look for Type (c) 'hot-spots'.

2.4.1 Direct emitters

As stated in the previous paragraph the first point of focus of this chapter are the direct emissions of the Chinese sectors. Table 2 demonstrates the top 10 most polluting sectors in terms of direct emissions, i.e. the sum of the elements along each sector's row in (7).

In Table 2 the first column of results ('Direct Emissions') refers to the sum of the elements along each sector's row in (7). In the second column these emissions are presented as a percentage share of the total direct emissions. The third column includes each sector's e_i element of matrix E (4), while the fourth column shows the y_j element of each sector in the final demand matrix D_Y. Finally, the last column is the sum of the elements along each sector's row in (3).

Table 2. Top 10 direct emission producers (row totals in (7))

Rank	WIOD Sector Code	Sector	Direct Emissions (kt of CO2)	% share of Total Direct Emissions	CO2 Emissions Intensity (kt of CO2/$m of Total Output) (in (4))	Total Final Demand ($m)	Total Output ($m)
1	E	Electricity, Gas and Water Supply	2,465,835	52.62%	9.85	16,677	250,290
2	26	Other Non-Metallic Mineral	534,003	11.40%	2.77	13,777	192,648
3	27t28	Basic Metals and Fabricated Metal	507,527	10.83%	0.98	67,289	518,324
4	24	Chemicals and Chemical Products	198,595	4.24%	0.59	49,798	337,557
5	C	Mining and Quarrying	135,625	2.89%	0.61	16,288	221,276
6	AtB	Agriculture, Hunting, Forestry and Fishing	134,333	2.87%	0.28	175,715	473,924
7	60	Inland Transport	85,011	1.81%	0.61	30,474	138,453
8	23	Coke, Refined Petroleum and Nuclear Fuel	81,973	1.75%	0.57	10,180	144,451
9	61	Water Transport	81,746	1.74%	1.23	21,967	66,354
10	F	Construction	57,564	1.23%	0.10	533,210	550,417
		All other sectors	403,757	8.62%			
		Total Direct Emissions	4,685,970	100.00%			

As can be seen in Table 2, sector 'Electricity, Gas and Water Supply' (hereafter EGWS) is the largest direct emitter of CO_2 in China. The emissions generated by EGWS significantly outweigh the emissions of any other sector. EGWS alone generates more CO_2 than all the remaining sectors combined. Apart from EGWS, sectors 'Other Non-Metallic Mineral' and 'Basic Metals and Fabricated Metal' generate significant emissions. These 3 sectors are the top 3 direct polluters in China and can be identified as Type (a) 'hot-spots'. In fact, the direct emissions of EGWS, 'Other Non-Metallic Mineral' and 'Basic Metals and Fabricated Metal' combined, account for 74.85% of the total Chinese emissions.

It is important though to explore what is the main driver of the direct emissions.

By examining the data in Table 2 it is easily noticeable that the difference in generated emissions between EGWS and the remaining sectors is due to EGWS CO_2 emissions intensity, which is the largest in China. EGWS is more than 3.5 times more emissions intensive than the second most CO_2 intensive sector, 'Other Non-Metallic Mineral'. These figures are a direct result of China's heavy dependence on fossil fuel to produce electricity, especially in 2005 where major projects like the Three Gorges Dam hydroelectric power plant were not in operation yet.

Emissions intensity is also the main driver of the total direct emissions of the second largest direct emitter, 'Other Non-Metallic Mineral'. On the other hand, the direct emissions of the third sector of Table 2, 'Basic Metals and Fabricated Metal', are a result of the sector having the 5th largest emissions intensity and at the same time being the 3rd largest in terms of value of total output.

Even though data show that the majority of the direct emissions are generated due to the operation of emissions intensive sectors, there are sectors featured on Table 2, despite their emissions intensity being relatively small. For example, the CO_2 intensity of 'Agriculture, Hunting, Forestry and Fishing' is significantly lower than the one of 'Water Transport'. Still the total emissions of 'Agriculture, Hunting, Forestry and Fishing' are significantly more than the ones of 'Water Transport'. It is the total volume of production that drives 'Agriculture, Hunting, Forestry and Fishing' onto the 6th position of the direct emitters. In fact, 'Agriculture, Hunting, Forestry and Fishing' is ranked 4th in gross total output amongst the 35 Chinese industrial sectors.

In any case the amount of emissions generated by Chinese EGWS, classify the sector as the top Type (a) 'hot-spot'. However as seen in Table 2, only 6.66% of the sector's total output is produced to meet the sector's final demand. In fact, out of the sector's total emissions, only 9.66% are generated for its own final demand. This part includes EGWS own requirements to produce for its final consumers. So it is important to look for 'hot-spots' on the EGWS downstream supply chain, which are presented in Table 3.

Table 3. 'Hot-spots' on 'Electricity, Gas and Water Supply' downstream supply chain

WIOD Sector Code	Sector	Embodied Emissions (kt of CO2)	% share of EGWS Total Direct Emissions	Emissions Multiplier (kt of CO2/$m of FD)(element of (6))	Total Final Demand ($m)
F	Construction	563,793	22.86%	1.06	533,210
30t33	Electrical and Optical Equipment	277,576	11.26%	0.74	373,152
E	Electricity, Gas and Water Supply	238,092	9.66%	14.28	16,677
29	Machinery, Nec	168,006	6.81%	1.09	153,890
17t18	Textiles and Textile Products	116,347	4.72%	0.81	144,123
27t28	Basic Metals and Fabricated Metal	108,305	4.39%	1.61	67,289
34t35	Transport Equipment	105,086	4.26%	0.87	120,172
L	Public Admin and Defence; Compulsory Social Security	89,880	3.65%	0.54	167,853
15t16	Food, Beverages and Tobacco	82,090	3.33%	0.50	163,866
M	Education	80,668	3.27%	0.74	108,823
24	Chemicals and Chemical Products	76,682	3.11%	1.54	49,798
N	Health and Social Work	71,475	2.90%	0.82	86,778
AtB	Agriculture, Hunting, Forestry and Fishing	66,186	2.68%	0.38	175,715
	All others	421,650	17.10%		
	Total	2,465,835	100.00%		

In Table 3 the 'Embodied Emissions' column (first column of results) shows the embodied emissions in the requirements of each sector of Table 3 for output from China's EGWS, i.e. the element of each sector on the row of EGWS in (7). In the second column the emissions of the first column are presented as a percentage share of the total direct emissions of EGWS. The third column shows the element of each sector listed in Table 3 on the row of EGWS in (6). The data from this column help understand whether each of the listed sectors has high requirements for output of EGWS to meet its final demand. Finally, the fourth column includes the final demand of each sector, i.e. the y_j of each sector in final demand matrix D_Y.

For an element of Chinese matrix (7) to be considered as a Type (c) 'hot-spot' it has to be above the average of the row maximums of (7), which is 44,900 kt of CO_2. On EGWS downstream supply chain there are 13 Type (c) 'hot-spots', the most compared to any other sector. As can be seen from Table 3 the Type (c) 'hot-spots' on EGWS downstream supply chain account for 82.9% of the sector's total direct emissions. The largest share is held by 'Construction', the requirements of which lead to the generation of 22.86% of EGWS emissions. 'Construction' is also the largest Type (b) 'hot-spot' as it will be shown in the following sub-section and its requirements for EGWS output make a significant contribution to the sector's footprint. Examining the emissions multiplier, element of (6), and the final demand of 'Construction' it seems that even though the emissions multiplier is slightly higher than the average of the other Type (c) 'hot-spots', 1.06 compared to an average of 0.89, it is 'Construction' final demand that leads to significantly more emissions generated.

From Table 3 it is noticeable that sectors 'Basic Metals and Fabricated Metal' and 'Chemicals and Chemical products' have significantly higher requirements for EGWS output, almost twice as much as the average of the Type (c) 'hot-spots'. Therefore, even though the value of their final demand is amongst the lowest on Table 3, still their requirements led to more CO_2 to be emitted, especially 'Basic Metals and Fabricated Metal', compared to other sectors with significantly higher final demand. However, the more characteristic example are the requirements of EGWS to meet its own final demand. The emissions shown in Table 3 though include both the CO_2 emitted during the production of output for the sector's final consumers and the emissions generated to support the production of that output. Out of the 238,092 kt of CO_2 emitted by EGWS to meet its own final demand, 164,304 kt are generated in producing final goods (i.e. the product of the sector's final demand multiplied by the CO_2 emissions intensity) while the remaining 73,788 kt are generated to support the production of output to meet EGWS final demand. The problem that arises in this case is that EGWS is an aggregated sector[7]. It is not possible then, using the data from the IO table, to make any distinction on which part of the 73,788 kt are generated by Gas to support the production of Electricity or by Electricity to support Water Supply. In the same way it is not possible to identify what is the share of each sector included in EGWS in producing output to meet EGWS final demand.

[7] Apart from the inability to make a distinction between the contribution of the different sectors aggregated into EGWS, there are problems that arise from the aggregation itself. Chapter 4 provides a more in-depth discussion on the aggregation problem.

2.4.2 Emissions attributed to final demand

The data of Table 2 show that for the majority of the sectors featured in Table 2 there is a significant difference between their final demand and their total output. The implication is that these sectors mainly produce output to support the final demand of other sectors. That being the case they must be featured on the upstream supply chain of other sectors that they might not be featured in Table 2. For instance, it can be seen from Table 3 that the downstream supply chain of EGWS includes Type (c) 'hot-spots' in sectors that are not in Table 2. It is necessary then to determine which Chinese sectors can be classified as Type (b) 'hot-spots', i.e. have the largest footprint, and focusing on the largest one, whether there are any Type (c) 'hot-spots' in its upstream supply chain. Table 4 shows the top 10 Chinese sectors in terms of domestic footprint. The domestic footprint of each sector is the sum of the elements of its column in (7).

The first column of Table 4 shows the footprint of each sector, i.e. the sum of the elements down the column of each sector in CO_2 emissions matrix (7). In the second column the footprint of each sector is presented as a percentage share of the total footprint of the Chinese sectors. Then in the next three columns the footprint is broken down by source of final demand. In the third column the focus is on private (household) and government consumption, in the fourth column on gross fixed capital formation and in the fifth column on exports. The numbers in columns 3, 4 and 5 are the sum of the elements down the column of each sector in (7), when (7) was calculated using private and government consumption, gross fixed capital formation and exports respectively as the elements of the final demand matrix D_Y.

Table 4. Top 10 sectors in terms of footprint (column totals in (7))

Footprint rank	Direct Emissions rank	WIOD Sector Code	Sector	Total Emissions (footprint) (kt of CO2)	% share of Total Domestic Footprint of Chinese Sectors	Emissions attributed to Domestic Private and Government Consumption (kt of CO2)	Emissions attributed to Domestic Gross Fixed Capital Formation and Inventory (kt of CO2)	Emissions attributed to Exported Final Demand (kt of CO2)
1	10	F	Construction	1,302,264	27.79%	9,451	1,284,984	9,200
2	22	30t33	Electrical and Optical Equipment	503,715	10.75%	24,722	73,454	350,311
3	15	29	Machinery, Nec	295,022	6.30%	2,162	208,373	113,109
4	1	E	Electricity, Gas and Water Supply	244,428	5.22%	222,021	5,133	18,808
5	3	27t28	Basic Metals and Fabricated Metal	236,897	5.06%	12,175	35,511	262,443
6	12	17t18	Textiles and Textile Products	207,174	4.42%	47,251	1,552	167,532
7	19	34t35	Transport Equipment	191,173	4.08%	20,267	131,233	35,975
8	11	15t16	Food, Beverages and Tobacco	180,638	3.85%	151,198	7,071	21,054
9	6	AtB	Agriculture, Hunting, Forestry and Fishing	162,120	3.46%	131,537	22,937	10,461
10	21	L	Public Admin and Defence; Compulsory Social Security	150,518	3.21%	150,078	0	618
			All others	1,212,020	25.86%	635,632	79,962	652,476
			Total Domestic Footprint of Chinese Sectors	4,685,970	100.00%	1,406,494	1,850,209	1,641,987

A first look in Table 4 reveals that some of the sectors included have a significant difference in their ranking in terms of footprint compared to their ranking in terms of direct emissions. Especially in the case of the top two sectors, 'Construction' and 'Electrical and Optical Equipment', the emissions generated to meet their final demand is over 22 and 38 times higher respectively than their direct emissions (the direct emissions of 'Electrical and Optical Equipment' are 13,111 kt of CO_2). This suggests that the magnitude of the footprint of both 'Construction' and 'Electrical and Optical Equipment' is due to the requirements from other sectors rather than 'Construction' and 'Electrical and Optical Equipment' own production. Therefore, 'Construction' and 'Electrical and Optical Equipment' are the largest Type (b) 'hot-spots'.

A rather interesting observation comes by substituting total final demand in (7) with different sources of final demand. By doing so it is possible to capture the impact of a specific type or groups of different types of final demand and the results can be seen in the third, fourth and fifth column of Table 4. For Chinese 'Construction' this shows that the majority of the sector's footprint is associated with domestic gross fixed capital formation, which is the main type of final demand for this sector and linked to development of production capacity to enable economic development. This observation is line with China's status as a developing country. For 'Electrical and Optical Equipment' the main type of final demand, and therefore the one that supports the majority of the sector's footprint, is exported final demand. 'Electrical and Optical Equipment' mainly produces output to be exported as final goods, 55.9% of the sector's exports, or intermediate goods, 44.1% of sector's exports. In total, 'Electrical and Optical Equipment' has the second highest total final demand in China in 2005, 69.5% of which is exported. In a similar fashion the footprint of 'Basic Metals and Fabricated Metal' and 'Textiles and Textile Products' is also supported by exports. Having 3 exporting sectors, 'Electrical and Optical Equipment', 'Basic Metals and Fabricated Metal' and 'Textiles and Textile Products', in the top 10 in terms of footprint seems somewhat logical since China is considered to be one of the major exporters.

Contrary to 'Construction' and 'Electrical and Optical Equipment', two of the most polluting sectors in terms of direct emissions (see Table 2), EGWS and 'Basic Metals and Fabricated Metal', are located significantly lower on the list of the Chinese Type (b) 'hot-spots' (see Table 4). In the case of EGWS the difference between the direct emissions (sum of EGWS row in (7)) and the emissions generated for the sector's final demand (sum of EGWS column in (7)) is over 2.2 billion tons of CO_2, i.e. over 46.9% of the total emissions generated by Chinese industries. Another interesting observation is that, with the exception of the top two sectors in terms of footprint, the emissions are spread more evenly across the whole of the remaining sectors. In essence the majority of the sectors have somewhat even shares of the total emissions attributed to final demand compared to the direct emissions case, where a handful of sectors had the most significant impact and the rest had only minor shares of the total direct emissions.

As in the case of direct emissions it is important to be in a position to determine the main driver of the footprint of the top 10 sectors of Table 4. Table 5 shows the Type I emissions multipliers, i.e. sum down the column of each sector in (6), for the top 10 sectors with the largest footprint.

Table 5. Type I emissions multipliers of top 10 sectors in terms of footprint

WIOD Sector Code	Sector	Total Emissions (footprint)(kt of CO2)	Type I Emissions Multiplier (kt of CO2/$m of Final demand)	Total Final Demand ($m)
F	Construction	1,302,264	2.44	533,210
30t33	Electrical and Optical Equipment	503,715	1.35	373,152
29	Machinery, Nec	295,022	1.92	153,890
E	Electricity, Gas and Water Supply	244,428	14.66	16,677
27t28	Basic Metals and Fabricated Metal	236,897	3.52	67,289
17t18	Textiles and Textile Products	207,174	1.44	144,123
34t35	Transport Equipment	191,173	1.59	120,172
15t16	Food, Beverages and Tobacco	180,638	1.10	163,866
AtB	Agriculture, Hunting, Forestry and Fishing	162,120	0.92	175,715
L	Public Admin and Defence; Compulsory Social Security	150,518	0.90	167,853

As in Table 4 the 'Total Emissions' column is the sum of each sector's column in (7). The 'Type I Emissions Multiplier' column refers to the sum of each sector's column in (6) and the 'Total Final Demand' column has the y_j element of final demand matrix D_Y for each sector of Table 5.

Analysis of the data shows that in China the average Type I emissions multiplier is 1.93 kt of CO_2/\$m worth of final demand. Examining the figures in Table 5 it can be seen that the majority of the top 10 sectors in terms of footprint have a Type I emissions multiplier quite close to the average. It is clear then that the magnitude of the Type (b) 'hot-spots' is mainly driven by the volume of final demand, rather than the Type I emissions multiplier. In fact, 8 out of the 10 sectors of Tables 4 and 5, are the ones with the highest final demand in China. The only two exceptions are EGWS and 'Basic Metals and Fabricated Metal' that even though their final demand is significantly smaller than the rest of the sectors in Table 5, their Type I emissions multiplier is much larger, causing them to be featured on the table. For 'Construction', the largest Type (b) 'hot-spot' in China, the result is a mixture of the fact that it has the 7th largest Type I emissions multiplier and the largest volume of total final demand amongst all Chinese sectors. However, as previously observed the difference between direct emissions and footprint suggests that the major contribution to the sector's footprint is made by the sector's requirements for other sectors' output.

The implication of the observations on 'Construction' is that there must be several Type (c) 'hot-spots' on the sector's upstream supply chain. These 'hot-spots' should make the most significant contribution to 'Construction' footprint. Therefore, it is important to study the structure of 'Construction' upstream supply chain. Table 6 shows the Type (c) 'hot-spots' along with row maximums on Construction upstream supply chain.

The first column of Table 6 shows the elements of each sector on the column of 'Construction' in (7) while the second column presents the elements as a share of the total emissions in the Type (b) 'hot-spot'. The 'Emissions Multiplier' column has the elements of each sector on the column of 'Construction' in (6) while the 'Output Multiplier' are the elements of each sector on the column of 'Construction' in Leontief inverse (2). The benefit of having both the 'Emissions Multiplier' and the 'Output Multiplier' column is that it offers a clearer view on whether the embodied emissions (first column on Table 6) are a result of 'Construction' requiring a large volume of output from a specific sector or that sector's production is CO_2 intensive.

As a reminder the threshold level above which a point of (7) is considered a Type (c) 'hot-spot' is 44,900 kt of CO_2. As seen in Table 6 there are 4 Type (c) 'hot-spots' on 'Construction' upstream supply chain. At the same time there are also the row maximums of 5 more sectors, on 'Construction' upstream supply chain, which do not embody enough emissions to be classified as Type (c) 'hot-spots'. The results reported in Table 6 verify that the magnitude of 'Construction' Type (b) 'hot-spot' is mainly due to the emissions generated by other sectors to support 'Construction' final demand. 'Construction' own production to meet its final demand contributes 4.32% to the sector's footprint. The requirements for output from EGWS as intermediate input of 'Construction' make the most significant contribution, followed by the output from 'Other Non-Metallic Mineral' and 'Basic Metals and Fabricated Metal'. Interestingly these three sectors, EGWS, 'Other Non-Metallic Mineral' and 'Basic Metals and Fabricated Metal', are also the ones with the highest amount of direct emissions as seen on Table 2. Additionally, the output from 'Other Non-Metallic Mineral' to support the final demand of 'Construction' embodies 67.8% of the total direct emissions of 'Other Non-Metallic Mineral'. In fact, all the elements of (7) shown on Table 6 are the row maximums, i.e. the most polluting outputs, of the respective sectors. Interestingly enough, even though the upstream supply chain of 'Construction' includes a number of Type (c) 'hot-spots' and row maximums, the output of 'Construction' is not a Type (c) 'hot-spot' in any other sector's upstream supply chain. This observation is to be expected as the data from Table 2 show that 'Construction' output is mainly final goods to meet the demand of final consumers, rather than intermediate goods for other Chinese sectors.

Table 6. 'Hot-spots' on Construction upstream supply chain

WIOD Sector Code	Producing Sector	Embodied Emissions (kt of CO2)	% share of Construction Footprint	Emissions Multiplier (kt of CO2/$m of final demand)	Output Multiplier ($m of output/$m of final demand)
E	Electricity, Gas and Water Supply	563,793	43.29%	1.057	0.107
26	Other Non-Metallic Mineral	362,077	27.80%	0.679	0.245
27t28	Basic Metals and Fabricated Metal	149,726	11.50%	0.281	0.287
F	Constructions	56,202	4.32%	0.105	1.008
C	Mining and Quarrying	39,164	3.01%	0.073	0.120
23	Coke, Refined Petroleum and Nuclear Fuel	19,613	1.51%	0.037	0.065
63	Other Supporting and Auxiliary Transport Activities; Activities of Travel Agencies	9,614	0.74%	0.018	0.039
21t22	Pulp, Paper, Paper , Printing and Publishing	4,912	0.38%	0.009	0.030
20	Wood and Products of Wood and Cork	3,761	0.29%	0.007	0.053
	All Others	93,402	7.17%		
	Total	1,302,264	100.00%		

The fact that ‘Construction’ has the largest volume of final demand amongst the Chinese sectors plays a significant role. At the same time, it is important to distinguish whether the Type (c) ‘hot-spots’ in ‘Construction’ upstream supply chain are driven by each sector’s CO_2 intensity or ‘Construction’ high requirements for output. Examining the emissions multipliers column of Table 6 is a first step. It can be seen that the requirements for output from EGWS and ‘Other Non-Metallic Mineral’ have the larger emissions multiplier, which, due to the large final demand, leads to large amounts of embodied emissions. However, that does not necessarily mean that ‘Construction’ requires large amounts of input from EGWS and ‘Other Non-Metallic Mineral’. Examining the ‘output multiplier’ column of Table 6, which shows the elements of Leontief inverse (2), it can be seen that in the case of EGWS, ‘Construction’ require less output per $m of final demand compared to requirements from other sectors. Still the large CO_2 emissions intensity of EGWS seen on Table 2 leads to a significant impact in terms of embodied emissions. ‘Other Non-Metallic Mineral’ is somewhat similar, being the second most CO_2 intensive sector, but at the same time ‘Construction’ production is significantly more dependent on output from ‘Other Non-Metallic Mineral’ than EGWS. In fact, ‘Construction’ is most dependent on inputs from sectors ‘Other Non-Metallic Mineral’ and ‘Basic Metals and Fabricated Metal’, with different degrees of associated emissions per unit of final demand, due to the different CO_2 emissions intensities.

2.5 Conclusions and extensions

Input Output is a well-established methodology to study the emissions generated as a result of economic activities. However, previous studies mainly used aggregated results in terms of Consumption Accounting Principle (CAP) and Production Accounting Principle (PAP) and focused their interpretation in terms of these two headline indicators on how they relate to each other. As a result, there is limited information obtained regarding the structure of the emissions, the generation of which and their drivers appear to be the output of a black box. Without a more detailed picture of the structure of the emissions, policy decisions can only be based on headline figures like the CAP and PAP emissions, which in turn means that policies target whole sectors that are identified as polluting rather than focusing on the components of their supply chains that hold the major shares of the emissions.

The goal of this study was to develop a method that provides transparency in the structure of both the direct emissions and the CO_2 footprint of each sector. Furthermore, by using such a transparent method, we established an approach by which it is possible to distinguish the most important amongst the different components of any given supply chain, i.e. the 'hot-spots'. In principal, the 'hot-spot' methodology builds on elements of the established key sector and 'important coefficient' analysis methods. The Type I multipliers presented in Table 5 are the analogous to the backward linkages of each sector in key sector analysis, whereas the discussion on output multipliers of Table 6 is in essence a basic 'important coefficient' analysis. To these elements of key sector and 'important coefficient' analysis, the 'hot-spot' methodology adds the analysis of emissions intensities, emissions multipliers, final demand and total output, so that it generates an as comprehensive report as possible on the structure and the driver of each sector's emissions.

We believe that the comprehensive nature of this analysis will be a useful tool for policy makers in developing climate change mitigation policies and meeting the goals set as part of international agreements. Furthermore, the identification of specific components of each sector's supply chains offers the potential for targeted policies. For example, the analysis of the results in this chapter has revealed that Chinese 'Construction' sector has the largest domestic CO_2 footprint amongst all sectors in China. Without a clear picture of the structure of the 'Construction' footprint, the policy option might have been to restructure the sector as a whole. However, 'hot-spot' analysis has revealed that the requirements from the Chinese EGWS sector contribute significantly to the footprint of the Chinese 'Construction' sector. This finding indicates to policy makers that significant gains can be made in terms of reduced CO_2 emissions either by reducing the 'Construction' requirements for output from EGWS or by making EGWS less emissions intensive.

As mentioned previously in this chapter the reasoning behind identifying 'hot-spots' is to highlight sectors as a whole and components of the supply chains of any sector, which embody significant emissions and therefore merit attention at the policy level. A similar driver led to the development of key sector analysis so that policy makers would be in a position to identify sectors where increased emphasis and allocation of resources would maximise the economy-wide benefits (Miller and Lahr, 2001). However, in this research project the 'hot-spot' methodology is used (and proposed to be used) to provide an ex-post analysis of the embodied emissions in supply chains, rather than for ex-ante planning purposes for which, as Midmore et al (2006) have pointed out, the usefulness of IO frameworks is limited.

This is one of the main limitations of the proposed methodology. It is a specialised tool focused on the identification of the most important amongst a number of elements. To be used for planning purposes it would be necessary to combine 'hot-spot' analysis with commonly used IO analysis tools like employment and value-added multiplier analysis so that it can be identified which of the 'hot-spots' present the minimum risk possible for losses in terms of employment positions and value-added generated. Following that the use of a sophisticated modelling tool like Computable General Equilibrium on the selected sectors would provide a more advanced representation of what would be the economy-wide impact of interventions on the selected 'hot-spots'.

The other main limitation is that 'hot-spot' analysis is a static picture of an otherwise dynamic system. This problem could be rectified by conducting a historical 'hot-spot' analysis in multiple years, which would reveal the evolution of the 'hot-spots' due to economic changes and/or implemented policies. At the same time though it would help clarify which of the initially identified 'hot-spots' manifest as on-going issues and which, if any, are just one-off problems that disappeared or were resolved.

However, historical analysis is only one of the potential steps forward in further applying 'hot-spot' analysis. Since the modern economy is globalised, the supply chains rarely are restricted within the borders of a single country. Therefore, it is important to extend the methodology introduced here to the global level and analyse the impact of international trade. Applying this methodology to Inter-Regional Input-Output seems to be a logical next step. IRIO offers the ability to study the supply chains of sectors in multiple countries. Furthermore, as we are not limited to the domestic side of supply chains, it is possible to identify 'hot-spots' on the international part of any supply chain.

Chapter 3: Carbon 'hotspots' in global supply chains: an inter-regional input-output analysis.

Abstract

This chapter extends the CO_2 'hot-spot' identification methodology to an Environmental Inter-Regional Input Output (EIRIO) accounting framework. Drawing on OECD Inter-Country Input Output tables, we decompose standard EIRIO headline calculations of production and consumption perspective emissions. We show how this facilitates consideration of downstream demands driving the production and associated emissions of CO_2 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.

3.1 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. 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, early indications show that policy focus in the upcoming UNFCCC COP21/CMP11 (in Paris, November 2015) will remain the same, which means that territorial PAP will most likely 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 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.

As shown in the previous chapter of this thesis for a Single Region IO (SRIO), a 'hot-spot' approach that 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. However, in a globalised economy, 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[8] (OECD, 2015)[9] 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

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

[9] In this thesis 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.

provides a review of the existing relevant literature. Section 3.3 expands on the methodology and the data used while in Section 3.4 some key results are presented and discussed. The final section concludes and offers suggestions for further research.

3.2 Literature background

Early CAP and PAP studies used 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 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, 2011a). 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 interregional 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 thesis 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.

3.3 Methodology and data

3.3.1 Inter-Regional Input Output

In the previous chapter, 'hot-spots' were identified in a SRIO. However, 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 chapter, is the following.

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

X^{11} is a $N\times1$ 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} now become 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)

As in the single region case, 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:

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

Each element y_{jz}^{rs} of $DY_{z\ IRIO}^{s}$ 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:

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

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[10]. 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.

3.3.2 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 chapter) generated by sector i in

[10] 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).

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}:

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

Cem_{IRIO} is the core matrix of the method used in this chapter 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.

3.3.3 Emissions 'hot-spots'

This chapter extends the methodology developed in a single region context in the previous chapter to identify 'hot-spots' both upstream and downstream on global supply chains. As in the single region case three types of 'hot-spots' are identified:

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

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'.

As can be seen in Table 1, but was also suggested by the findings in the previous chapter, Type (c) 'hot-spots' more often than not either have the major share of a sector's direct emissions or contribute the majority of emissions to a sector's footprint. As an illustrative example of a 'hot-spot' threshold, we may identify 'hot-spots' of this type by first identifying the row maximums for each row in (7), in the same way that is was calculated in the previous chapter. Then, if we take the average of row maximums, every element of (7) above this average may considered a Type (c) 'hot-spot'. 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.

In practice there may be some more specific and policy-motivated means of specifying thresholds (in the context of emissions targets etc.). In the previous chapter it was indicated that '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. 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 thesis 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.

3.3.4 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 2.A for a full list of countries);
- Industrial sectors have been grouped into 37 sectors following ISIC v3.1 (see Appendix 2.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 thesis 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 2.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.

3.4 Results

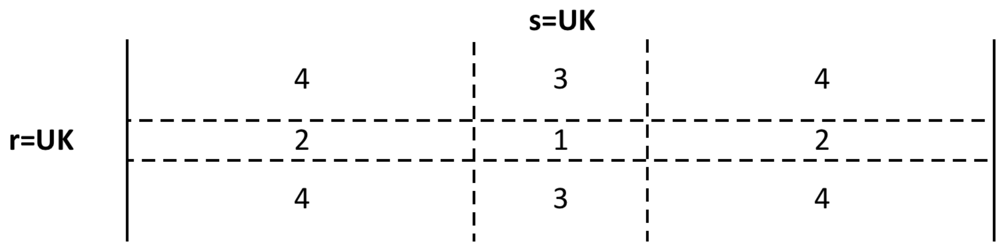
3.4.1 General overview

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 3.3.4). 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 2.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 $r, s \neq$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 the SRIO described in the previous chapter.

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 chapter, 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 3.3.4) 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.

3.4.2 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 chapter 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 CO_2)	% share of Total Direct Emissions (UK Total Final Demand)	% share of sector's Direct Emissions (Total Final Demand)	CO_2 Intensity (Mt CO_2/$m output)	UK Total Final Demand ($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, as discussed in the conclusion of the previous chapter, 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 we return to in the next chapter, where sub-national regional data are used to further analyse 'hot-spots' identified via IRIO analyses. 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%[11]. 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 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

[11] 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.

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 inter-Regional 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 hotspots 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.

3.5 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.

Expanding 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 thesis 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 (which will be discussed in the next chapter) 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 thesis 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 thesis, 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 mentioned in the previous chapter 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 the analysis on SRIO. Whereas at the national level (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 inter-regional 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 (as was the case in Chapter 2). 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 (and will be used in the next chapter), 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.

Chapter 4: The benefits of using regional Input Output tables and the importance of region-specific satellite emissions data.

Abstract

Environmental Multi- and Inter-Regional Input Output methods are commonly used tools to account for CO_2 emissions generated by production of and demand for output of economic sectors in different countries and, crucially, to capture the impact of international trade. However, the need for harmonised data can result in a high level of aggregation, which reduces the detail on activity within a given economy and leads to biases and errors. Single Region Input Output analysis based on national/regional statistics can be significantly more detailed in terms of interactions between producing and consuming sectors within the region. The additional details on the regional level can be a useful tool for regional governments that aim to reduce the emissions generated within their borders. However, regional IO tables lose in terms of details and accuracy when it comes to interaction between producing and consuming sectors located in different regions/countries. This chapter argues that Single Region Input Output can be used as a follow on to the type of 'hot-spot' analysis reported in the previous chapter to provide the details lost through the greater level of sectoral aggregation imposed in an Inter-Regional Input Output framework. Moreover, taking the UK as a case study, we consider the implications of moving from an IRIO down to a SRIO analysis for a region where key polluting sectors have distinct pollution characteristics (e.g. Scottish electricity supply). Analysis of Scottish data reveals that the major Scottish direct emitting sectors form important but distinct parts of the aggregated top direct emitting UK sectors as identified using IRIO. However, we find that the emissions 'hot-spots' calculated for some of the Scottish sectors will be overestimated if region-specific emissions data for Scotland are not considered. We demonstrate how region-specific satellite emissions data are crucial to perform

accurate calculations and that adjusting the emissions intensity of one sector using region specific data has an impact on the CO_2 footprint of all the sectors in an economy.

4.1 Introduction

Climate change is a policy problem that has attracted significant research attention from a range of disciplines over the past decades. As explained in the previous two chapter, there have been numerous studies, many involving application of input-output (IO) methods on the impact of human economic activities, especially in terms of emissions of greenhouse gases. On the policy front there have been efforts to mitigate the climate change especially via the multi-lateral decisions made in the conferences of UNFCCC parties. This chapter moves on to consider the context of where agreements made at national level (e.g. UK) involve devolution of responsibility in setting and meeting targets to regions (e.g. Scotland), where the composition and nature of polluting activity may be quite distinct.

To recap, IO analysis has become a widely used framework due to the fact that it is a rigorous and systematic approach to study the direct emissions and the footprint, the emissions attributed to final demand, of all the sectors in an economy. Due to the importance of international trade, more recent studies have tended to favour IO frameworks that include multiple regions and capture the environmental impact of international trade, i.e. Multi-Regional (MRIO) or Inter-Regional (IRIO) Input-Output.[12] However due to the nature of the datasets required for IRIO, there are losses in terms of accuracy as sectors need to be aggregated permitting harmonisation across a single dataset incorporating many countries.

[12] The distinction between MRIO and IRIO is explained in the previous chapter. From this point onwards the chapter will focus mainly on IRIO.

In general, there is a trade-off between using Single Region Input Output (SRIO) created from published IO tables based on national/regional statistics and IRIO, which involves harmonising data from numerous sources. In particular, SRIO offers a high level of detail due to the fact that the industrial sectors included in national/regional statistics are generally less aggregated than in IRIO tables. On the other hand, by reporting trade flows in IO format, IRIO allows us to consider the environmental impacts of emissions/energy/water uses embodied in international trade. Focusing on the UK as a country and Scotland as a (devolved) region of the UK (with its own climate change targets[13]), this chapter argues that there are significant gains to be made by using the results of IRIO as a guideline to identify sectors that would benefit from more in-depth analysis at national or sub-national level using SRIO. Furthermore, it is suggested in this chapter that having region-specific emissions data for key sectors (e.g. electricity supply) operating at regional level within the UK (e.g. Scotland, where generation from renewables is more prevalent than at national level) is of paramount importance.

The structure of this chapter is as follows. The second section offers a brief review of relevant literature. The third section briefly presents the methodology used while the fourth section compares the results obtained by using IRIO and SRIO. The fifth section compares the results from SRIO to the emissions reported by the Scottish industries and the sixth section concludes and suggests potential extensions.

4.2 Literature background

The extent of international trade in modern economy has led numerous researchers to study its environmental impact. To that end MRIO has been a rather useful and evolving tool. Wiedmann et al (2011) provide an extensive review of the evolution of MRIO. The problem is that to create MRIO and IRIO tables it is necessary to have a common sector mapping as pointed out by Turner et al (2007). This

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13 See http://www.gov.scot/Topics/Environment/climatechange

leads to the use of aggregated sectors. Any level of sector aggregation, including over-aggregation, has the potential to generate bias and lead to aggregation errors. Ara (1959) and Miller and Blair (1981), both present criteria that determine whether an aggregation is acceptable or not. Following these criteria, for two or more sectors to be aggregated in an acceptable way, they need to have similar structures in terms of required inputs from other sectors.

Even when that is the case though it has been shown by de Mesnard and Dietzenbacher (1995), that the input coefficients of an aggregated sector do not match the weighted input coefficients of the sectors included in the aggregated sector. This finding indicates the potential for errors that is driven by over-aggregating sectors. As pointed out by Lahr and Stevens (2002) both the aggregation error as a concept and the methods in which the aggregation bias can be measured have been explored by various studies. Unfortunately though, the method for estimating the aggregation bias presented by Miller and Blair (2009, pp 165-167) requires the availability of both the aggregated and disaggregated IO tables in order to estimate the bias. This is a problem faced by studies where the IO tables have been obtained by external sources that have already aggregated the sectors. Therefore, the underlying assumption when using highly aggregated IO tables is that the people that have created the tables have aggregated sectors in such a way that follows the criteria of Ara (1959) and Miller and Blair (1981).

So far the discussion involved aggregating sectors at the economic level. When considering the environmental impact of different sectors, the aggregation criteria can be expanded to include similar emissions. However, according to Hawdon and Pearson (1995), over-aggregated sectors can include industries with significantly different pollution characteristics. As a result, analysis of the data from IRIO tables where, for example, we have a single 'Electricity, Gas and Water Supply' sector in each country, could mask significant levels of emissions involved in key inter-sector interactions, such as the emissions generated producing electricity used to support water supply. Furthermore, different industries with different emissions intensities that are aggregated together in an IRIO may be viewed as sharing the same (average) emissions intensity, which would generate misleading results particularly where marginal changes in activity impacting just one sub-industry. Especially in the case of electricity generation several studies argue in favour of a high degree of disaggregation (e.g. McNicoll and Blackmore, 1993; Gale, 1995). In fact, Wyckoff and Roop (1994) have shown that by using more aggregated sectors leads to underestimations in the total CO_2 emissions.

Depending on several parameters, including but not limited to funding, national/regional IO tables can less aggregated, although as discussed by Lahr and Stevens (2002) regional IO tables that are not implemented properly can be highly aggregated compared to national IO tables and therefore lead to significant errors. Comparing the OECD Inter-Country Input Output database (OECD, 2015), that was used in the first two chapters (and will also be used in this one), with the database used by Munksgaard and Pedersen (2001), for example, it is easily noticeable that the latter includes far less aggregated sector mapping, 130 sectors (for the tables after 1988) compared to 37 in the OECD database. Therefore, SRIO based on national/regional IO tables with a lower level of aggregation offers the opportunity for analysis without errors due to over-aggregation issues highlighted by Miller and Blair (1981 and 2009), de Mesnard and Dietzenbacher (1995) and Hawdon and Pearson (1995).

Unfortunately choosing between the single region framework (SRIO) and the multiple regions (IRIO) includes significant trade-offs. Focusing on one country potentially compromises the accuracy of any findings regarding impacts of international trade, as shown by Lenzen et al (2004) and Shui and Harriss (2006). At the same time the aggregation of every extra-regional region or country into a limited number of aggregated regions, leads to the introduction of bias (Miller and Blair, 1981). It can be seen then that moving from a highly aggregated IRIO to a disaggregated SRIO involves reducing the biases due to the aggregation level of industrial sectors but increasing the bias due to the aggregation of countries and regions. Ideally, when there is an option to do so, one should select an IO framework based on the minimum bias due to aggregation. However, more often than not the selection is directed by the research interests as pointed out by Lahr and Stevens (2002). In the case of our 'hot-spot' analysis, focusing on the national/regional level not only benefits from enhanced level of intra-country detail, but the findings may be more relevant to policy makers as they usually focus on territorial production-driven emissions, partly due to the type of jurisdictional issues raised by Turner et al (2011a).

4.3 Methodology

4.3.1 Environmental Input Output

Recapping on the methodology detailed in the previous chapter, our first step is to use the IRIO method presented by Miller and Blair (2009), Turner et al. (2007). The key transmission mechanism in a demand-driven IRIO, and indeed every IO, model is the Leontief Inverse matrix. For an IRIO it is the following:

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

The Leontief Inverse is the matrix of output multipliers. 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 sum of the elements down the column of each sector j is the Type I multiplier which reflects the value of the output required by all the sectors in all regions to support one monetary unit worth of final demand for the output of sector j in region s.

When the Leontief Inverse is post-multiplied with the diagonal matrix of final demand then the result is the following matrix:

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

Matrix X is the $N \times N$ output matrix. Each element $l_{ij}^{rs} y_j^s$ represents the output of sector i in region r required to meet the final demand of sector j in region s; $i, j = 1, \ldots, N$ and $r, s = 1, \ldots T$. When the focus is on a single region then $r = s$. For the purposes of this chapter as final demand is considered total final demand.

The IRIO can be extended to report the emissions generated during the production of output. Since environmental impact is considered an externality is usually omitted from national statistics and needs to be calculated indirectly (Leontief, 1970). To achieve this, it is necessary to use emissions coefficients that will transform the standard IRIO so that it reports output in terms of emissions rather than monetary value. The emissions coefficients are arranged in a matrix format, matrix E.

$$E_{IRIO} = \begin{bmatrix} E^r & & 0 \\ & \ddots & \\ 0 & & E^T \end{bmatrix} = \begin{bmatrix} e_i^r & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & \ddots & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & e_N^r & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & \ddots & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & e_i^T & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & \ddots & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & e_N^T \end{bmatrix} \quad (3)$$

Each element e_i^r of matrix E is the emissions coefficient of sector i and shows the emissions generated by each unit of output produced by sector i in region r. To calculate the emissions coefficient of any sector, the total emissions generated are divided by the total output of the sector. For this process it is necessary to have a satellite emissions data at the sector level for every sector in every country included in the IRIO.

Pre-multiplying the E matrix (3) to the Leontief Inverse (1) generates what in the previous two chapters was described as Emissions multipliers matrix.

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

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. Similarly to the Leontief Inverse, summing the elements down the column of each sector j gives us the Type I emissions multiplier for that sector. This corresponds to the emissions generated by all sectors in all regions in producing output to support the final demand of sector j in region s.

Post-multiplying the Emm_{IRIO} by the diagonal matrix of final demand results in the core matrix of the Environmental IRIO (EIRIO), which throughout the previous two chapters was called CO_2 emissions matrix (Cem).

$$Cem_{IRIO} = EL_{IRIO}DY_{IRIO} = \begin{bmatrix} e_i^1 l_{ij}^{11} y_j^1 & \cdots & e_i^1 l_{ij}^{1s} y_j^s & \cdots & e_i^1 l_{iN}^{1T} y_N^T \\ \vdots & \ddots & \vdots & \ddots & \vdots \\ e_i^1 l_{ij}^{r1} y_j^1 & \cdots & e_i^r l_{ij}^{rs} y_j^s & \cdots & e_i^r l_{iN}^{rT} y_N^T \\ \vdots & \ddots & \vdots & \ddots & \vdots \\ e_N^T l_{Nj}^{T1} y_j^1 & \cdots & e_N^T l_{Nj}^{Ts} y_j^s & \cdots & e_N^T l_{NN}^{TT} y_N^T \end{bmatrix} \quad (5)$$

Cem is the main matrix that will be used for analysis in this chapter. Each element $e_i^r l_{ij}^{rs} y_j^s$ of (5) shows the emissions generated by sector i in region r to support the final demand of sector j in region s. As with the case of output matrix (2) when focusing on a single region we have that $r = s$. The elements on the row of each sector i represent the different components of the sector's downstream supply chain, the output produced to support the final demand of other sectors, and the sum of all the elements along the row is the amount of the direct emissions generated by sector i. On the other hand, the elements down the column of each sector j are the different components of the sector's upstream supply chain, the requirements from other sectors to meet its final demand, and the sum of the elements down the column is the footprint of sector j.

The SRIO variant of the above is detailed in Chapter 2 of this thesis. However, it simply involves assuming that $r = s = 1$ in the above system. For purposes of comparison between IRIO results for the UK and moving to the Scottish IRIO analysis, we focus on the own-country (i.e. $r = s$) results for equation (5).

4.3.2 Emissions 'hot-spots'

In the first chapter we established a methodology to identify 'hot-spots' in downstream and upstream supply chains. There are three types of 'hot-spots':

(a) A sector that in producing output generates directly significantly more emissions compared to other sectors in an economy either to support total final consumption demand or components thereof; i.e. has a larger sum of its row in CO_2 emissions matrix (5);

(b) A sector where the output produced to meet its final demand (again, either in total or components thereof), directly and/or indirectly, has a larger footprint, i.e. larger sum down its column in (5), compared to other sectors in an economy;

(c) A point in a sector's downstream or upstream supply chain, an element within (5), that embodies emissions above a set threshold level in serving all or particular type(s) of final consumption demand.

The same methodology is also used in this chapter to identify the 'hot-spots' in Scottish supply chains. The sum of the elements on each sector's row in (5) is calculated and the sectors with significantly higher sum are classified as Type (a) 'hot-spots'. In the same way the sum of the elements down the column of each sector in (5) is calculated and the sectors with the largest sum are considered as Type

(b) ‘hot-spots’. Finally, for the purposes of this chapter, and this thesis as a whole, the average of the row maximums in (5) is set to be a threshold level, above which every element of (5) is considered as a Type (c) ‘hot-spot’.

4.3.3 Data

This chapter employs two distinct databases. For the IRIO analysis, focusing on the UK as a case study therein, the pilot OECD Inter-country Input-Output Database (OECD, 2015)[14] is used focusing on the most recent data of 2009. The database consists of

- 57 countries, both OECD and non-OECD members, plus a composite Rest Of the World region (see Appendix 3.A for a full list of countries);
- Industrial sectors have been grouped into 37 sectors following ISIC v3.1 (see Appendix 3.B for complete list of sector groupings);
- 5 sources of final demand.

For the SRIO the 2009 Scottish Industry by Industry IO tables have been used (The Scottish Government, 2014). The reason is to match the year of the IRIO so that the findings could be compared. The Scottish IO tables include

- 98 industrial sectors;
- 8 types of Scottish final demand;
- 2 types of exported final demand, including Rest of UK and Rest of World.

[14] In this chapter an earlier version of the database is used.

The data in the Scottish IO tables were reported in GBP therefore to match the data in the OECD Inter-Country Input Output Database it was necessary to convert them to US Dollars using the average exchange rate of 2009; 1GBP = 1.564856USD.

Also in the interest of enabling comparisons the emissions account used in the IRIO and also in the third chapter was also used here. We start out by applying UK intensities, e_i, for each sector in the Scottish system (and later introduce Scottish-specific data). This allows us to consider the impact of focusing on the region-specific economic interactions that are important in the Scottish case, abstracting from the region-specific polluting characteristics.

Mapping from the UK data within the OECD emissions dataset ensures that the same types of emissions are allocated to each group of sectors (i.e. emissions from fuel combustion, autoproducer emissions, fugitive gases, industrial processes). However, since the Scottish IO tables use UK Standard Industrial Classification of economic activities 2007 (SIC 2007), while the OECD database used the International Standard Industrial Classification of all economic activities rev. 3.1 (ISIC rev. 3.1), it was necessary to match the OECD sectors with the Scottish IO sectors. Appendix 3.B shows how OECD sectors are matched to Scottish IO sectors. Additionally, because of different levels of aggregation, it is assumed that multiple Scottish IO sectors that belong in the same group under OECD classification, share the same CO_2 emissions intensity. There is a single case where three UK sectors under OECD classification are included in one Scottish IO sector and in this case the CO_2 emissions intensity used is the average of the intensities of the OECD sectors. Appendix 3.C shows the CO_2 emissions intensities of the Scottish sectors.

The initial analysis then in Section 4.4 is conducted using the same data, and therefore the same emissions account, that was used in the previous chapter. In Section 4.5 we consider the impact of introducing Scottish specific emissions-intensity data for key polluting sectors, an approach that has been followed by McGregor et al (2008). There we draw on data produced by the Scottish Environmental Protection Agency (SEPA)[15] as published on their website as well as data from the Longannet power station EMAS 2014. Since 'Electricity' is found to be a rather important Scottish sector in terms of direct CO_2 emissions, it is necessary to have a clear picture on the active thermal power plants in Scotland. A list of the currently operational thermal power stations in the UK can be found at the Gov.uk website[16].

4.4 Case study demonstrating the benefits of using SRIO based on national/regional economic IO data to add information to an IRIO 'hot-spot' analysis

As explained in the introduction, the Scottish regional economy within the UK national economy is used in this chapter as a case study. The process that will be followed in this section is to first present and discuss results of an IRIO 'hot-spot' analysis focused on UK sectors. These results are then compared to the results derived from a SRIO analysis based on the published Scottish IO tables. The goal of this section is to demonstrate in a clear way the additional information that can be obtained by using national/regional IO tables when focusing on a single country/region.

Our first point of focus, which is important going forward, is direct emissions. By analysing IRIO data for $r=$UK as the producing region, we identify the total direct emissions of UK sectors. Table 1 shows the top 10 UK sectors with the largest volume of direct emissions, i.e. the largest sum of elements along their row in (5).

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15 http://apps.sepa.org.uk/spripa/Search/Options.aspx

16 https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/446457/dukes5_10.xls

Table 1. Top 10 UK sectors in terms of direct emissions

Rank	OECD Sector Code	Sector	Total Direct Emissions (Mt of CO2)	%share of Total UK Direct Emissions	CO2 Intensity (Mt of CO2/$m of output)	Total Final Demand ($m)	Total Output ($m)
1	C40T41	Electricity, Gas and Water Supply	342.40	37.47%	0.00299	57,877.36	114,527.34
2	C60T63	Transport and Storage	141.71	15.51%	0.00079	57,679.74	178,982.35
3	C50T52	Wholesale and Retail; Repairs	50.81	5.56%	0.00012	246,461.62	411,641.78
4	C23	Coke, Refined Petroleum and Nuclear Fuel	35.92	3.93%	0.00113	7,198.71	31,812.09
5	C24	Chemicals and Chemical Products	31.62	3.46%	0.00045	27,832.84	70,494.93
6	C85	Health and Social Work	22.79	2.49%	0.00007	278,692.36	345,408.46
7	C74	Other Business Activities	21.11	2.31%	0.00004	69,853.79	487,861.48
8	C27	Basic Metals	17.71	1.94%	0.00028	14,937.90	63,299.86
9	C55	Hotels and Restaurants	15.72	1.72%	0.00012	123,294.18	130,026.50
10	C90T93	Other Community, Social and Personal Services	15.60	1.71%	0.00009	118,498.87	173,974.91
		All Others	218.52	23.91%			
		Total UK Direct Emissions	913.92	100.00%			

The 'Total Direct Emissions' column (first column of results) shows the sum of the elements along the row of each sector in (5) and the second column presents them as a percentage share of the total UK direct emissions. The third column refers to the element e_i^r of each sector in (3) for r =UK. The fourth column is the total final demand of each sector, y_j^s in (2) and (5), while the last column is the sum of the elements along the row of each sector in (2).

From the data in Table 1 it can be seen that the sectors that have the most significant share of UK's total direct emissions are 'Electricity, Gas and Water Supply' (hereafter EGWS), 'Transport and Storage' and 'Wholesale and Retail; Repairs'. These three sectors can be classified as Type (a) 'hot-spots'. However, they all share a common characteristic. As can be seen in Appendix 3.B, all three sectors are aggregated groups of industries under ISIC rev3.1. The gives rise to a problem in that it is not possible to make a distinction on which part of the aggregated sectors is generating the majority of the direct emissions. For example, 'Transport and Storage' is the second largest Type (a) 'hot-spot' amongst UK sectors. However, transportation of passengers and cargo can utilize numerous means, all of which are likely to have different environmental impacts in practice. If data are only available on the aggregated sector it is not possible to identify which of the means of transportation is generating the largest share of the aggregated sector's direct emissions. From a policy perspective this lack of information limits the information set available to policy-makers and, thus, their ability to target policies. It is not possible for policy makers to identify whether the main contributor to the aggregated sector's total emissions is road transports, railroads, marine traffic, aviation or even the transportation support activities (e.g. warehouses, travel agencies etc.). Under this information constraint the only possible approach is to implement policies that involve all of these activities, even if most of emissions are generated by only one of them. Therefore, any implemented policies may be somewhat "broad-brush" rather than well targeted/focused.

A different aspect of the over-aggregation problem is demonstrated by the third largest Type (a) 'hot-spot'. Data on Table 1 show that the emissions intensity of 'Wholesale and Retail; Repairs' is amongst the lowest in all the sectors of Table 1. Therefore, the volume of direct emissions generated is due to the volume of output involved, which is the second largest amongst the Table 1 sectors. Examining columns 'Total Final Demand' and 'Total Output' for 'Wholesale and Retail; Repairs' it can be seen that more than half of the sector's output is produced to meet the demand from final consumers (i.e. not the wholesale part of the sector). Having a large aggregated sector makes it impossible to identify exactly which part of the sector's activity is serving the largest share of the aggregated sector's final demand so that different demand drivers of associated emissions cannot be clearly identified.

In both cases having additional information and more details on sectoral level interactions can aid in making more informed decisions. By being in a position to identify exactly which part of an aggregated sector holds the largest share of the sector's emissions, enables the introduction of policies that focus directly on the activities of this specific part/sub-sector. The potential benefit from such an approach is to use the available resources in a more efficient way, achieving the desired results faster and with reduced costs compared to trying to change an aggregated sector.

To that end, disaggregated regional and national statistics[17] can prove to be a valuable source of data. Table 2 shows the top 10 Scottish sectors in terms of direct emissions, i.e. the sum of the elements along the row in (5) for $r = s =$Scotland. As a reminder the disaggregated Scottish sectors have the same emissions intensities as the aggregated UK sectors. For the matching between UK and Scottish sectors please refer to Appendix 3.B.

Table 2: Top 10 Scottish sectors in terms of direct emissions

Rank	Scottish Sector Number	Sector	Total Direct Emissions (Mt of CO2)	% share of Total Scottish Direct Emissions	CO2 Intensity (Mt of CO2/$m of output)	Total Final Demand ($m)	Total Output ($m)
1	46	Electricity	37.27	35.49%	0.00299	4,975.39	12,466.09
2	26	Coke, Petroleum & Petrochemicals	9.49	9.04%	0.00113	6,723.15	8,407.34
3	49	Waste, Remediation & Management	6.34	6.04%	0.00299	1,562.72	2,122.02
4	48	Water and Sewerage	6.19	5.89%	0.00299	1,342.76	2,070.58
5	47	Gas etc	6.18	5.88%	0.00299	1,163.73	2,066.92
6	58	Support Services for Transport	4.60	4.38%	0.00079	1,537.68	5,815.21
7	55	Other Land Transport	4.12	3.92%	0.00079	2,079.21	5,198.28
8	53	Retail - excl vehicles	1.75	1.67%	0.00012	13,952.37	14,184.41
9	52	Wholesale - excl vehicles	1.50	1.43%	0.00012	8,653.86	12,138.72
10	8	Mining Support	1.43	1.36%	0.00017	7,719.12	8,364.61
		All others	26.14	24.89%			
		Total Scottish Direct Emissions	105.01	100.00%			

Similarly to Table 1, the first column of Table 2 is the sum of the elements along each sector's row in (5) while the second column shows the emissions of the first column as percentage share of the total Scottish direct emissions. 'CO2 Intensity' column shows the element e_i^r of each sector in (3) for $r =$Scotland. Finally the 'Total Final Demand' column shows the y_j^s for each sector in (2) and (5) and for $s =$Scotland, where 'Total Output' is the sum of the elements along the row of each sector in (2).

Note that the activity level results reported for Scotland in Table 2 are significantly smaller the UK equivalents in Table 1. This is broadly in line with the fact that Scottish sectors produced around 8.4% of the total value of output produced in the UK. At the same time the calculations performed using the Scottish SRIO indicate that the total direct emissions of Scottish sectors are roughly 11.5% of the total

[17] As discussed during the literature review it has been show by Lahr and Stevens (2002) that highly aggregated regional and national IO tables have significant errors as a result of the aggregation level. Our goal though is to demonstrate the benefits of using disaggregated tables, therefore, from this point onwards whenever regional and national IO tables are mentioned it is implied that they are disaggregated unless stated otherwise.

direct emissions of the UK sectors. However, the key benefit of IO analysis is that it allows us to examine the composition of activity and this is what Table 2 allows us to begin doing.

In Table 2, 4 of the top 5 sectors ('Electricity', 'Waste, Remediation & Management', 'Water and Sewerage' and 'Gas etc.') are all disaggregated sub-sectors of the IRIO 'Electricity, Gas and Water Supply' (EGWS). Thus, it can be seen that using disaggregated regional IO tables such as the Scottish IO tables allows for the disaggregation of highly aggregated sectors such as EGWS. This is a fitting illustration of the discussion above on how disaggregation allows researchers and policy makers alike to clearly view that the main share of the emissions of Scottish EGWS is generated by 'Electricity'. In fact, 'Electricity' as a sector has the largest share amongst all Scottish sectors, 35.49% of the total Scottish direct emissions. Under a full EGWS aggregation the output of the analysis would indicate that Scottish EGWS generated 55.98 Mt of CO_2 and would draw the attention equally to all of its components, whereas the data in Table 4 clearly show that 'Electricity' generation requires increased policy attention, in the context of CO_2 emissions, compared to 'Water and Sewerage'.

Another example, related to the observations from Table 1, comes from the examination of the sectors ranked 8th and 9th in Table 2. As discussed above, 'Wholesale and Retail; Repairs' is a Type (a) 'hot-spot' for the UK and the main driver of the sector's emissions is the sector's total output, more than half of which involves the production of final goods and services. Scottish sectors 'Retail-excl vehicles' and 'Wholesale-excl vehicles' are both parts of the aggregated UK sector 'Wholesale and Retail; Repairs'. By using the Scottish IO tables, it is possible to identify that 'Retail-excl vehicles' is generating more direct emissions but also that the majority of the emissions are generated to meet the sector's final demand, as the value of the final demand is almost the same as the sector's total output. From a policy point of view, this finding indicates that in order to reduce the emissions generated by 'Retail-excl vehicles' it might be preferable to examine the consumer behaviour and trends. Additional reflection will be required to identify ways in which changes to consumption patterns can be achieved with the minimum losses possible in terms of employment or value-added. On the other hand, the data in Table 2 show that there needs to be limited attention on the emissions generated by the 'Retail-excl vehicles' sector, as its emissions intensity is significantly lower that any of the sectors in Table 2. In general, comparing the data in Tables 1 and 2 it can be seen that the Scottish sectors included in Table 2 make up the aggregated UK sectors of Table 1, or at least they are part of the sectors in Table 1. It can be seen then that by using regional IO tables we obtain more information on which parts of each aggregated sector have the most significant environmental impact.

Regional IO tables also have a rather important advantage when the focus is on the identification of Type (c) 'hot-spots' in supply chains. Table 3 shows the Scottish type (c) 'hot-spots' where the producing sector is also included in Table 2. In Scottish SRIO the threshold level for an element of (5) to be considered a Type (c) 'hot-spot' is 0.74 Mt of CO_2[18].

Table 3. Type (c) 'hot-spots' with top 10 Scottish direct emitters as the producing sector

Producing Sector	Supporting the Final Demand of Sector	Embodied Emissions (Mt of CO2)	% share of Producing Sector's Total Direct Emissions	% share of Total Scottish Direct Emissions
46 Electricity	8 Mining Support	1.35	3.62%	1.28%
46 Electricity	46 Electricity	25.25	67.75%	24.05%
26 Coke, Petroleum & Petrochemicals	26 Coke, Petroleum & Petrochemicals	7.71	81.20%	7.34%
49 Waste, Remediation & Management	49 Waste, Remediation & Management	5.22	82.34%	4.97%
48 Water and Sewerage	48 Water and Sewerage	4.44	71.71%	4.23%
47 Gas etc	46 Electricity	1.03	16.66%	0.98%
47 Gas etc	47 Gas etc	3.55	57.47%	3.38%
58 Support Services for Transport	58 Support Services for Transport	1.56	33.88%	1.49%
55 Other Land Transport	55 Other Land Transport	1.68	40.79%	1.60%
53 Retail - excl vehicles	53 Retail - excl vehicles	1.73	98.57%	1.64%
52 Wholesale - excl vehicles	52 Wholesale - excl vehicles	1.08	71.90%	1.03%
8 Mining Support	8 Mining Support	1.39	97.12%	1.32%

18 As shown in the previous chapters the threshold for Type (c) 'hot-spots' is set to be the average of the row maximums in the CO_2 emissions matrix. Therefore for the Scottish SRIO it is the average of the row maximums of (5) when calculated using the published Scottish IO tables.

The 'Embodied Emissions' column of Table 3 shows the element of (5) where $i =$ 'Producing Sector' and $j =$ 'Supporting the Final Demand of Sector'. In the other two columns, the emissions of the first column are presented as a percentage share of the total direct emissions of the producing sector and the total direct emissions of Scottish industries, respectively.

As can be seen in Table 3 the majority of the 'hot-spots' account for a large share of the total direct emissions of the producing sector in question. Moreover, in some cases, e.g. the production of 'Electricity' and 'Coke, Petroleum & Petrochemicals' to meet own-sector final demand, the 'hot-spot' also accounts for a significant share of the total Scottish direct emissions. It can also be seen that the majority of the Type (c) 'hot-spots' in Table 3 involve the production of sectors to meet their own final demand. There are, however, two key exceptions, the production of 'Electricity' to support the final demand of 'Mining Support' and the production of 'Gas etc.' to support the final demand of 'Electricity'. The latter shows one of the advantages of using regional IO tables. Looking for UK Type (c) 'hot-spots' on the IRIO, the largest one is the production of UK EGWS to meet its own final demand. With EGWS being an aggregated sector it is not possible to distinguish between (a) what share of the emissions embodied in this 'hot-spot' involve output of one sub-sector of EGWS that is used as an intermediate input by another, and (b) which share is generated in directly serving final demand in any one sub-sector. Using the Scottish IO tables, which have EGWS disaggregated into 4 sectors, it can be seen that a significant part of the emissions generated by 'Gas etc.' (16.66% in Table 3) is supporting the final demand of 'Electricity'.

However, the use of regional IO tables has failed to provide a solution to one of the problems highlighted earlier in this section. We identified that 'Transport and Storage', the second largest UK Type (a) 'hot-spot', involves different means of transportation and support services, each with different environmental impact. By using the UK emissions intensities for the Scottish SRIO, the problem is carried through to the disaggregated sectors like 'Support Services for Transport' and 'Other Land Transport' that are included in Table 2. These sectors are part of the UK 'Transport and Storage' sector in the IRIO and as a result of not using region-specific emissions data, they are assigned the UK emissions intensity. However, the 'Support Services for Transport' sector includes activities such as the handling of cargo and the operation of travel agencies, which involve significantly less use of fossil fuel and therefore CO_2 emissions intensity compared to 'Other Land Transport' activities. In short, it would seem then that the use of the same emissions intensities for the IRIO and the SRIO that uses regional IO tables leads to errors in terms of the calculated emissions.

4.5 Added value from introducing region-specific data for Scotland

4.5.1 Emissions reported by Scottish industries

The Scottish direct emissions presented in Table 2 in the previous section were the result of calculations performed using the Scottish-specific economic component but UK emissions intensities from the OECD framework in a SRIO analysis. From those calculations it was found that 'Electricity' and 'Coke, Petroleum & Petrochemicals' are the sectors that generate the majority of emissions in Scotland and actually 'Electricity' has a rather large share of the total Scottish direct emissions. It is interesting then to see how the calculated figures compare to the ones reported to SEPA for our accounting year (2009). Starting with the 'Electricity' sector, according to Gov.uk (2015) there were 10 thermal power plants operational in Scotland at the time of reporting. Of these the only ones currently included in data reported by SEPA are the coal-fired Longannet, the CCGT plant in Peterhead and the diesel-fired plant in Lerwick. The remaining plants are minor producing units located in Scottish Isles and mainly cater for the needs of local residents. However, for our accounting year of 2009 though there were two more power plants in operation and reported to SEPA. The one was the coal-fired plant Cockenzie and the other the CCGT plant in Fife.

In the situation for 2009 analysed in the SRIO work above, the level of CO_2 emissions reported by the 5 plants included in the SEPA data was approximately 13.4 Mt of CO_2. Clearly this figure is significantly smaller than the total we have calculated using UK intensities (from our OECD dataset) applied to the Scottish SRIO analysis, which was found to be 37.3 Mt of CO_2 in Table 2. Given the size of the remaining thermal power plants, the emissions left unreported should not be enough to fill the gap between what is calculated for Scotland using UK intensities and the reported emissions for Scotland in 2009. A reasonable explanation on the observed difference is that the emissions intensity of the Scottish 'Electricity' sector is significantly smaller that the intensity of the aggregated UK sector EGWS. In fact, the mixture of electricity producing installations in Scotland suggests that this is the case and that the Scottish 'Electricity' sector is likely to be less CO_2-intensive than its UK counterpart (which is hidden within the EGWS sector above). Scotland has a large number of wind farms, while there are also hydro plants and biomass units. This essentially means that a relatively large share of Scottish electricity is being generated without the emission of CO_2 and therefore the sector's emissions intensity is reduced (Turner et al, 2011b). The Scottish 'Electricity' sector still contributes approximately 10% of the total value of electricity produced in the UK, but with reduced embodied emissions compared to the rest of the UK.

Despite being slightly irrelevant, given the focus of this chapter, we should note in considering recent industrial emissions data a key limitation of IO analyses (either SRIO or IRIO). This is that – due to their complexity – economic IO tables tend to be reported with a time lag that may be important when we are considering an issue such as emissions generation in a rapidly changing energy supply environment. Scottish IO tables are now available for 2012 and the most recent year with reported emissions in SEPA is 2013 so that the SRIO analysis conducted here could be updated. However, for the purposes of illustrating the move from and comparability between IRIO and SRIO analyses of emissions generation, we continue to focus on our accounting year of 2009. However, in doing so we should note some key changes that have occurred between now and then. For example, by 2013 the CCGT plant in Fife was no longer operational and even though the emissions by Longannet and Lerwick were significantly increased, drops in emissions by Peterhead and especially Cockenzie, which actually was decommissioned in 2013, meant that the emissions total from Scottish thermal plants in 2013 was down to 11.3 Mt of CO_2. Emissions for 2014 have not been reported but according to Longannet's EMAS for 2014 the level of emissions was slightly reduced relative to 2013.

Another Scottish sector that has distinct characteristics in terms of CO_2 emissions is 'Coke, Petroleum & Petrochemicals'. This Scottish sector partially maps to the OECD-defined 'Coke, Refined Petroleum Products and Nuclear Fuel' but also includes petrochemicals industries that in the IRIO table are part of the OECD-defined 'Chemicals and Chemical Products' sector. However, since we have not enough data to be able to identify which part of the 'Chemicals and Chemical Products' output involves the production of petrochemicals, the results reported above are generated under the assumption that 'Coke, Petroleum & Petrochemicals' includes the same industries as the OECD-defined UK sector 'Coke, Refined Petroleum Products and Nuclear Fuel'. There are a number of industries in Scotland belonging to this sector and in 2009 their CO_2 emissions as reported in the SEPA data were 5.6 Mt of CO_2. The data from SEPA suggest that the analysis (using UK intensities from the OECD data) overestimated the emissions of that sector. The direct emissions reported in Table 2 are around 9.5 Mt of CO_2[19].

However, in this case there is an important detail that must be taken into account. The UK CO_2 intensity derived from the OECD data also accounts for the operation of CHP autoproducing plants in industries. The emissions of such plants are not reported as part of the emissions generated by the industries of Scottish sector 'Coke, Petroleum & Petrochemicals'. They are instead reported for thermal power plants. However, since they are not connected to the grid and are used for the needs of specific industries, these emissions are not captured by the calculations performed for the 'Electricity' sector

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19 The CO_2 emissions of petrochemicals industries are just 0.228 Mt of CO_2

either. To avoid having such sources of emissions left unaccounted for, the practice used in constructing the OECD data set was to allocate them to the industries where they are actually used to facilitate the production. The amount of emissions associated with autoproducing plants is not negligible. For example, in 2009 the CHP plant that operates in Grangemouth generated approximately 0.7 Mt of CO_2. Correcting for this issue will then close the gap between the SEPA figure and what is calculated (using UK intensities) for the Scottish 'Coke, Petroleum & Petrochemicals' sector. When the emissions of the CHP plant are accounted for, the calculated emissions - using the Scottish SRIO and UK intensities- are still 3.2 Mt of CO_2 larger that the emissions reported to SEPA.

4.5.2 The importance of region specific satellite emissions data

As has been shown for both Scottish sectors 'Electricity' and 'Coke, Petroleum & Petrochemicals' the emissions calculated by using the UK intensities from the OECD IRIO system in Scottish SRIO led to overestimations compared to emissions actually reported for Scotland in the same accounting year of 2009. The most obvious implication is that the direct emissions allocated to both sectors were larger than the actual emissions generated. However, the implications do not stop there. In an IO analysis the direct emissions of one sector impact the multipliers and emissions attributable to activity in other sectors. To consider the wider impacts that even one of these overestimations has across the SRIO for Scotland, we use the SEPA reported emissions for 'Electricity' sector in recalculating the sector's CO_2 intensity. Given the problems discussed above in allocating emissions to the Scottish 'Coke, Petroleum & Petrochemicals' sector (both in terms of using UK-intensities and the problems of accounting for CHP plants), we do not attempt to introduce region-specific data for this sector. Rather, we focus attention on the impact of making a single adjustment for region-specific data in the key polluting sector of 'Electricity'. We recalculate the SRIO system with just the single change of introducing the SEPA Scottish-specific data for e_i where i = 'Electricity'.

In Table 2 we found that the majority of the emissions generated by 'Electricity' sector are used to support the final demand of other sectors rather than meet the sector's own final demand. This means that, apart from the difference in 'Electricity' direct emissions, there is a difference in how the emissions intensity of 'Electricity' impacts the Type I emissions multiplier for each sector j, i.e. the sum down the column of each sector in (4), for every Scottish sector. As a result, when we recalculate there are differences in the footprints of Scottish sectors, with major differences being observed, as would be expected, in sectors that require large amounts of 'Electricity' output. Table 4 shows the new results using the adjusted (for region-specific data) Scottish 'Electricity' intensity. We report results for the top 10 Scottish sectors in terms of footprint (Scottish emissions attributable to final demand for sectoral output), presenting these alongside a summary in the same format for what we found using the UK intensity from the OECD IRIO system.

Table 4. Top 10 Scottish sectors in terms of footprint

IRIO CO2 Emissions Intensity					Adjusted 'Electricity' CO2 Emissions Intensity			
Sector Number	Sector Name	Total Emissions (Footprint) (Mt of CO2)	Type I Emissions Multiplier (Mt of CO2/$m of Final Demand)		Sector Number	Sector Name	Total Emissions (Footprint) (Mt of CO2)	Type I Emissions Multiplier (Mt of CO2/$m of Final Demand)
46	Electricity	26.70	0.00537		46	Electricity	10.52	0.00212
26	Coke, Petroleum & Petrochemicals	8.08	0.00120		26	Coke, Petroleum & Petrochemicals	8.00	0.00119
49	Waste, Remediation & Management	5.47	0.00350		49	Waste, Remediation & Management	5.44	0.00348
48	Water and Sewerage	4.58	0.00341		48	Water and Sewerage	4.55	0.00339
47	Gas etc	4.02	0.00346		47	Gas etc	3.74	0.00321
8	Mining Support	3.71	0.00048		52	Wholesale - excl vehicles	3.14	0.00036
87	Public Administration & Defence	3.65	0.00020		87	Public Administration & Defence	3.10	0.00017
89	Health	3.60	0.00021		89	Health	3.04	0.00017
50	Construction	3.58	0.00020		50	Construction	3.00	0.00017
52	Wholesale - excl vehicles	3.41	0.00039		8	Mining Support	2.84	0.00037

In Table 4 the column 'Total Emissions (Footprint)' shows the sum of the elements down each sector's column in (5) while the column 'Type I Emissions Multiplier' is the sum of the elements down each sector's column in (4).

As can be seen from the data in Table 4, adjusting the CO_2 emissions intensity of 'Electricity' has changed the footprint of every sector and changed the ranking. The most significant change was on the footprint of 'Electricity' itself, which was expected given that the data from Tables 3 and 4 show that the most significant contributor to the pre-adjusted 'Electricity' footprint was the sector's own production. Therefore, the adjustment of 'Electricity' CO_2 emissions intensity, which is significantly smaller than the one in the IRIO, led to a major reduction to the sector's own footprint. The 'identity' of the other 9 of the top 10 sectors in terms of footprint are exactly the same in both cases. However, it can be observed that there is a (downward) change in terms of the magnitude of the footprint and also in the ranking of the sectors. The most significant changes are the 'Wholesale – excl vehicles' being ranked 6th (it was originally 10th) after the adjustment and 'Mining Support' being ranked 10th after the adjustment when it was 6th originally. Especially in the case of 'Mining Support' the reduction in the sector's footprint is 0.86 Mt of CO_2, the second largest after the reduction in 'Electricity' footprint. This result may have been expected given that the output of 'Electricity' used to support the final demand of 'Mining Support' is a Type (c) 'hot-spot', as can be seen in Table 3. In fact, adjusting the CO_2 intensity of 'Electricity' has reduced the emissions embodied in the 'Electricity' output produced to support 'Mining Support' final demand enough to be below the threshold level for Type (c) 'hot-spots', even though the threshold level was also reduced to 0.57 Mt of CO_2.

4.6 Conclusions and extensions

The goal of this study was to demonstrate that the use of disaggregated national/regional IO tables can provide additional details on the results found by using IRIO tables. UK and Scotland were used as a case study. It was shown that the aggregated sector EGWS is a major UK Type (a) 'hot-spot' and that the sectors that are included in EGWS are Type (a) 'hot-spots' within Scotland (the trade-off in moving to SRIO is that which provides argument for IRIO in the literature – not being able to account for impacts of international trade, or even interregional UK trade here). However, disaggregation at the Scottish level has revealed that it is in fact the 'Electricity' component that has the largest share of EGWS emissions in Scotland and therefore is the largest Scottish Type (a) 'hot-spot'. Furthermore, it was revealed that there are significant emissions generated by 'Gas etc.' to support the final demand of 'Electricity', which would otherwise be included in the EGWS production to meet its own final demand.

However, there have been observed significant issues that need to be addressed in future projects. The most important one is that it is required to use region specific emissions data where possible. Using common emissions intensities at both regional and country level does ensure that each regional sector has been allocated the same emissions with the sectors at the country level (for example petroleum refineries attributed emissions also include the emissions of autoproducing plants). However, lack of region-specific information could lead to major errors in both PAP and CAP calculations. Particularly in sectors such as 'Electricity', where there is a wide variety of generation technologies, the use of non-region specific emissions data can lead to significant overestimation or underestimation of the total emissions. The fact that potential overestimations might occur was uncovered by retrieving the reported emissions of specific sectors, while it was demonstrated that using the reported emissions to adjust the emissions intensity of 'Electricity' led to a reduction of footprint for all the Scottish sectors.

The findings of this chapter are in line with the findings of Turner (2006) regarding the benefits from using region specific data to study the environmental impact of economic activities in Jersey. Arguably then, devolved governments with powers over environmental targets and regulations like Scotland, would have a strong incentive to promote the development of regional emissions data to be used with their existing IO tables. The ability to implement targeted/focused policies is even more important as the available resources for the reduction of emissions will potentially be less compared to the national/federal government. However, as was discussed at the conclusion of the previous chapter, even though Scottish Government has a dedicated department that develops and publishes high quality IO data, there has been limited emissions related application. Furthermore, in some cases UK data were used instead of Scotland specific. The findings of this chapter could then act as an argument in favour of publishing Scottish emissions data for each sector in the Scottish IO tables. Especially since Scotland has set ambitious emissions reduction goals (Climate Change (Scotland) Act 2009 found at: Legislation.gov.uk, 2016), being in a position to identify the sectors where policy interventions will have the most significant impact could prove to be rather helpful in meeting both the interim and the 2050 target. What was mentioned above though does not mean that the only benefited parties from detailed emissions data are regional governments (e.g. Scottish Government). However, national governments (e.g. UK Government) are more likely to have the resources and the necessary funds to develop both the disaggregated IO tables and the satellite emissions accounts.

This issue has been highlighted by Turner (2006). There is a significant resource cost in developing and publishing region specific emissions data, which is higher the larger the economy. The cost will be larger for Scotland, being a much larger economy than Jersey. In that sense, an important factor that determines whether there should be investment in publishing region specific data is the gap between the expected benefits of those data against the associated cost of development. It is not the scope of this thesis to answer this question, which could be the subject of a different research project. However, given the significant differences observed as a result of introducing Scotland specific data in a single – but important – sector, it is our belief that region specific data need to be developed, at least to an extent that can be used to gauge their benefits against their costs (Turner, 2006).

Reflecting on the findings of this chapter in association with the conclusions of the previous chapters, as well as remarks from the literature, inevitably the issue of the quality of the data is brought forward. As mentioned before, the Scottish IO tables are produced by a dedicated department of the Scottish Government and can be trusted on the quality and the accuracy of the tables they publish. The same cannot be said for the CO_2 emissions. It was observed that the reported emissions were mostly calculated by industries using SEPA approved methods. Although this is a common practice in calculating and reporting the emissions generated for example due to combustion of coal, obtaining actual physical measurements data would be beneficial in our understanding of the impact of specific sectors, in terms of CO_2 emissions. Keeping these parameters in mind a future step for this project would require the acquisition of Scottish emissions data that, where possible, is suitable for following the standards of emissions satellite accounting used in the second chapter. Using the region-specific data would then make it possible to identify again the highest emitters with a higher degree of accuracy and to use findings of IO 'hot-spot' analysis as a guideline to help focus policy and industry attention on the need for better and more updated physical measurements on which to focus current policy attention. Such an approach will help policy-makers better understand the nature of present production conditions at the location of industries belonging to those sectors with the IO analysis (both SRIO and IRIO) adding insight in terms of demand drivers, key supply chain relationships etc.

Chapter 5: Thesis Conclusion

As it has been discussed throughout this thesis, Input Output (IO) has been used extensively to calculate the CO_2 emissions generated by economic activities. Researchers have used both Single Region IO (SRIO) and Inter-Regional IO (IRIO) to measure the emissions generated under a Production Accounting Principle (PAP) and a Consumption Accounting Principle (CAP). The differences in allocated emissions under each of the two principles has been the subject of different studies, given that international climate change mitigation agreements, like the UNFCCC agreements, utilise a territorial PAP to assign responsibility for the emissions generated to each participating party. There have been arguments against this approach and in favour of CAP claiming that PAP does not capture the emissions embodied in international trade correctly (e.g. Wyckoff and Roop, 1994; Munksgaard and Pedersen, 2001) or pointing out that PAP could lead developed countries in relocating their most polluting activities in developing countries with more lenient environmental regulations, i.e. 'carbon leakage' (Arrow et al, 1995). We believe that both PAP and CAP can contribute significantly in our understanding of the drivers of emissions. However, the way these headline figures are calculated there is limited transparency on the structure of the emissions; PAP and CAP do not provide any information on the share of emissions embodied in each of components of any sector's downstream and upstream supply chains, the role of each sector's emissions intensity or the impact of final demand. Recognising these limitations of working with headline figures, our project aimed to develop a methodological tool that makes use of the information provided by PAP and CAP while providing transparency in their calculation, which most of the time has the characteristics of a black box.

Motivated by this limited transparency on the structure of emissions and the lack of information on the impact of emissions intensity and final demand on the total volume of generated emissions, we developed what we call a 'hot-spot' analysis method. 'Hot-spots' were identified by initially using the headline figures of total direct emissions and CO_2 footprint, which we called Type (a) and Type (b) 'hot-spots'; they reflected the emissions embodied in each sector's downstream and upstream supply chains and they are part of the PAP and CAP emissions of each sector. Through the analysis of direct emissions, it became possible to understand whether the volume of emissions is driven by the sector's emissions intensity or the total volume of output, while the comparison between the total output and the final demand helped distinguish between the sectors that mainly produced to support other sectors and those that produced to meet their own final demand. In a similar way, analysing the CO_2 footprint of different sectors helped identify sectors that have significant emissions embodied in their upstream supply chain due to the volume of their final demand and others that their emissions were driven mainly by their Type I emissions multiplier, a feature of our method that builds on the estimation of backward linkages using Type I output multiplier that was established by Rasmussen (1957) and Hirschman (1958).

We then used the Type (a) and Type (b) 'hot-spots' we found as a guideline to identify downstream and upstream supply chains that would be interesting to disaggregate and look for Type (c) 'hot-spots' in components of these supply chains. This is one of the key benefits that we believe that can be gained by using 'hot-spot' analysis. We were able to highlight the components of downstream and upstream supply chains of different sectors, both within the same and across different regions, that hold the largest shares of the total embodied emissions in the supply chains. Putting this feature into policy perspective it means that policy makers who have identified important sectors in terms of being large direct emitters and/or having a large CO_2 footprint can focus their attention, policies and resources on Type (c) 'hot-spots' on the supply chains of those important sectors, rather than implement policies on those sectors as a whole.

Furthermore, we were able to analyse the Type (c) 'hot-spots' and reveal which, amongst the emissions multiplier or the receiving sector's final demand in the case of 'hot-spots' on the downstream supply chains; and the emissions intensity and the requirements of the consuming sector from the producing sector in the case of 'hot-spots on upstream supply chains, was the main driver of the embodied emissions in these Type (c) 'hot-spots. This is similar to the analysis of the Type (a) and Type (b) 'hot-spots' and the other key benefit of 'hot-spot' analysis. Policy makers not only have the ability to identify where the major shares of emissions are located on the sectors' supply chains, but they are also in a position to understand how different parameters influence the embodied emissions and which one of them is the main driver. All these features of our method make for a more complete set of information regarding the emissions generated by different industrial sectors and making use of this information can eventually lead to more informed and better targeted/focused policies, as discussed throughout this thesis.

In the different chapters of this thesis the proposed methodology has been applied to different IO frameworks ranging from a SRIO which was derived by an IRIO table, hence it had the same level of sectoral aggregation, to a full IRIO to a disaggregated sub-national IO dataset published by the Scottish Government. Applying the methodology to a range of IO frameworks offered us the opportunity to develop the methodology but at the same time identify its limitations which can be addressed in future research projects associated with this thesis.

In the second chapter the methodology was applied to a SRIO for China in 2005, which used the data from the Chinese component of the OECD Inter-Country Input Output database. Conducting 'hot-spot' analysis led to the identification of a number of Chinese sectors as 'hot-spots' based on their direct CO_2 emissions, i.e. Type (a) 'hot-spots'. The largest Type (a) 'hot-spot' was found to be the aggregated 'Electricity, Gas and Water Supply' (EGWS) sector, which generated more than half of the total emissions directly generated by Chinese sectors. However, further analysis of the sector's downstream supply chain has shown that the majority of the emissions were generated to support the final demand of other Chinese sectors, mainly 'Construction', while the emissions generated to meet its own final demand accounted for just 9.7% of EGWS total direct emissions. Analysis of all Chinese industries (as defined in the OECD database) has shown that 'Construction' is the largest 'hot-spot' in terms of domestic footprint of production to meet final demand (i.e. Type (b) ‘hot-spot’), mainly in the form of domestic capital formation. This is an interesting finding, given that capital formation in 2005 will have played a key role in facilitating economic development, including increased production to meet export demands over the subsequent decade. Additionally, ‘hot-spot’ analysis of ‘Construction’ upstream supply chain has highlighted a number of components of the ‘Construction’ upstream supply chain that can be classified as Type (c) ‘hot-spots’ and which are also the most polluting outputs of the respective sectors, e.g. the output of ‘Mining and Quarrying’ and ‘Coke, Refined Petroleum and Nuclear Fuel’ to support ‘Construction’ final demand.

As was discussed in the chapter, our findings indicate that if policy makers in China wish to reduce the embodied emissions in the EGWS downstream supply and the ‘Construction’ upstream supply chain, it would be worthwhile to address the ‘Construction’ requirements for EGWS output. Having the information from ‘hot-spot’ analysis available means that policy makers are aware of the different options; to either re-structure EGWS to achieve a lower emissions intensity or reduce the ‘Construction’ requirements for EGWS output by introducing more energy efficient building technologies. Unfortunately, as pointed out throughout this thesis, ‘hot-spot’ analysis is not a stand-alone tool that can be used to conclusively decide which of these two options is preferable. Additional analysis on the employment and value-added impacts would be necessary to reach to valid conclusions, while a more sophisticated modelling tool like Computable General Equilibrium (CGE) would be crucial in simulating the impact of any policies over a longer period of time. However, ‘hot-spot’ analysis still reveals that the volume of embodied emissions in the supply chains of EGWS and ‘Construction’ heavily depend on the interaction of the two sectors and policy makers can focus on this interaction rather than implement policies on each of the sectors separately.

Apart from the fact that ‘hot-spot’ analysis is a specialised rather than a stand-alone analytical tool, in the second chapter a few more limitations of the methodology were identified. A basic sensitivity analysis conducted in section 2.3.3 of the second chapter showed how important it is to set the Type (c) 'hot-spot' threshold correctly. A small variation in the threshold level could mean that several components of different supply chains will be considered or disregarded as Type (c) 'hot-spots'. Looking back at Tables 3 and 6 in Chapter 2 and 3 and 5 in Chapter 3, it is noticeable that in every one of these tables there are sectors included, which have embodied emissions near the threshold level. In much the same way there are sectors in the CO_2 emissions matrix that have embodied emissions just under the threshold level and are therefore excluded from the tables.

Even though this is a characteristic of every type of system that uses a cut-off point to distinguish between important and less important entries, this is a feature that needs to be taken into account when conducting 'hot-spot' analysis. The fact that a sector generates emissions just below the threshold level does not imply that it does not merit any policy attention and, more importantly, that it does not offer the possibility to achieve reduction in the country's or region's total emissions with a relatively small cost. To solve this issue, it was suggested that the threshold level can be set based on the average embodied emissions required per sectoral transaction for each country to meet its targets set either voluntarily or by international agreements. Alternatively, a confidence level type of approach could be implemented by using the difference between the threshold level (which we set at the average of the row maximums) and the smallest Type (c) 'hot-spots'. Any components of supply chains with embodied emissions below the threshold level but within that confidence level could be considered as Type (c) 'hot-spots'. This is purely a suggestion of what could be done in future projects that was not applied to this project as any calculations were done for illustration purposes, to show how the proposed methodology can be used, highlight its strong points and reveal its limitations.

The other limitation that was highlighted in Chapter 2 involves the application of the 'hot-spot' analysis on single, discrete years. Economies are dynamic systems and as such they change over the years. By examining a static picture of an economy does not provide any insight on whether the identified 'hot-spots' are recurring or were one-off phenomena. Being able to make this distinction is very important to avoid the allocation of resources to sectors that for any reason generated or contributed to the generation of significant emissions at a single point in time and by the time of the analysis the problem has been resolved either by existing policies or due to changes in the structure of the economy. The lesson learned from considering this limitation is that historical 'hot-spot' analysis would be necessary, when facilitated by the availability of data, to reinforce the robustness of the findings in the later years.

In the third chapter the 'hot-spot' methodology was extended and applied in an Inter-Regional Input Output (IRIO) framework, with a novel focus on decomposition of IRIO emissions accounting results, in order to allow the identification of 'hot-spots' in global supply chains. In the applied work in the chapter, the focus was placed on considering the composition of the CO_2 footprint of UK total final consumption demand. Using the 'hot-spot' methodology it was possible to identify a number of sectors outside the UK that directly generate significant volumes of emissions either to directly meet UK final demand or to support the UK final demand requirements of other sectors further up the global supply chain. The largest external Type (a) 'hot-spot' serving UK final consumption demand was found to be the Chinese EGWS sector. Given that UK final consumers do not directly consume Chinese utilities services, as would be expected, examination of international side of the sector's downstream supply chain revealed that UK-supported 'hot-spots' are located at points on the supply chain where the output of China's EGWS supports the UK final demand of other industries, primarily in the UK itself. This is an interesting finding on its own, one that flags up an important issue associated with all types of IO analysis. Given the nature of the outputs of EGWS, one might think that there is limited export potential from the Chinese EGWS to UK sectors. However, the findings show that at least some UK sectors do import significant volumes of inputs from the Chinese EGWS.

This result act as a reminder that the quality and the accuracy of the results of every type of IO analysis are closely correlated to the quality and the accuracy of the IO tables used. UK's Department of Energy and Climate Change (DECC) has raised the issue that there is lack of credible international data, especially for use on consumption-based approaches (House of Commons Energy and Climate Change Committee, 2012a). For this chapter, and this project as a whole, the OECD Inter-Country Input Output database has been used, which, alongside the transparency achieved by the proposed methodology, addressed the concerns of DECC over the availability of data while providing a step forwards regarding the quality of data. Even though we have the utmost confidence that the people who created this dataset have the highest standards, still the fact that only a pilot version of database was used, casts shadows on the credibility of results. Fortunately, the sole purpose of these results was to demonstrate the ways in which the developed methodology can be used and not provide conclusions to be used in a policy making setting. However, further applications of the 'hot-spot' analysis methodology will need to be conducted in the final and most credible version of the data, which will not include any discrepancies.

Another unanticipated finding was that the second largest Type (b) 'hot-spot' was the UK 'Health and Social Work' sector. It was found to have a significant number of 'hot-spots' on the international side of its upstream supply chain. This is a finding that could have important policy implications. Particularly in public sector activity, actions to reduce the 'carbon footprint' of health sector activities often focus very much on direct energy use, improved efficiency in buildings etc. That is, things that policy-makers have ready access to information on and a high degree of control over. However, the finding that the footprint of the UK health sector is impacted by emissions related to chemical production in other countries, while intuitive (given the international nature of industries such as pharmaceuticals), it raises challenges in terms of how these might be reduced. The chapter raised the issue of jurisdictional limits to what policy-makers in one country can do about emissions in another. However, it also highlighted the role that purchasing managers etc. both in the UK health sector and firms in their supply chains can play in applying commercial pressure on upstream suppliers to reduce their emissions. Furthermore, the findings of 'hot-spot' analysis on international supply chains can be used, alongside a set carbon price, as the basis to determine the mandatory contribution of each developed country to carbon reduction funds, which in turn will assist in the implementation of carbon reduction innovations in developing countries under the carbon finance concept.

This is a good point to reflect on some of the issues that arise from applying the 'hot-spot' analysis methodology on an IRIO. The identification of 'hot-spots' on supply chains relies on setting a 'hot-spot' threshold. It has been discussed so far the threshold level can be set to be the average intersectoral transaction required to meet the emissions targets of any country. However, different countries have different emissions targets, either set voluntarily or by international agreements. Setting then a common threshold level across all countries was useful for illustration purposes but does not reflect the differences in emissions goals. Keeping that parameter in mind, any future applications need to set different, country-specific, threshold levels and consequently the findings to reflect the differences between each country. The other issue is related to the very nature of IRIO tables. As was discussed in the previous chapters, the creators of the OECD database that we have used in this project had to harmonise data from various sources that do not follow the same approaches in collecting and reporting their data. As a result, it was necessary to aggregate sectors so that each country in the dataset has the same industrial classification, often leading to over-aggregated sectors like EGWS. However, as demonstrated by Miller and Blair (1981) and de Mesnard and Dietzenbacher (1995) amongst others, over-aggregation can lead to significant biases and errors. Therefore, 'hot-spot' and any other kind of IO analysis would benefit from the use of disaggregated IO tables, at least at the national and sub-national level.

The work in the fourth chapter focused on demonstrating exactly that; how it is possible to gain an additional insight on the findings from 'hot-spot' analysis in an IRIO by moving to a more focused and sectorally detailed SRIO analysis. Building on the applied work in the third chapter, the UK was used as a case study for identifying 'hot-spots' within the UK economy using IRIO methods and the OECD Inter-

Country Input Output (ICIO) database. Once the UK hot-spots were identified we then shifted our attention to examining the existence and nature of these at the Scottish level. This involved conducting the same type of analysis as was developed in Chapter 2 (there for the Chinese case study using an extract for that country from the OECD ICIO) but in the context of Scotland and using the regional IO tables published by the Scottish Government. This allowed us to work at a higher level of sectoral disaggregation.

A key finding of the Scottish SRIO analysis was the revelation that Scotland does indeed share the same – and the Scottish sectors are part of – what we labelled as Type (a) or direct emissions generation 'hot-spots' for the UK using the IRIO. However, and with attention to the highly aggregated 'Electricity, Gas and Water Supply' sector in the OECD ICIO, the Scottish findings reflected the concerns that have been expressed in the literature regarding aggregation issues. Using the more disaggregated Scottish IO system we found that what is identified a single direct CO_2 'hot-spot' in the UK IRIO analysis actually involves key sectoral interactions between the component 'Electricity' and 'Gas etc.' sectors in particular (use of gas in electricity generation). This is likely to be true at UK national level as well (indeed, in many countries) and emphasises the need to 'drill down' on IRIO results to provide a fuller information set for policy analysts and decision makers.

Another key finding of the analysis on the fourth chapter emerged from the examination of the emissions calculated using (a) region-specific economic data in the form of the Scottish IO tables but with UK emissions intensities reported in the OECD environmental satellite account (which the author was involved in the construction of) and (b) results when some region-specific environmental data were also introduced. We considered bottom-up industry level data on Scottish electricity generation reported via the Scottish Environment Protection Agency (SEPA). It was found that the system based on UK average industrial CO_2 intensities leads to false over-estimates not only of emissions directly generated in the Scottish 'Electricity' sector but also in what we labelled as Type (b) and (c) 'hot-spots' in the overall and key upstream points in the CO_2 footprint estimates for sectors that directly and indirectly use electricity in their supply chains. Generally, we found that adjusting the emissions intensity for just one of the Scottish sectors (albeit an important one) it has an impact to the Type I emissions multiplier and therefore the footprint of all Scottish sectors.

This finding and the one discussed previously highlight the importance of using region-specific economic and emissions data. Unfortunately, the resource cost of developing and publishing such data is a limiting factor, as highlighted by Turner (2006), especially since larger economies will have to face higher costs. However, the findings of our analysis suggest that there are benefits to be gained that merit investments in the development of such data, especially in countries and/or regions like Scotland that already have developed disaggregated IO tables. The example of 'Support Services for Transport' and 'Other Land Transport' in Table 2 in Chapter 4 is rather eye-opening. Without region-specific data the two sectors share a common emissions intensity as they both are part of the aggregated UK sector 'Transport and Storage' from the IRIO. Following the findings in Table 2 without further consideration would suggest that 'Support Services for Transport' merits more policy attention compared to 'Other Land Transport'. However, it is a known fact that the dependence of 'Other Land Transport' on fossil fuel is far greater than that of 'Support Services for Transport' and therefore the two sectors should have had different emissions intensities. This can be achieved by introducing region-specific data, which as a result would lead to a higher degree of certainty that the sectors in Table 2 of Chapter 4 indeed directly generate the most CO_2 emissions in Scotland and hence require further investigation of their supply chains.

In summary, this thesis has made important developments in terms of decomposing IO multiplier methods and applying these in the context of analysing 'hot-spots' in domestic and global supply chains. It has also made an important applied contribution in terms of demonstrating the types of insights that can be gained through application of this methodology. However, even though every effort was put through to produce the best results possible there is always potential to expand and improve the work presented in this thesis. For example, the IO datasets are constantly improving to reduce any discrepancies but also to include more countries and recent years. Therefore, a potential future project could conduct the analysis presented in this thesis using the most up-to-date datasets. Especially in the cases where more countries are included, analysis of the data could lead to the identification of additional 'hot-spots'. Another potential future project could be to conduct physical measurements or use orbital measuring to obtain a picture of the present volume of emissions at the location of the Scottish industries identified as 'hot-spots'. Such a project would involve combining the findings obtained by analysing the different supply chains with actual geographical data, so that a true spatial disaggregation of the supply chains is achieved.

On a more practical application, several parties amongst which the House of Commons (2012a) have brought forward the concept of educating consumers, making it clear for them what is the economy-wide environmental impact of £100, for example, worth of private consumption/final demand. Our methodology can identify both the total impact and the specific locations in the domestic and global economy where this amount of final demand has the most significant impact. Finally, a key conclusion of the fourth chapter is that it is important to focus in on IRIO findings at national and sub-national regional level using more detailed economic IO data and to use, where possible, region specific emissions data. That being the case, if it becomes possible to obtain Scottish emissions data with the same characteristics as the ones used to create the OECD satellite emissions account in the third chapter, it would be rather interesting to conduct a full 'hot-spot' analysis for the UK, Scotland and Wales (where region-specific IO tables are also available) and compare the findings. Where interregional trade data can be identified, it would also be interesting to apply IRIO methods to consider CO_2 hot-spots linked to trade flows within the UK economy.

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Appendices

Appendix 1.A: The Industry×Industry industrial sectors of WIOD database

WIOD Sector Code	Sector Name	ISIC rev. 3.1
AtB	Agriculture, Hunting, Forestry and Fishing	01,02,05
C	Mining and Quarrying	10,11,12,13,14
15t16	Food, Beverages and Tobacco	15,16
17t18	Textiles and Textile Products	17,18
19	Leather, Leather and Footwear	19
20	Wood and Products of Wood and Cork	20
21t22	Pulp, Paper, Paper , Printing and Publishing	21,22
23	Coke, Refined Petroleum and Nuclear Fuel	23
24	Chemicals and Chemical Products	24
25	Rubber and Plastics	25
26	Other Non-Metallic Mineral	26
27t28	Basic Metals and Fabricated Metal	27,28
29	Machinery, Nec	29
30t33	Electrical and Optical Equipment	30,31,32,33
34t35	Transport Equipment	34,35
36t37	Manufacturing, Nec; Recycling	36,37
E	Electricity, Gas and Water Supply	40,41
F	Construction	45
50	Sale, Maintenance and Repair of Motor Vehicles and Motorcycles; Retail Sale of Fuel	50
51	Wholesale Trade and Commission Trade, Except of Motor Vehicles and Motorcycles	51
52	Retail Trade, Except of Motor Vehicles and Motorcycles; Repair of Household Goods	52
H	Hotels and Restaurants	55
60	Inland Transport	60
61	Water Transport	61
62	Air Transport	62
63	Other Supporting and Auxiliary Transport Activities; Activities of Travel Agencies	63
64	Post and Telecommunications	64
J	Financial Intermediation	65,66,67
70	Real Estate Activities	70
71t74	Renting of M&Eq and Other Business Activities	71,72,73,74
L	Public Admin and Defence; Compulsory Social Security	75
M	Education	80
N	Health and Social Work	85
O	Other Community, Social and Personal Services	90,91,92,93
P	Private Households with Employed Persons	95,96,97

Appendix 2.A; Table 2.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 2.B; Table 2.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 2.C: The creation of satellite emissions account

2.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 2.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.

2.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.

2.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. 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		

Appendix 3.A: 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 3.B: Scottish sectors matched to OECD sectors

ISIC rev. 3.1	OECD Sector Code - Sector Name	Scottish Sector Number - Sector Name
01,02,05	C01T05 Agriculture, hunting, forestry and fishing	1 Agriculture
		2 Forestry planting
		3 Forestry harvesting
		4 Fishing
		5 Aquaculture
10,11,12,13,14	C10T14 Mining and quarrying	6 Coal & lignite
		7 Oil & gas extraction, metal ores & other
		8 Mining Support
15,16	C15T16 Food products, beverages and tobacco	9 Meat processing
		10 Fish & fruit processing
		11 Dairy products, oils & fats processing
		12 Grain milling & starch
		13 Bakery & farinaceous
		14 Other food
		15 Animal feeds
		16 Spirits & wines
		17 Beer & malt
		18 Soft Drinks
		19 Tobacco
17,18,19	C17T19 Textiles, textile products, leather and footwear	20 Textiles
		21 Wearing apparel
		22 Leather goods
20	C20 Wood and products of wood and cork	23 Wood and wood products
21,22	C21T22 Pulp, paper, paper products, printing and publishing	24 Paper & paper products
		25 Printing and recording
23	C23 Coke, refined petroleum products and nuclear fuel	26 Coke, petroleum & petrochemicals
24	C24 Chemicals and chemical products	27 Paints, varnishes and inks etc
		28 Cleaning & toilet preparations
		29 Other chemicals
		30 Inorganic chemicals, dyestuffs & agrochemicals
		31 Pharmaceuticals
25	C25 Rubber and plastics products	32 Rubber & Plastic
26	C26 Other non-metallic mineral products	33 Cement lime & plaster
		34 Glass, clay & stone etc
27	C27 Basic metals	35 Iron & Steel
		36 Other metals & casting
28	C28 Fabricated metal products except machinery and equipment	37 Fabricated metal
29	C29 Machinery and equipment n.e.c	40 Machinery & equipment
30	C30 Office, accounting and computing machinery	38 Computers, electronics & opticals
32	C32 Radio, television and communication equipment	
33	C33 Medical, precision and optical instruments	
31	C31 Electrical machinery and apparatus n.e.c	39 Electrical equipment
34	C34 Motor vehicles, trailers and semi-trailers	41 Motor Vehicles
35	C35 Other transport equipment	42 Other transport equipment
36,37	C36T37 Manufacturing n.e.c; recycling	43 Furniture
		44 Other manufacturing
		45 Repair & maintenance

ISIC rev. 3.1	OECD Sector Code - Sector Name	Scottish Sector Number - Sector Name
40,41	C40T41 Electricity, gas and water supply	46 Electricity
		47 Gas etc
		48 Water and sewerage
		49 Waste, remediation & management
45	C45 Construction	50 Construction
50,51,52	C50T52 Wholesale and retail trade; repairs	51 Wholesale & Retail - vehicles
		52 Wholesale - excl vehicles
		53 Retail - excl vehicles
55	C55 Hotels and restaurants	60 Accommodation
		61 Food & beverage services
60,61,62,63	C60T63 Transport and storage	54 Rail transport
		55 Other land transport
		56 Water transport
		57 Air transport
		58 Support services for transport
64	C64 Post and telecommunications	59 Post & courier
		64 Telecommunications
65,66,67	C65T67 Finance and insurance	67 Financial services
		68 Insurance & pensions
		69 Auxiliary financial services
70	C70 Real estate activities	70 Real estate - own
		71 Imputed rent
		72 Real estate - fee or contract
71	C71 Renting of machinery and equipment	81 Rental and leasing services
72	C72 Computer and related activities	65 Computer services
73	C73 Research and development	77 Research & development
74	C74 Other Business Activities	66 Information services
		73 Legal activities
		74 Accounting & tax services
		75 Head office & consulting services
		76 Architectural services etc
		78 Advertising & market research
		79 Other professional services
		80 Veterinary services
		82 Employment services
		83 Travel & related services
		84 Security & investigation
		85 Building & landscape services
		86 Business support services
75	C75 Public admin. and defence; compulsory social security	87 Public administration & defence
80	C80 Education	88 Education
85	C85 Health and social work	89 Health
		90 Residential care and social work
90,91,92,93	C90T93 Other community, social and personal services	62 Publishing services
		63 Film video & TV etc; broadcasting
		91 Creative services
		92 Cultural services
		93 Gambling
		94 Sports & recreation
		95 Membership organisations
		96 Repairs - personal and household
		97 Other personal services
95	C95 Private households with employed persons	98 Households as employers

Appendix 3.C: The CO_2 emissions intensities of Scottish sectors

Sector Number	Sector Name	CO2 Emissions Intensity (Mt of CO2/$m of output)
1	Agriculture	0.000289
2	Forestry planting	0.000289
3	Forestry harvesting	0.000289
4	Fishing	0.000289
5	Aquaculture	0.000289
6	Coal & lignite	0.000171
7	Oil & gas extraction, metal ores & other	0.000171
8	Mining Support	0.000171
9	Meat processing	0.000123
10	Fish & fruit processing	0.000123
11	Dairy products, oils & fats processing	0.000123
12	Grain milling & starch	0.000123
13	Bakery & farinaceous	0.000123
14	Other food	0.000123
15	Animal feeds	0.000123
16	Spirits & wines	0.000123
17	Beer & malt	0.000123
18	Soft Drinks	0.000123
19	Tobacco	0.000123
20	Textiles	0.000152
21	Wearing apparel	0.000152
22	Leather goods	0.000152
23	Wood and wood products	0.000070
24	Paper & paper products	0.000117
25	Printing and recording	0.000117
26	Coke, petroleum & petrochemicals	0.001129
27	Paints, varnishes and inks etc	0.000448
28	Cleaning & toilet preparations	0.000448
29	Other chemicals	0.000448
30	Inorganic chemicals, dyestuffs & agrochemicals	0.000448
31	Pharmaceuticals	0.000448
32	Rubber & Plastic	0.000466
33	Cement lime & plaster	0.000767
34	Glass, clay & stone etc	0.000767
35	Iron & Steel	0.000280
36	Other metals & casting	0.000280
37	Fabricated metal	0
38	Computers, electronics & opticals	0.000018
39	Electrical equipment	0
40	Machinery & equipment	0.000064
41	Motor Vehicles	0.000041
42	Other transport equipment	0
43	Furniture	0.000494
44	Other manufacturing	0.000494
45	Repair & maintenance	0.000494
46	Electricity	0.002990
	Adjusted Electricity CO2 emissions intensity	0.001075
47	Gas etc	0.002990
48	Water and sewerage	0.002990
49	Waste, remediation & management	0.002990

Sector Number	Sector Name	CO2 Emissions Intensity (Mt of CO2/$m of output)
50	Construction	0.000041
51	Wholesale & Retail - vehicles	0.000123
52	Wholesale - excl vehicles	0.000123
53	Retail - excl vehicles	0.000123
54	Rail transport	0.000792
55	Other land transport	0.000792
56	Water transport	0.000792
57	Air transport	0.000792
58	Support services for transport	0.000792
59	Post & courier	0.000071
60	Accommodation	0.000121
61	Food & beverage services	0.000121
62	Publishing services	0.000090
63	Film video & TV etc; broadcasting	0.000090
64	Telecommunications	0.000071
65	Computer services	0
66	Information services	0.000043
67	Financial services	0.000042
68	Insurance & pensions	0.000042
69	Auxiliary financial services	0.000042
70	Real estate - own	0.000014
71	Imputed rent	0.000014
72	Real estate - fee or contract	0.000014
73	Legal activities	0.000043
74	Accounting & tax services	0.000043
75	Head office & consulting services	0.000043
76	Architectural services etc	0.000043
77	Research & development	0
78	Advertising & market research	0.000043
79	Other professional services	0.000043
80	Veterinary services	0.000043
81	Rental and leasing services	0
82	Employment services	0.000043
83	Travel & related services	0.000043
84	Security & investigation	0.000043
85	Building & landscape services	0.000043
86	Business support services	0.000043
87	Public administration & defence	0.000065
88	Education	0.000039
89	Health	0.000066
90	Residential care and social work	0.000066
91	Creative services	0.000090
92	Cultural services	0.000090
93	Gambling	0.000090
94	Sports & recreation	0.000090
95	Membership organisations	0.000090
96	Repairs - personal and household	0.000090
97	Other personal services	0.000090
98	Households as employers	0.007840

Appendix 4.A: List of abbreviations

Abbreviation	Full Phrase
CAP	Consumption Accounting Principle
CCGT	Combined Cycle Gas Turbine
CGE	Computable General Equilibrium
CHP	Combined Heat and Power
CO2	Carbon Dioxide
DECC	Department of Energy and Climate Change (UK)
EGWS	Electricity Gas and Water Supply
EIRIO	Environmental Inter-Regional Input Output
EMAS	Eco Management and Audit Scheme
ESRIO	Environmental Single Region Input Output
GBP	Pound Sterling
GHG	Greenhouse Gases
GTAP	Global Trade Analysis Project
ICIO	Inter-Country Input Output
IEA	International Energy Agency
IO	Input Output
IRIO	Inter-Regional Input Output
ISIC	International Standard Industrial Classification of all economic activities
MRIO	Multi-Regional Input Output
OECD	Organisation for Economic Cooperation and Development
PAP	Production Accounting Principle
ROW	Rest Of the World
SEPA	Scottish Environment Protection Agency
SIC	Standard Industrial Classification of economic activities
SRIO	Single Region Input Output
UK	United Kingdom
UNFCCC	United Nations Framework Convention on Climate Change
USA	United States of America
USD	United States of America Dollar
WIOD	World Input Output Database