ATTRIBUTING UK CARBON EMISSIONS TO FUNCTIONAL CONSUMER NEEDS: METHODOLOGY AND PILOT RESULTS

by

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RESOLVE Working Paper 01-07

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Abstract

This paper presents a framework for attributing carbon emissions to all goods and services purchased by consumers to meet their needs. A two-region, input-output model is employed to re-allocate all direct and indirect carbon emissions associated with UK consumption to high-level functional consumer needs. The study shows that in 2002 consumers used goods and services with a combined carbon footprint of 176.4MtC (million tonnes carbon per annum). This is shown to be 11.7 MtC greater than the emissions from all UK production indicating that the UK is a net importer of carbon intensive goods and services from abroad.

The three high-level consumer needs found to have the highest carbon footprint are Recreation and Leisure (31.6 MtC), Space Heating (24 MtC) and Food and Catering (22.4 MtC). Together they account for almost half of the total UK carbon emissions associated with household consumption. However, the carbon emissions associated with each of these high-level consumer needs accounts differ considerably. It is shown that approximately 50% of the carbon emissions attributed to Recreation and Leisure are travel related, whereas the emissions attributed to Space heating are direct emissions occurring in the home and carbon emissions attributable to Food and Catering are embodied in the products consumed.

This paper argues that even though the production-based carbon footprint remains important in understanding and managing the carbon impact within national boundaries, the consumption-based carbon footprint has the potential of offering insights to consumers, governments and industries alike to progress towards a low carbon economy.

1. Introduction

The mitigation of climate change has mainly focused on domestic producers (i.e. industries within an economy) to reduce their carbon emissions when producing goods and services. Typically, national emission accounts tend to identify the carbon emissions associated directly with fuel consumption in specific production sectors. This is useful in quantifying the carbon emitted at the level of the economy as a whole by fuel consumption processes within the UK national boundary. It is also useful in comparing the relative carbon intensity of different production sectors. The outcome of such analyses tends to reveal that the carbon burden associated with primary sectors – such as electricity production or the manufacture of iron and steel – is higher than the carbon burden associated with secondary or service sectors - say grain milling or financial services.

Since the general tendency in developed economies has been to reduce the predominance of primary (energy-intensive) sectors in the economy and to increase the so-called service sectors, it is not surprising to find that most industrialised nations have witnessed a steady decline in the energy and carbon intensity of economic output (Jackson 1996, Jänicke et al 1997, Rothman 1998). Some absolute declines in energy consumption and carbon emissions have also been observed over certain periods of time in various countries. But this production-based perspective neglects two important features of a consumption-based system.

Firstly, its does not allow the carbon emissions attributable to imports to be calculated. This is especially important when a country shifts from a manufacturing to service-orientated economy with increasing amounts of imported manufactured goods entering the domestic economy to satisfy consumption (Rothman 1998, Ekins et al. 1994). The UK's sustainable development strategy, "Securing the Future", stated that "[t]here would be little value in reducing environmental impacts within the UK if the result were merely to displace those impacts overseas,…" (DEFRA 2005:43).

Secondly, in allocating carbon emissions to production sectors fail to identify the underlying drivers for production in those sectors. From a consumption perspective, primary commodities such as electricity and iron and steel are not particularly useful in their own right. Rather they provide functional inputs to a variety of other production processes whose purpose is to meet the 'final demand' for a wide range of other commodities: cars, appliances, buildings, grain milling, financial services and so on. These commodities, in turn are desired by consumers, not generally for their own sake, but rather for the services they provide in meeting certain underlying functional needs.

Figure 1 illustrates this relationship between functional needs, product-service systems and production sectors using recreation and leisure as an example.

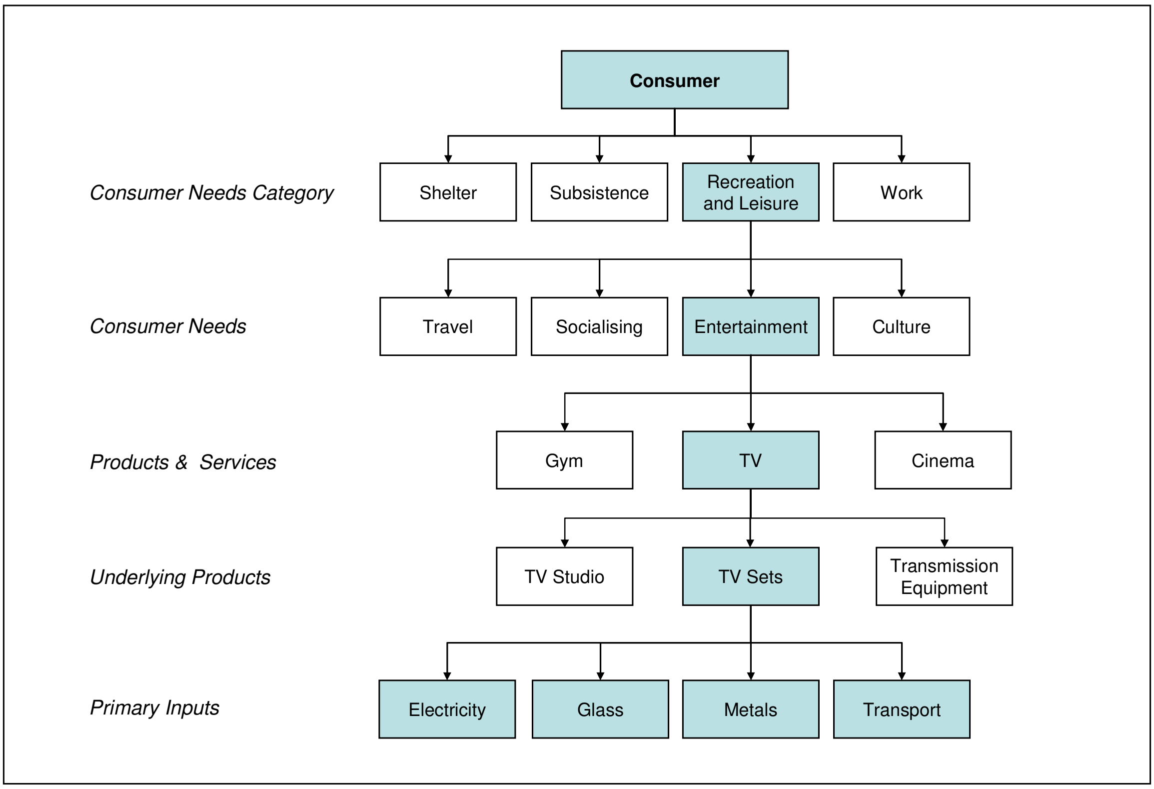

Figure 1: Mapping the Production Implications of Consumer Needs

Figure 1 shows how the satisfaction of the need for recreation and leisure drives a number of subsidiary needs, amongst them the desire for entertainment. This desire stimulates a demand for a specific set of product-service systems such as gyms, cinemas and TV systems. These systems in turn generate a demand for specific consumer goods – such as TVs – and services – such as electricity. These goods and services have in their turn to be produced in the economy through a variety of different production processes, using a variety of different material and energy inputs, and generating a variety of different environmental impacts.

The principal aim of this paper is to develop a framework for mapping carbon emissions onto a specific set of high-level functional needs. In the next section we set out a broad methodology for approaching this objective, drawing strongly on environmental input-output analysis and discuss the data sources used for the model. In Section 2 we present the results of applying this methodology to the UK and validate the overall findings against conventional carbon emission accounts. In the final section we conclude with a discussion of the implications of the model.

2. Methodology

The premise of this study is that responsibility for carbon emissions in the UK economy lies ultimately with the satisfaction of different consumer needs and desires. Or more precisely, that the consumer demand for commodities (goods and services) is what drives the production processes that consume energy resources and emit carbon dioxide (and other greenhouse gases). From a production perspective, we can think of sectors such as electricity production, iron and steel and so on as being typically the most carbon-intensive sectors in the economy. From a consumer demand perspective however, electricity and iron and steel are both 'intermediate goods' in the satisfaction of a wide variety of other consumer purposes.

The aim of this work is to develop a method for allocating carbon emissions to underlying consumer commodities (goods and services) along the whole of the supply-chain whether the consumer commodities are produced within the domestic economy or imported. The methodology employed within this research builds on an input-output accounting framework developed at the University of Surrey over the last five years to interrogate precisely these kinds of questions about the environmental impacts of consumer demand.

The carbon attribution model is based on the pioneering work of Wassily Leontief (1966) and a later development of this framework to account for international trade by Proops et al (1993). It uses a broad EIO framework to prepare six distinct sets of carbon accounts for the UK economy for the year 2002. Specifically, the six accounts are as follows:

- Account A: Production-Based Account
- Account B: Consumption-Based Account
- Account C: Consumption Account with Fixed Capital Re-allocated
- Account D: Consumption Account with Fixed Capital and Distribution Reallocated
- Account E: Domestic Functional Use Account
- Account F: High-Level Consumer Need Account

Each of these accounts is described in more detail in the following subsections.

Account A: Production-Based Account

Carbon emission accounts at the national level are approximated by using carbon emission factors to estimate the emissions associated with the direct consumption of fossil fuels in different sectors: industry and commerce, the public sector and by households. This production perspective provides a pretty straightforward accounting framework and is usually reasonably successful in allocating emissions to specific industrial, commercial and domestic processes in an exhaustive and mutually exclusive way within a given geographical boundary.

Essentially, the carbon emissions c_i from each industrial sector i are assumed to be linearly related to sector output x_i and can be calculated by:

$$c_i = u_i\, x_i \tag{1}$$

where

u_i is the carbon intensity coefficient for each sector i calculated as shown below:

$$u_i = \frac{\sum_{n=1}^{n=m} f_n e_n}{x_i} \tag{2}$$

where:

f_n is the quantity of fuel type n used in sector i (n =1 to m)
e_n is the carbon emission factor for fuel type n
x_i is the output of sector i

In vector notation, the total carbon C associated with all production sectors across the economy (including the public sector) is given by:

$$\mathrm{C} = \sum_i c_i = \mathbf{u}'.\mathbf{x} \tag{3}$$

To this production sector carbon, C, we must also add the carbon C_{dom} associated with the direct consumption of fossil fuels for heating, cooking and so on in people's homes and also the carbon C_{trans} associated with the direct consumption of transport fuels by private households. Total carbon, C_{tot}^{prod}, reported in the production perspective is therefore given by:

$$\mathrm{C}_{tot}^{prod} = \mathrm{C} + \mathrm{C}_{dom} + \mathrm{C}_{trans} \tag{4}$$

(See Appendix 2 for data sources)

Account B: Consumption Based Account

The first step in attributing carbon emissions to functional consumer needs is to map the production sector carbon C onto final demand sector commodities. This is the familiar use of the EIO framework following the pioneering work of Leontief (1966). More extensive details of the underlying methodology can be found in a number of places including Miller and Blair (1985), Proops et al (1993), Papathanasopoulou (2005). Broadly speaking, the vector of industry output, **x**, is related to the vector of final demand, **y**, using the conventional input-output equation:

$$\mathbf{x} = (\mathbf{I} - \mathbf{A})^{-1}\mathbf{y} \tag{5}$$

where:

I is the identity matrix;
A is the matrix of technology coefficients;
$(\mathbf{I} - \mathbf{A})^{-1}$ is the Leontief inverse.

Substitution for **x** in equation (3) using equation (5) yields:

$$C = \mathbf{u'}.(\mathbf{I} - \mathbf{A})^{-1}.\mathbf{y} \qquad (6)$$

By diagonalising **u'** and splitting **y** into separate final demand column vectors corresponding to the separate final demand components of household demand, government demand, investment (gross fixed domestic capital formation) and exports, it is possible to identify the carbon induced in the economy for each commodity sector and for each category of final demand. So for example, we can identify the carbon attributable to the final demand by households for textiles, and this will be equivalent to the carbon induced in all contributing sectors in the economy as a result of the demand for textiles by households.

Since the aim of this exercise is to identify the carbon attributable to UK consumers, any carbon attributable to final consumer demand abroad, even if these were produced in the UK, are excluded from the calculation. On the other hand, all carbon associated with goods consumed in the UK, even if these goods are produced abroad, are now included.

These boundaries are illustrated in Figure 2. UK[1] production is shown in the upper left hand rectangle in the Figure. Most of this production (shown by the flow P) is destined for UK consumption (the oval on the upper right of the picture). A small part of UK production, however, marked by the green (lighter shaded) area in the upper left rectangle, is destined for consumption overseas (Rest of World), either as intermediate demand (flow S) or as final consumption (flow T). Likewise a small part of the Rest of the World[2] production, shown by two red (darker shaded) areas in the large rectangle on the bottom left of the Figure is destined for the UK. Some of this (illustrated by flow Q) is destined for intermediate consumption by UK industries and some is destined for final consumption by UK consumers (flow R).

[1] The UK is also referred to as region 1 in this paper.
[2] The Rest of the World is also referred to as region 2 in this paper.

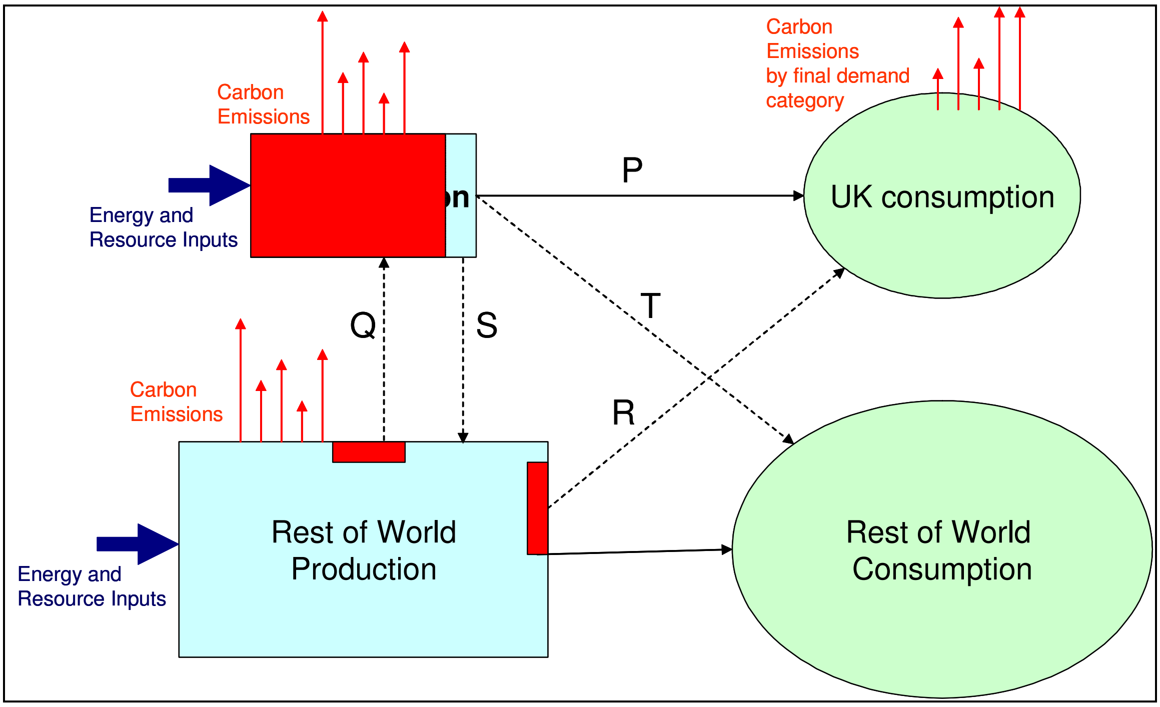

Figure 2: Two-Region Carbon Attribution Model

In summary therefore, we denote by:

C_P – the carbon associated with the flow P of goods produced in the UK to meet final demand in the UK;

C_Q – the carbon associated with the flow Q of goods produced in the Rest of the World to meet intermediate demand in the UK for goods destined for final demand in the UK;[3]

C_R – the carbon associated with the flow R of goods produced in the Rest of the World to meet UK final demand;

C_S – the carbon associated with the flow S of goods produced in the UK to meet intermediate demand in the Rest of the World;[4] and by

C_T – the carbon associated with the flow T of goods produced in the UK to meet final demand in the Rest of the World;

Then we can express the carbon, C_{tot}^{prod}, associated with the UK from a production perspective as:

$$C_{tot}^{prod} = C_P + C_S + C_T + C_{dom} + C_{trans} \tag{7}$$

3 Note that for accounting purposes this flow must exclude the goods required to produce the demand for exports back to the Rest of the World.

4 Note that, in principle, some of the carbon C_S may support intermediate processes used in the Rest of the World to produce goods destined for intermediate or final demand in the UK. This carbon is usually ignored in the literature on the basis of the relative size of the UK by comparison with the Rest of the World – an assumption known as the small country assumption (Proops et al 1993).

while the carbon C_{tot}^{cons} associated with the UK from a consumption perspective is given by:

$$\mathrm{C}_{tot}^{cons} = \mathrm{C_P} + \mathrm{C_Q} + \mathrm{C_R} + \mathrm{C_{dom}} + \mathrm{C_{trans}}. \quad (8)$$

Equation (7), denoting the carbon associated with the UK economy from the production perspective can be calculated easily from the identity:

$$\mathrm{C} = \mathrm{C_P} + \mathrm{C_S} + \mathrm{C_T} \quad (9)$$

where C is given by equation (3). For the consumption perspective, we need to derive explicit expressions for each of the components $\mathrm{C_P}$, $\mathrm{C_Q}$ and $\mathrm{C_R}$. This derivation is given in Appendix 1 of this paper and further details and explanations can be found in Proops et al (1993) and Papathanasopoulou (2005). It turns out that, after making the small country assumption (footnote 4) the following identities hold:

$$\mathrm{C_P} = \mathbf{u}^{\mathbf{1}'}(\mathbf{I}-\mathbf{A}_1)^{-1}\mathbf{y}^{\mathbf{11}} \quad (10)$$
$$\mathrm{C_Q} = \mathbf{u}^{\mathbf{2}'}(\mathbf{I}-\mathbf{A}_2)^{-1}\mathbf{B}_{\mathbf{21}}(\mathbf{I}-\mathbf{A}_1)^{-1}\mathbf{y}^{\mathbf{11}} \quad (11)$$
$$\mathrm{C_R} = \mathbf{u}^{\mathbf{2}'}(\mathbf{I}-\mathbf{A}_2)^{-1}\mathbf{y}^{\mathbf{21}} \quad (12)$$

where:

$\mathbf{A}_1$ is the matrix of intra-regional technical coefficients for region 1;
$\mathbf{B}_{21}$ is the imports use coefficients matrix for imports from region β to region α;
$\mathbf{u}^1$ is the vector of carbon coefficients for region α; and
$\mathbf{y}^{21}$ is the vector of final demand for commodities produced in region β and consumed in region α.

In order to simplify the data requirements, we also make the assumption that imported goods have the same carbon footprint as those produced domestically. In other words, we assume the following condition holds:

$$\mathbf{u}^{\mathbf{1}'}(\mathbf{I}-\mathbf{A}_1)^{-1} = \mathbf{u}^{\mathbf{2}'}(\mathbf{I}-\mathbf{A}_2)^{-1} \quad (13)$$

Equation (13) then allows us to express equations (11) and (12) as:

$$\mathrm{C_Q} = \mathbf{u}^{\mathbf{1}'}(\mathbf{I}-\mathbf{A}_1)^{-1}\mathbf{B}_{\mathbf{21}}(\mathbf{I}-\mathbf{A}_1)^{-1}\mathbf{y}^{\mathbf{11}} \quad (14) \text{ and}$$
$$\mathrm{C_R} = \mathbf{u}^{\mathbf{1}'}(\mathbf{I}-\mathbf{A}_1)^{-1}\mathbf{y}^{\mathbf{21}} \quad (15)$$

and it is then possible to construct the carbon attribution model using available UK data sources (see Appendix 2). As with Account A, equation (8) also includes data on direct emissions due to fossil fuels consumed in residential homes and transport fuel demand by private consumers.

Account C: Consumption Based Account with Fixed Capital Reallocated

The aim of this study was to get as close as possible to attributing carbon to final consumer needs. Account B allows us to allocate carbon to final demand sectors on a commodity by commodity basis. One of the final demand sectors reported in the final demand vector **y** is gross domestic fixed capital formation (GDFCF) or 'investment'. Strictly speaking, investment supports present and future consumption activities in a wide variety of different sectors. So, for example, most of final demand in the construction sector is classified as investment. But construction – building and refurbishment – is carried out in support of a variety of different industrial sectors: retail, manufacturing, hospitals, schools, offices, distribution and so on.

In one sense these investments – and the carbon associated with them – are still intermediate inputs to the other commodity sectors. To pursue our aim of attributing carbon to final demand, we should ideally re-distribute the carbon associated with these investments as an input to the sectors supported by the investment. This task is complicated by two factors. In the first place, data on capital investment in different sectors are reported – in the UK *Blue Book* – but only at relatively high levels of aggregation of industrial sector, whereas we need to be able to allocate investment carbon as an input to each of the 122 input-output sectors in the model. In the second place, allocating the carbon associated with this year's GDFCF, represents a crude proxy for a much more complicated allocation which ought ideally to involve the stream of past investments supporting current activities and exclude the components of current investment that support future activities.

In order to make progress here, we make two simplifying assumptions about the allocation of investment carbon to final commodity sectors. The first is that the carbon associated with investment within each high-level SIC code is proportional to the output from the sub-sectors within that code. The second is that the economy is in a steady state – ie, it is legitimate to take investment carbon in the current economic cycle as a proxy for the investments required to support consumption in the current cycle.[5] Using these two assumptions it is possible to allocate the carbon associated with GDFCF in the following way:

- first, the total carbon from final demand in the category GDFCF is allocated to high-level industrial sectors according to the allocation of GDFCF to SIC sectors in the *Blue Book*;
- next, the carbon associated with high-level sectors is allocated to IO sectors within each high-level sector on the basis that investment carbon in each IO subsector is proportional to the output of the subsectors;
- an 'additional' carbon coefficient $u_{i,fcf}$ is calculated for each IO subsector i by dividing the investment carbon attributed to each subsector by the output from that subsector;

5 This assumption is also made by Lenzen (1998) for Australia and by Hertwich et al (2002) for Norway, the only other studies we have encountered which attempt to endogenise investment as an input to commodity sectors.

- the carbon attribution model described in Account B is re-run with a new vector **v** of carbon coefficients with components given by $v_i = u_i + u_{i,fcf}$ for each sector i.

Carbon from the domestic sector and from private transport is unaffected by the calculation.

Account D: Consumption Based Account with Fixed Capital and Distribution Reallocated

From a functional use perspective, distribution is required to deliver final commodities to consumers. Once again, therefore, this 'final demand' category is really an intermediate demand required to support the distribution of other final demand commodities to consumers. Therefore the carbon associated with the sectors 'Retail Distribution', 'Wholesale Distribution' and 'Motor Vehicle Distribution and Repair' is re-allocated to the commodity sectors that are served by the distribution industries. Carbon associated with the sector 'Motor Vehicle Distribution and Repair' is allocated to the sector 'Motor Vehicles'. The carbon associated with wholesale and retail distribution is allocated to the other commodity sectors on a proportional basis, using data on distribution margins in each commodity sector reported in the UK final consumer expenditure accounts. Carbon from the domestic sector and from private transport is unaffected by the calculation.[6]

Account E: Domestic Functional Use Account

Up to this point, we have allocated all the carbon associated with economic sectors on the basis of IO commodity categories such as iron and steel, textiles, meat processing, electricity production, financial services and so on. With the aim of identifying the carbon associated with high-level functional needs, a method of allocating these commodity sectors to the high-level needs is required. A useful way of proceeding here is to use the United Nations Classification Of Individual COnsumption by Purpose (COICOP) which allocates household final demand commodity purchases into around 40 functional use categories, divided into 12 high-level categories:[7]

1. Food and non-alcoholic beverages;
2. Alcohol and Tobacco;
3. Clothing and Footwear;
4. Housing, water, electricity, gas and other fuels;
5. Furnishings, household equipment and routine household maintenance;
6. Health;

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6 This account is used for illustrative purposes. The later Accounts are based in fact on Account C, rather than on Account D, as the COICOP classification makes its own allocation of the distribution sector outputs to consumer expenditure categories.

7 The data for the COICOP allocation are taken from Table 4 in the Supply and Use Tables published by the Office for National Statistics.

7. Transport;
8. Communication;
9. Recreation and culture;
10. Education;
11. Restaurants and hotels; and
12. Miscellaneous goods and services.

For a variety of reasons, neither the 12 high-level categories nor the 40 or so lower-level categories quite work for our purposes. Keeping 40 separate categories does not help us in attributing carbon to high-level needs. On the other hand 12 categories is too few. For example, we need to keep separate the carbon associated with expenditures on gas, electricity and other fuels as these are accounted for separately using DUKES data; we need to separate out the carbon associated with expenditures on transport fuels (petrol and DERV); we want to be able to identify separately expenditures on different types of electrical appliances as these are associated with different high-level needs; and so on.

To overcome these difficulties we have aggregated the more detailed COICOP classification into a variety of domestic functional categories as set out in Table 1. This classification allows us to attribute all the carbon associated with commodity categories from household final demand calculated in Account C to the domestic functional use categories in Table 1.[8] In addition, Table 1 illustrates how we have addressed the issue of carbon emissions from the public sector.[9] Specifically, where public sector categories (such as spending on health, on education and on recreation) have a matching category in the COICOP classification, we have allocated the carbon emissions attributable to public sector final demand to these household categories. The assumption here is, once again, that it is the demand for health, education and recreation by households that ultimately must be regarded as the driver for public expenditures in these areas. The remaining (relatively small) carbon emissions from the public sector (mainly associated with administration and defence) have all been allocated to one functional category 'Other Government'.

8 We have used the allocation of economic sector carbon from Account C, rather than Account D, because the COICOP matrix provides its own allocation of distribution sector outputs to functional use categories.

9 Where public sector allocations have been added to COICOP subcategories we have indicated this with the word public in Table 1.

Functional Use Category	COICOP Sectors
Food and non-alcoholic drink	1.1, 1.2
Alcohol and Tobacco	2.1, 2.2
Clothing and Footwear	3.1, 3.2
Housing	4.1, 4.2, 4.3, 5.5, 5.6, 11.2
Water Supply and other misc. services	4.4 (+ public)
Furnishings and other household (ex appliances)	5.1, 5.2, 5.4
Household Appliances	5.3
Health and Hygiene	6.1, 6.2, 6.3, 12.1 (+ public)
Transport Services (ex private transport fuels)	7.1, 7.2, 7.3
Post and Communications	8.1, 8.2, 8.3
Recreation and Entertainment	9.1 – 9.4 (+ public)
Books and Newspapers	9.5
Other Personal Effects	12.3
Holidays	9.6
Education	10 (+ public)
Financial and Other Services	12.4, 12.5, 12.6, 12.7
Other Government	(public)
Delivered Fuels (Indirect)	4.5 (part)[10]

Table 1: Mapping COICOP Sectors to Functional Use Categories

Finally, Account E breaks down the carbon associated with direct consumption of fossil fuels by households into a number of distinct end-use categories on the basis of data on household energy consumption by fuel type and end-use obtained from DUKES (2005) and from DTI statistical databases available on the website.[11] These end-use categories include:

- space heating
- water heating
- cooking
- lighting
- cold appliances
- wet appliances
- brown appliances (consumer electronics) and
- other miscellaneous electrical appliances.

Account E therefore provides a breakdown of carbon emissions in terms of a set of 27 domestic functional use categories. Some of these categories relate to the 'upstream' or indirect carbon emissions associated with the production of goods and services provided to households either on the market or via the public sector. Other categories relate to the direct consumption of delivered fuels (coal, oil, gas, electricity and transport fuels) by households.

10 COICOP category 4.5 includes emissions from electricity production, which are excluded from this domestic functional category as they included directly elsewhere.

11 http://www.dti.gov.uk/energy/inform/energy_consumption/table.shtml

Account F: High-level Consumer Needs Account
In the final account, an illustrative attribution has been made to high-level functional needs categories. We have selected 10 high-level needs to include:

- Space heating
- Household
- Food & catering
- Clothing & footwear
- Health & Hygiene
- Recreation & Leisure
- Education
- Communications
- Commuting
- Other Government

The rationale for this selection is in part to reflect the range of material, social and psychological needs that are associated with modern lifestyles (Jackson and Marks 1999, Jackson et al 2004, Jackson 2005). Some of these are basic functional needs for material subsistence, protection and health. Others are associated more with social needs such as communication and education. Others cover a range of social and psychological motivations for leisure, relaxation, and interacting with friends and family. A part of the aim of this paper is to be able to identify the importance of these different categories of need in terms of their carbon impact.

These high-level categories are derived essentially through an allocation (or re-allocation) of the 27 domestic functional use categories derived in Account E. For example, emissions related to 'Clothing and Footwear' and to 'Other Personal Effects' have been aggregated into one high level category. Likewise emissions related to 'Financial Services' are assumed to be a necessary part of running the household and are allocated to the high level category 'Household'.

In addition to aggregating some emission categories, an attempt to re-allocate household appliance use and direct fuel consumption to individual high level needs is made. For example, the Food and Catering category includes carbon associated with purchases of food products, the purchase and use of cooking equipment, the use of catering facilities and the private and public travel required to meet these different requirements. A complete allocation of the 27 domestic functional use categories to the 10 high level consumer needs categories is shown in Table 2. Data for the re-allocation of transport related emissions to functional needs categories are based on data from the Department of Transport's Travel Use Survey and from data on transport use published on the DfT website.[12]

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12 Available at: http:www.dft.gov.uk/stellent/groups/dft_control/documents/contentservertemplate/dft_index.hcst?n=14133&l=4.

	Account 6: High-Level Functional Needs									
Account 5 Domestic Functional Use Categories	**Household**	**Recreation & Leisure**	**Space Heating**	**Food & Catering**	**Commut-ing**	**Health & Hygiene**	**Clothing & Footwear**	**Education**	**Communi-cation**	**Total**
Space Heating			100%							100%
Private Transport	3%	41%		5%	36%	7%	3%	4%		100%
Transport Services (indirect)	3%	41%		5%	36%	7%	3%	4%		100%
Food & Non-alcoholic drink				100%						100%
Health & Hygiene						100%				100%
Water Heating						50%	50%			100%
Recreation & Entertainment		100%								100%
Financial & Other Services	100%									100%
Other Personal Effects							100%			100%
Education								100%		100%
Housing	100%									100%
Public Admin & Defence									100%	100%
Household Appliances	25%	25%		25%		13%	13%			100%
Electricity (lighting)	100%									100%
Electricity (brown goods)		100%								100%
Electricity (cold appliances)				100%						100%
Holidays		100%								100%
Furnishings & Other Household	100%									100%
Clothing & Footwear							100%			100%
Electricity (wet appliances)						50%	50%			100%
Delivered Fuels (indirect)			75%			13%	13%			100%
Cooking				100%						100%
Alcohol & Tobacco		100%								100%
Electricity (misc)	100%									100%
Post & Communication									100%	100%
Water Supply & Other Misc Services						75%	25%			100%
Books & Newspaper								100%		100%

Table 2: Allocating Domestic Functional Use Categories to High-Level Consumer Needs

3. Results

The model described in the previous section is used to attribute carbon emissions from fossil fuel consumption to production and consumption sectors and to high-level consumer needs for the year 2002. The results for each of the six different Accounts are now described, and a top-level reconciliation exercise of the overall carbon burden based on existing national inventory data is provided.

Account A: Production Based Account

From a production perspective, the total carbon dioxide emitted by the UK economy in 2002 was 164.7 million tonnes of carbon (MtC)[13]. The largest proportion of these emissions (88 MtC or 57% of the total) came from 'indirect' emissions from the production of private and public sector goods and services in the economy (Figure 3).[14] When looking in more detail at the production sectors responsible for indirect emissions, we find that the highest emitter is the electricity supply industry with a total of 24 MtC (excluding production of electricity for domestic consumption). Other significant commodity sectors include Other Land Transport (7.9 MtC), the Refining Industries (7.1 MtC), Water Transport (5.8), Oil and Gas Extraction (4.7 MtC) and the Iron and Steel sector (2.53).

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13 Greenhouse gas emissions are measured throughout in this report as tonnes of carbon. For carbon dioxide emissions, this measure is calculated by taking the tonnes of carbon dioxide and multiplying this number by 12/44 – the ratio of molecular weights of carbon to carbon dioxide. This convention is in line with reporting in the UK national greenhouse gas emission inventory.

14 Note that this total excludes the emissions associated with the production of electricity for use in domestic households which is counted as a 'direct' emissions and attributed separately to households.

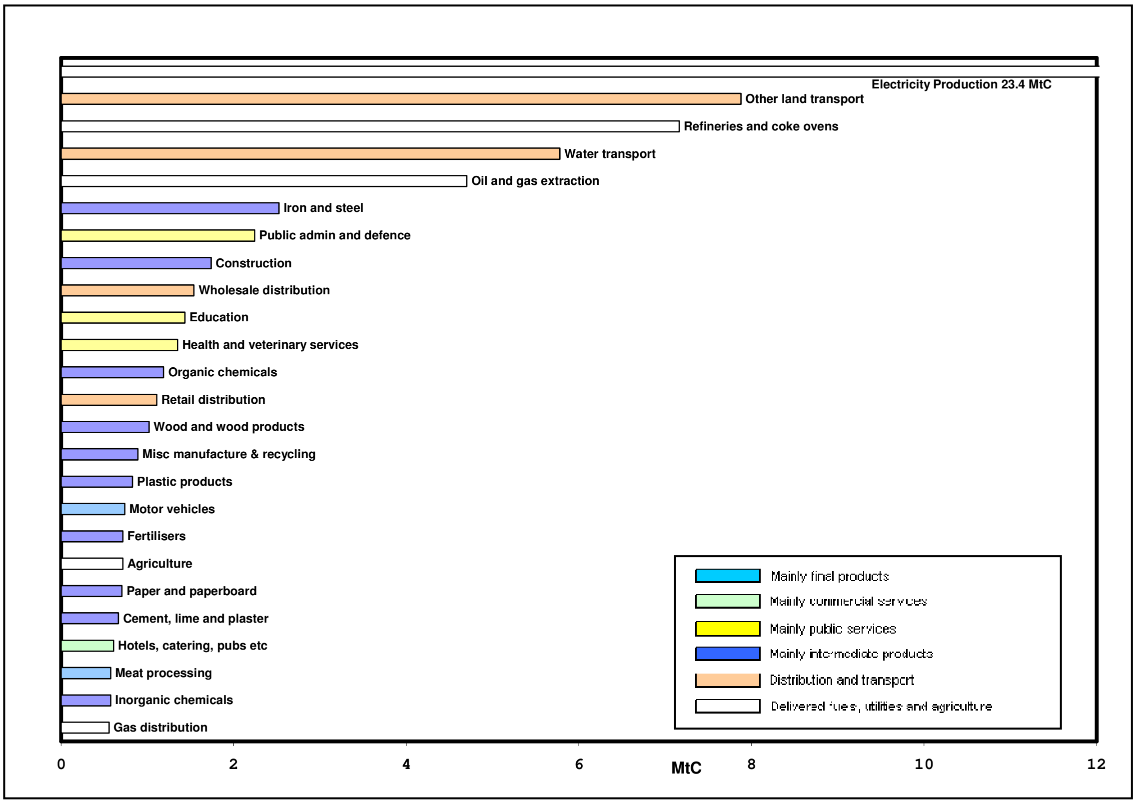

Figure 3: Indirect Carbon Emissions by Production Sector (Account A)

Domestic electricity consumption accounted for an additional 22 MtC, the direct consumption of fossil fuels in households accounted for 25.3 MtC and the direct consumption of transport fuels for private transport (cars) by households accounted for 18.3 MtC. An additional 11.0 MtC is attributable to emissions from the consumption of aviation fuels by airlines registered in the UK.

Account B: Consumption Based Account

When considered from a consumption-based perspective, the total carbon emissions attributable to UK consumers in 2002 were 176.4 MtC, approximately 11.7 MtC higher than the emissions from a production-based account. This difference is a result of the different basis for the treatment of imported and exported goods and services on the consumption-based account.

The 'indirect' emissions associated with Account B leads to a re-prioritisation of the 'indirect' carbon emissions associated with commodity sectors. At this point the model has allocated to each commodity sector all the carbon 'induced' directly or indirectly both in the UK economy and overseas as a result of the final demand (by households, government and investment) for that commodity in the UK. After this reallocation, it appears that largest carbon emissions (10.69 MtC) are attributable to the demand for construction (Figure 4). This is explained by the energy-intensive nature of the demand for building materials required by the construction sector as well as by the fuel inputs to construction.

The next most important categories on the consumption perspective are the Distribution sectors (12.5 MtC), Hotels and Restaurants (5.66 MtC), and Health Services (5.35). The importance of these sectors can be explained in part by the infrastructure demands of these sectors and in part by the high level of fuel use for space heating, water heating and building services in these sectors. Following these service sectors, we also find that Motor Vehicle Production (4.23 MtC) becomes significant on the consumption-based perspective. This reflects the size of the industry and the carbon intensive nature of the materials and processes used in vehicle manufacturing.

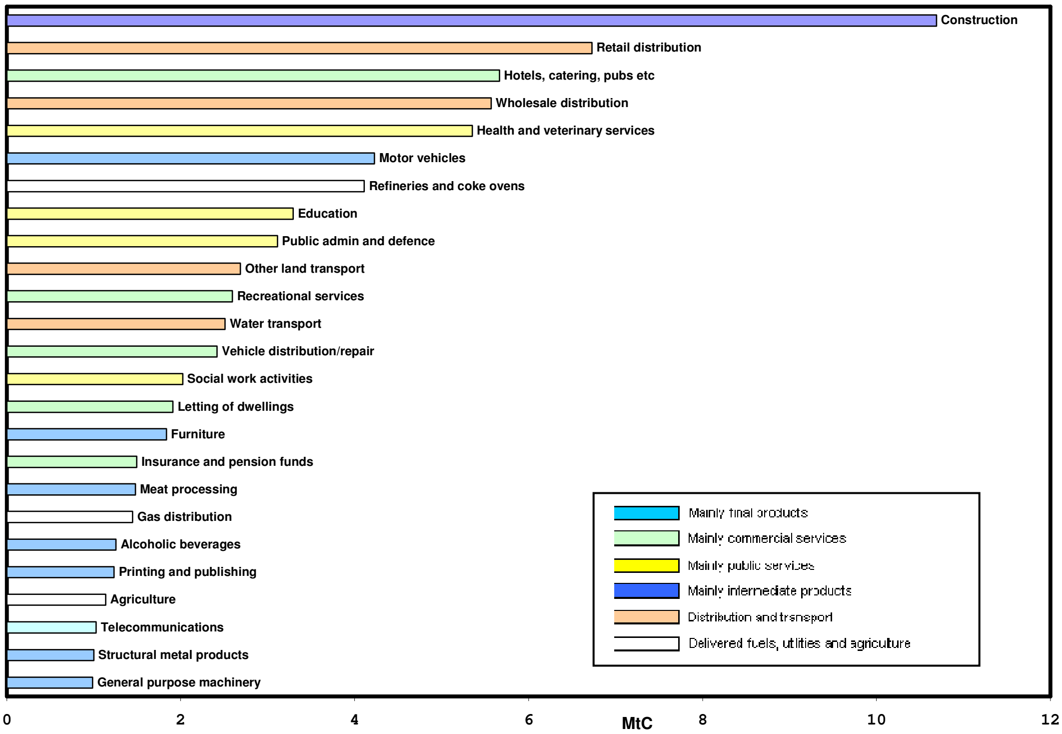

Figure 4: Indirect Carbon Emissions by Commodity Sector (Account B)

Accounts C and D: Re-allocating Fixed Capital and Distribution Carbon

The total carbon attributable to UK consumption is unchanged in Accounts C and D, since these accounts simply re-distribute the carbon associated with fixed capital (investment) and distribution respectively. However, the priority sectors change on the basis of these re-allocations. After re-distributing investment carbon (Account C) the most important commodity sectors are the Retail and Wholesale Distribution sectors with a combined emissions total of 17.2 MtC, the Hotels and Catering sector (8.3 MtC), Health Services (6.1 MtC) and the indirect emissions from the Refining Industries (4.3 MtC) (Figure 5).

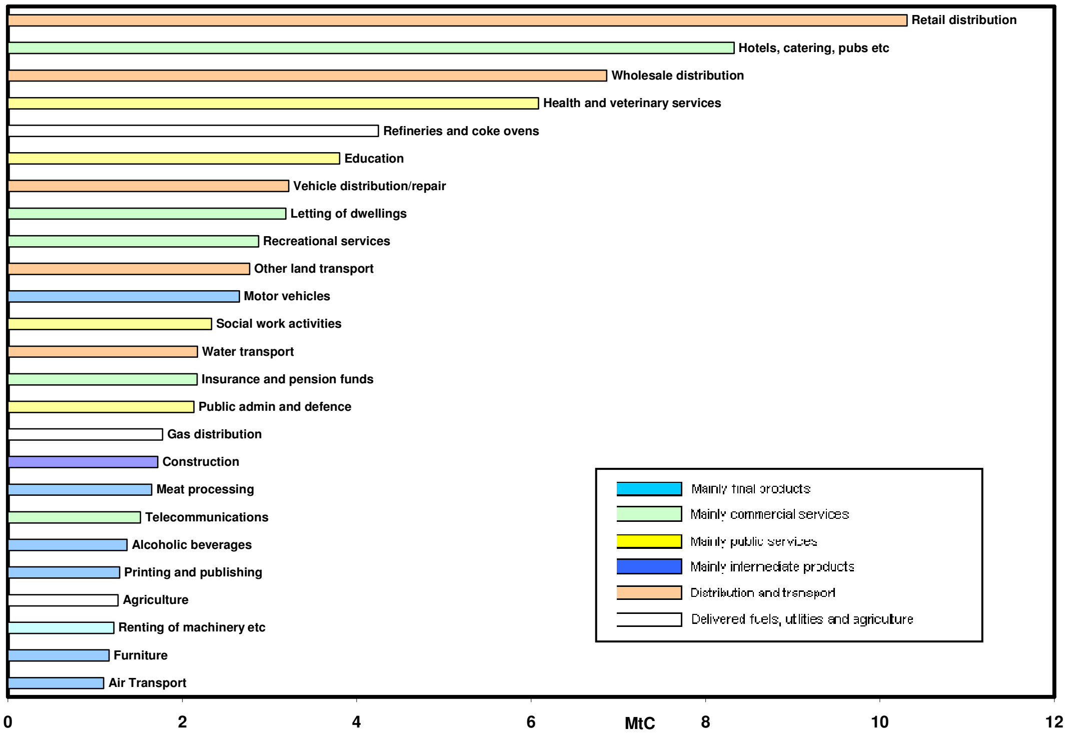

Figure 5: Indirect Carbon Emissions by Commodity Sector (Account C)

It can be seen that the distribution categories still dominate a high position on the chart as shown in Account B along with Motor vehicle Production and a variety of service categories. It can also be seen that the service categories (presented by the light green and yellow bars) and distribution (orange coloured bar) now dominate the highest ranking place. Intermediate categories (dark blue bar), i.e. construction, with its reallocation of carbon emissions to relevant categories has now dropped in its ranking.

After re-distributing the carbon associated with wholesale and retail distribution the picture changes again (Figure 6). At this point, the most important commodity sector in carbon terms is the Hotel and Catering sector with emissions of 8.3 MtC. The explanation for this is the high level of infrastructure, space and water heating requirements in this sector. Other priority sectors include Motor Vehicle Production (7.1 MtC), Health Services (6.1 MtC), Refining Industries (4.5 MtC), Education (3.8 MtC), Letting of Dwellings (3.2 MtC) and Recreational Services (2.9 MtC).

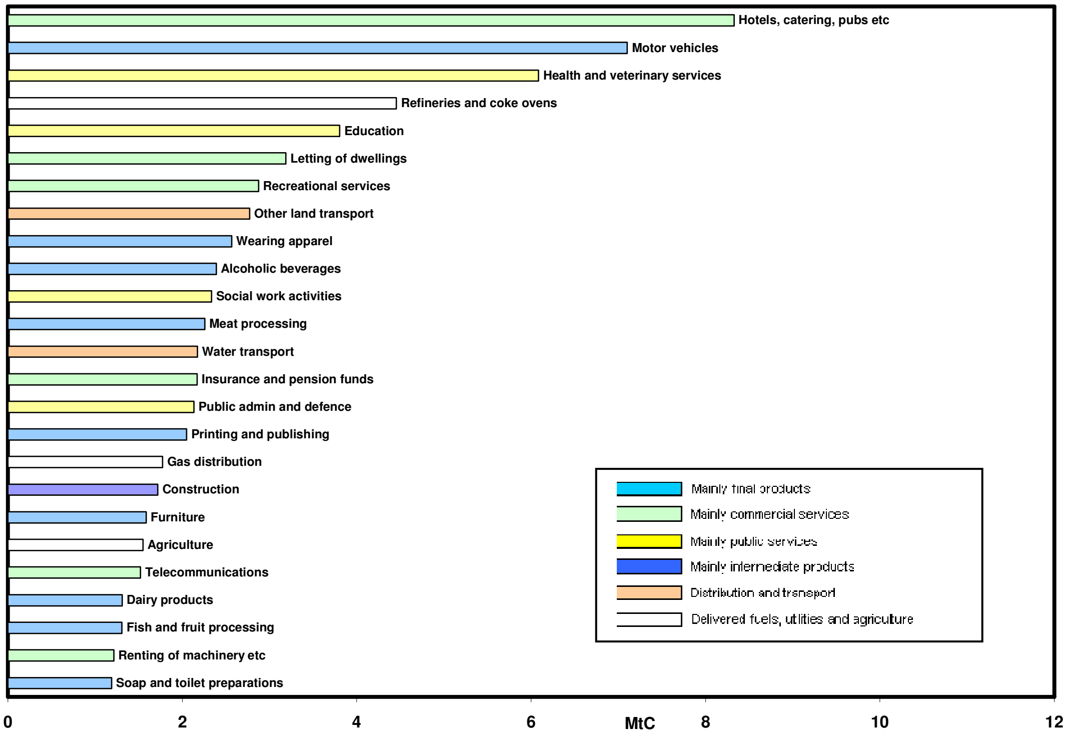

Figure 6: Indirect Carbon Emissions by Commodity Sector (Account D)

The general trend in priority sectors between Accounts A and D is worth commenting on briefly.[15] Commodity sectors are colour coded in Figures 3 to 6 according to the following schema:

- mainly final product sectors are coloured in light blue;
- mainly commercial service sectors are coloured in light green;
- mainly public service sectors are coloured in yellow;
- mainly intermediate product sectors are coloured in darker blue;
- distribution and transport sectors are coloured in orange; and
- delivered fuel sectors, utilities and agriculture are left white.

This colour coding allows us to illustrate graphically the transition through the different Accounts. Whereas Account A tends to prioritise primary production, transport and manufacturing sectors, by the time we get to Account D, more priority is given to commodity sectors which deliver a range of final products and services to consumers. This reflects the general intention in the study to allocate carbon more and more to delivered final services. In Accounts E and F we take this intention a step further and allocate commodity sector carbon to functional purposes.

15 Note that Figures 3 to 6 illustrate only the top 25 categories in each of Accounts A to D.

Account E: Domestic Functional Use Account

This account is the first stage in re-allocating the indirect carbon emissions from commodity sectors to functional uses. It employs a variation on the COICOP classification as described in Section 2 and allocates carbon emissions to 27 domestic functional use categories. The total carbon emissions across Account E are exactly as for Accounts B to D, namely 176.4 MtC (including emissions from aviation fuels which are treated separately as for Accounts B to D).

However, the impact of Account E is to reduce the number of indirect commodity sectors and to expand the number of delivered fuel consumption sectors, with the aim of getting closer to household functional purposes. This is shown within the results by now using a colour code which describes the different stages in the supply chain. The six key supply emission types are: electricity use, direct fossil fuel consumption, transport, utilities (water and waste services, excluding power), final products and final services.

The results of this exercise are illustrated in Figure 7, which includes all UK carbon emissions except for those associated with aviation fuels.[16] It can be seen that the most important function categories are for Space Heating (22.6 MtC), Private Transport fuels (18.3 MtC), the indirect emissions associated with the demand for Transport Services (18.2 MtC) and the Food and Non-Alcoholic drink category (14.5 MtC). These findings are in line with a number of other studies which have indicated that Housing, Transport and Food are the three most significant consumption sectors (for example Tukker et al 2005). The results also highlight how different consumer needs and purchasers impact different sectors of the economy, for example the high carbon emissions related to heating in the home and private transport.

[16] These emissions are excluded from the graphical illustrations in Accounts E and F, because insufficient data were found to allocate them to functional purposes. Though the National Travel Survey provides a useful account of domestic (inland) travel, it does not provide any breakdown of overseas travel by purpose. In addition, aviation emissions have not been through the input-ouput model in the same way that other production sector emissions have, because of the lack of clarity over the precise allocation of final demand for aviation services by UK (as opposed to overseas) consumers.

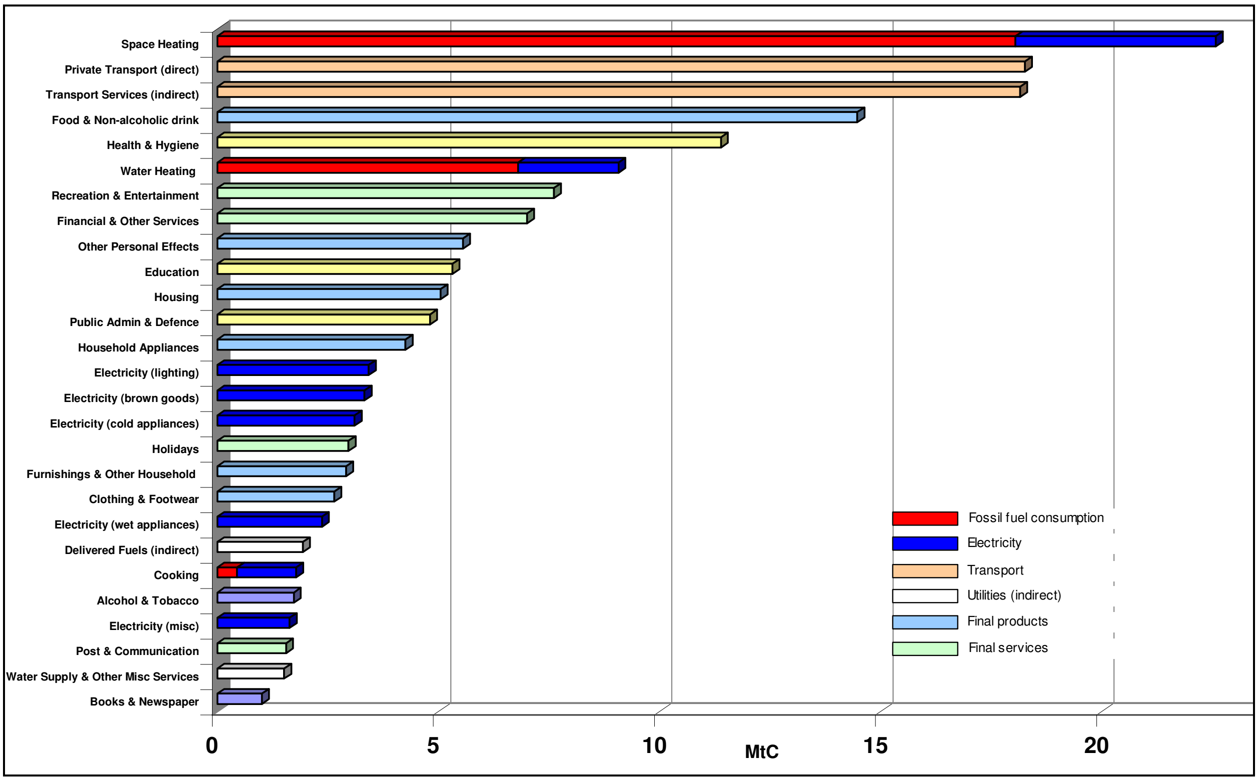

Figure 7: Carbon Allocated to Domestic Functional Uses (Account E)

Account F: High Level Consumer Needs Account

The final step in the process is to allocate carbon according to high-level consumer needs as discussed in Section 2. Total carbon emissions remain the same (176.4 MtC). But the number of categories in the high-level account is reduced from 27 functional use categories to 10 high level needs categories.

The most important categories in terms of carbon emissions on this Account are Recreation and Leisure which totals 31.6 MtC and of which approximately half of these carbon emissions are travel related. Space Heating represents 24 MtC and are mainly emitted directly in the home , while Food and Catering (22.4 MtC) has the majority of its carbon emissions embodied in the products consumed. Carbon attributable to maintaining the household (22.2 MtC) is also significant and is explained by the carbon emissions attributable to the production of building materials, while the high carbon emissions of health and hygiene (21.7 MtC) are explained by emissions attributable to water heating (which is a direct emission source). Figure 8 illustrates the final breakdown of carbon emissions according to high-level needs. As with Account E, aviation emissions are excluded from this breakdown because insufficient data were available to allocate air travel by functional purpose.

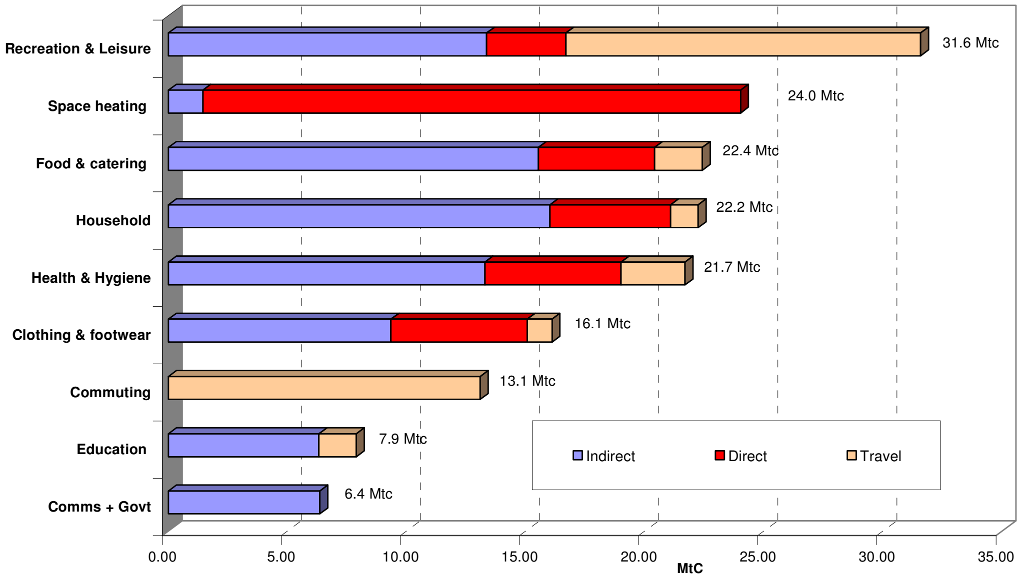

Figure 8: Carbon Allocated to Consumer Needs (Account F)

It has been noted that that the total emissions attributable to the consumption accounts amounts to 176.4 MtC (which includes 11.0 MtC attributable to aviation fuel emissions). This figure differs from the 2002 UK production carbon footprint published by DEFRA (e-Digest[17]), mainly due to the difference in emissions attributable to imports from the consumption perspective. To show this difference more clearly, a reconciliation exercise is undertaken.

Reconciliation of Production and Consumption Carbon Footprints

UK consumption emissions are calculated at 165.4 MtC plus 11.0 MtC attributable to aviation fuel use to give a total carbon consumption footprint of 176.4 MtC.

This total amount shows a difference of 27.4 MtC from the 149.0 MtC 2002 UK carbon footprint published in the Defra e-Digest (Figure 9). This difference is due to:

- The Defra figures excluding emissions from all aviation fuel use of 11.0 MtC;
- The Defra figures assume lower water transport emissions of 1.0 MtC against 5.8 MtC in these accounts; and
- The Defra figures are based on UK production whereas this analysis estimates the carbon emissions attributable to UK consumption. The remaining difference of 11.7 MtC is the estimated carbon "trade balance". In essence, the positive difference between the carbon footprint of UK imports versus UK exports.

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[17] DEFRA 2005 e-Digest Table 5, available from www.defra.gov.uk/environment/statistics/download/xls/gatb05.xls.

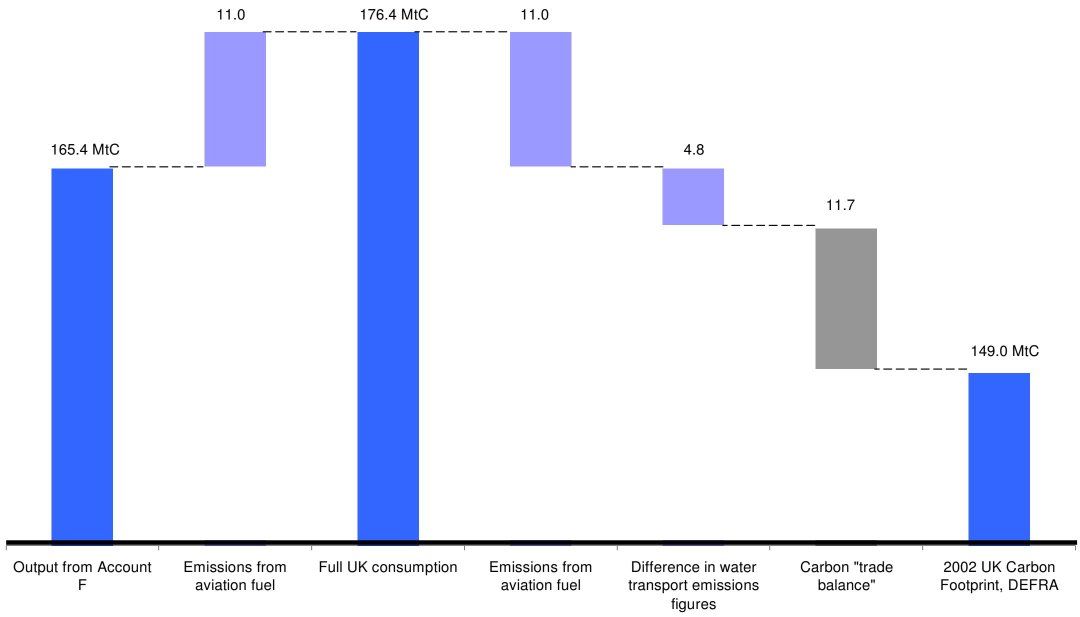

Figure 9 Production versus Consumption Carbon Footprint: Reconciliation with DEFRA accounts

It is seen from these findings that the carbon associated with UK imports from abroad is greater than the carbon associated with UK exports. This is likely to be a result of the development of the UK towards as a service-based economy. Satisfaction of consumer demand from primary and manufactured products are now merely imported from abroad. This implies that there the more carbon intensive industries have relocated overseas. Given this trend, the carbon trade balance of 11.7 MtC (representing 7% of the total consumption carbon footprint) is not as large as may have been expected. This may be due to an underestimation of the carbon attributable to imports due to the assumption that trading partners have a similar economic and resource structure as the UK.

5. Conclusion

The findings of this study offer some interesting insights into the different approaches which can be used to calculate the carbon footprint of the UK. Firstly, it has shown that even though the production-based approach is still important in understanding and managing the carbon emissions within national boundaries, the consumption-based approach ensures that a clearer knowledge of the carbon emissions attributable to consumer behaviour and purchasing practices is gained. This is a fundamental requirement if the long term goals for carbon emission set by the UK government are to be met through changes in consumption patterns.

On this note, the consumption Accounts B to D showed that through the processes of attributing carbon on a consumption basis and re-allocating carbon attributable to fixed-capital and distribution to household demand, there was a shift in the carbon intensive categories. Compared to the production Account A which showed primary manufacturing, distribution and investment categories to be the highest emitting categories, Accounts B to D progressively showed that the delivery of final goods and services (for example Hotels and Catering, Motor vehicle production and Health and veterinary services) to consumers were the highest emitters. This highlights the need for a consumption-based perspective to calculating carbon footprints to ensure that the demand by consumer for particular products and services can be calculated throughout the supply chain.

Additionally, it was shown in Account E that the top functional headings which are the largest carbon emitters are: the use of electricity and fuels in the home and transport. Account F showed that based on a high-level consumer needs perspective, the supply chain associated with recreation and leisure activities had the highest emissions, of which just under half was transport related. Space heating represented the second highest emitter of which the vast majority of emissions are considered as direct emissions and Food and Catering indicated that over half of its emissions were embodied emissions.

Mapping carbon to the functional needs of consumers can in turn highlight which activities are driving carbon emissions. Efforts towards reducing these carbon emissions through changes in consumer behaviour, infrastructure and institutions can then be more effectively examined and the appropriate policy interventions created.

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Appendix 1: Two-Region Input-Output Model

Ultimately, it is the demand for final goods and services that drives carbon emissions. To 'attribute' the carbon associated with each final demand category, an input-output model of the UK economy, combined with carbon intensity coefficients is used. This environmental input-output model allocates to each commodity sector all the carbon 'induced' directly and indirectly both at home and abroad as a result of the demand for that commodity in the UK.

Inter-regional input-output model

The model employed is based on the work of Proops et al. (1993:133 – 138) and is split between goods produced domestically and imported. Imports are further separated into intermediate and final goods within the model to ensure total carbon associated with imports is calculated. As imports are considered explicitly within the calculations, an inter-regional model is used. Detailed description of a two-region inter-regional relationship is shown in the table below taken from Proops et. al. (1993:133)

Table 2.1: Inter-regional trade input-output table

	1.1.1.1.1	*Region 1*	*1.1.1.1.2*	*Region 2*	*1.1.1.1.3*	*Final Demand*	*1.1.1.1.4*	*Total Output*
Region 1	$\mathbf{X}^1$		$\mathbf{H}^{12}$		$\mathbf{y}^{11}$	$\mathbf{y}^{12}$	$\mathbf{x}^1$	
Region 2	$\mathbf{H}^{21}$		$\mathbf{X}^2$		$\mathbf{y}^{21}$	$\mathbf{y}^{22}$	$\mathbf{x}^1$	

Where,
$\mathbf{X}^1$ - Matrix of intermediate flows for region 1
$\mathbf{H}^{12}$ - Matrix of import flows from region 1 to region 2
$\mathbf{y}^{12}$ - Vector of final demand from region 1 delivered to region 2
$\mathbf{x}^1$ - Vector of total demand by region 1

The matrix of intra-regional technical coefficients of region 1, i.e. the inter-industry flows within a region, is defined as $\mathbf{A}^1$ with elements:

$$a_{ij}^1 \equiv \frac{X_{ij}^1}{x_j^1} \qquad (2.1)$$

The matrix of inter-regional technical coefficients is denoted as $\mathbf{B}^{12}$. In the particular case of the consumption perspective for region 1 we are interested in $\mathbf{B}^{21}$, which describes the intermediate goods from region 2 demanded by industry in region 1.

The elements of this matrix are specific to the demand of region 1's industry in producing final goods to satisfy final demand. In other words the $\mathbf{H}^{21}$ matrix and its derived coefficient $\mathbf{B}^{21}$ matrix describe the imported intermediate flows of the domestic economy, i.e. those flows which go to the domestic industries for further processing to produce domestic final goods. These semi-manufactured imports act as additional inputs into the production processes of the domestic industries in order to satisfy final demand for domestically produced final goods, $\mathbf{y}^{11}$. The elements of $\mathbf{B}^{21}$ are defined as:

$$b_{ij}^{21} \equiv \frac{H_{ij}^{21}}{x_j^1} \tag{2.2}$$

Using (2.1) and (2.2) in the structure of Table 2.1 we have in matrix-vector notation:

$$\begin{pmatrix} \mathbf{A}^1\mathbf{x}^1 & \mathbf{B}^{12}\mathbf{x}^2 \\ \mathbf{B}^{21}\mathbf{x}^1 & \mathbf{A}^2\mathbf{x}^2 \end{pmatrix} + \begin{pmatrix} \mathbf{y}^1 \\ \mathbf{y}^2 \end{pmatrix} = \begin{pmatrix} \mathbf{x}^1 \\ \mathbf{x}^2 \end{pmatrix} \tag{2.3}$$

then,

$$\begin{pmatrix} \mathbf{A}^1 & \mathbf{B}^{12} \\ \mathbf{B}^{21} & \mathbf{A}^2 \end{pmatrix} \cdot \begin{pmatrix} \mathbf{x}^1 \\ \mathbf{x}^2 \end{pmatrix} + \begin{pmatrix} \mathbf{y}^1 \\ \mathbf{y}^2 \end{pmatrix} = \begin{pmatrix} \mathbf{x}^1 \\ \mathbf{x}^2 \end{pmatrix} \tag{2.4}$$

By re-arranging (2.4) so that total output, **x**, is made the subject we arrive at the result, Proops et.al. (1993:134):

$$\begin{pmatrix} (\mathbf{I}-\mathbf{A}^1) & -\mathbf{B}^{12} \\ -\mathbf{B}^{21} & (\mathbf{I}-\mathbf{A}^2) \end{pmatrix}^{-1} \begin{pmatrix} \mathbf{y}^1 \\ \mathbf{y}^2 \end{pmatrix} = \begin{pmatrix} \mathbf{x}^1 \\ \mathbf{x}^2 \end{pmatrix} \tag{2.5}$$

Final demand of region 1, $\mathbf{y}^1$, can be decomposed to be equivalent to the sum of its component parts, i.e.:

$$\mathbf{y}^1 \equiv \mathbf{y}^{11} + \mathbf{y}^{12} \tag{2.6}$$

Where,

$\mathbf{y}^{11}$ - Supply of goods from region 1 to final demand of region 1

$\mathbf{y}^{12}$ - Supply of goods from region 1 to final demand of region 2 (i.e. exports)

Then using the disaggregation of final demand:

$$\begin{pmatrix} \mathbf{y}^1 \\ \mathbf{y}^2 \end{pmatrix} \rightarrow \begin{pmatrix} \mathbf{y}^{11} & \mathbf{y}^{12} \\ \mathbf{y}^{21} & \mathbf{y}^{22} \end{pmatrix} \tag{2.7}$$

and additionally the disaggregation of total output:

$$\begin{pmatrix} \mathbf{x}^1 \\ \mathbf{x}^2 \end{pmatrix} \rightarrow \begin{pmatrix} \mathbf{x}^{11} & \mathbf{x}^{12} \\ \mathbf{x}^{21} & \mathbf{x}^{22} \end{pmatrix} \tag{2.8}$$

and setting:

$$\begin{pmatrix} (\mathbf{I}-\mathbf{A}^1) & -\mathbf{B}^{12} \\ -\mathbf{B}^{21} & (\mathbf{I}-\mathbf{A}^2) \end{pmatrix}^{-1} = \begin{pmatrix} \mathbf{M}^* & \mathbf{Q}^* \\ \mathbf{R}^* & \mathbf{S}^* \end{pmatrix} \tag{2.9}$$

Then using (2.7), (2.8) and (2.9) equation (2.5) can be written as:

$$\begin{pmatrix} \mathbf{M}^* & \mathbf{Q}^* \\ \mathbf{R}^* & \mathbf{S}^* \end{pmatrix} \cdot \begin{pmatrix} \mathbf{y^{11}} & \mathbf{y^{12}} \\ \mathbf{y^{21}} & \mathbf{y^{22}} \end{pmatrix} = \begin{pmatrix} \mathbf{x^{11}} & \mathbf{x^{12}} \\ \mathbf{x^{21}} & \mathbf{x^{22}} \end{pmatrix} \tag{2.10}$$

Conversion of these monetary flows into emissions requires the use of emission intensity vectors as described below.

Emission intensity vectors

These monetary flows are converted into emissions by using the emission intensity vectors $\mathbf{c^1}$ and $\mathbf{c^2}$, for region 1 and 2 respectively. Total emission, ${}^{prod}E^1$, associated with domestic production of goods, $\mathbf{x^1}$, in region 1 is then stated as:

$${}^{prod}E^1 = \mathbf{c^1}' \cdot \mathbf{x^1} \tag{2.11}$$

Similarly the same relationship can be said to hold for region 2's production processes and stated as:

$${}^{prod}E^2 = \mathbf{c^2}' \cdot \mathbf{x^2} \tag{2.12}$$

Adding these two structural equations (2.11) and (2.12) into combined matrix notation, and rearranging, gives:

$$\begin{pmatrix} \mathbf{c^1}' & \mathbf{c^2}' \end{pmatrix} \cdot \begin{pmatrix} \mathbf{x^1} \\ \mathbf{x^2} \end{pmatrix} = {}^{prod}E \tag{2.13}$$

where,

$${}^{prod}E = {}^{prod}E^1 + {}^{prod}E^2 \tag{2.14}$$

Disaggregating the energy intensity vector as follows:

$$\begin{pmatrix} \mathbf{c^1}' & \mathbf{c^2}' \end{pmatrix} \rightarrow \begin{pmatrix} \mathbf{c^1}' & 0 \\ 0 & \mathbf{c^2}' \end{pmatrix} \tag{2.15}$$

and substituting (2.15) and (2.8) into (2.13), we have:

$$\begin{pmatrix} \mathbf{c^1}' & \mathbf{0} \\ \mathbf{0} & \mathbf{c^2}' \end{pmatrix} \cdot \begin{pmatrix} \mathbf{x^{11}} & \mathbf{x^{12}} \\ \mathbf{x^{21}} & \mathbf{x^{22}} \end{pmatrix} = \begin{pmatrix} E^{11} & E^{12} \\ E^{21} & E^{22} \end{pmatrix} \tag{2.16}$$

Finally, 2.10 is substituted into 2.16 to give:

$$\begin{pmatrix} \mathbf{c^1}' & 0 \\ 0 & \mathbf{c^2}' \end{pmatrix} \cdot \begin{pmatrix} \mathbf{M}^* & \mathbf{Q}^* \\ \mathbf{R}^* & \mathbf{S}^* \end{pmatrix} \cdot \begin{pmatrix} \mathbf{y^{11}} & \mathbf{y^{12}} \\ \mathbf{y^{21}} & \mathbf{y^{22}} \end{pmatrix} = \begin{pmatrix} E^{11} & E^{12} \\ E^{21} & E^{22} \end{pmatrix} \tag{2.17}$$

Where

$${}^{prod}E^1 = E^{11} + E^{12} \tag{2.18}$$

and,

$${}^{prod}E^2 = E^{21} + E^{22} \tag{2.19}$$

Working the multiplication on the left hand side of (2.17) we have:

$$\begin{pmatrix} \mathbf{c^1}'\mathbf{M}^* & \mathbf{c^1}'\mathbf{Q}^* \\ \mathbf{c^2}'\mathbf{R}^* & \mathbf{c^2}'\mathbf{S}^* \end{pmatrix} \begin{pmatrix} \mathbf{y^{11}} & \mathbf{y^{12}} \\ \mathbf{y^{21}} & \mathbf{y^{22}} \end{pmatrix} = \begin{pmatrix} E^{11} & E^{12} \\ E^{21} & E^{22} \end{pmatrix} \tag{2.20}$$

And subsequently;

$$\begin{pmatrix} \mathbf{c^{1\prime}M^{*}y^{11}} + \mathbf{c^{1\prime}Q^{*}y^{21}} & \mathbf{c^{1\prime}M^{*}y^{12}} + \mathbf{c^{1\prime}Q^{*}y^{22}} \\ \mathbf{c^{2\prime}R^{*}y^{11}} + \mathbf{c^{2\prime}S^{*}y^{21}} & \mathbf{c^{2\prime}R^{*}y^{12}} + \mathbf{c^{2\prime}S^{*}y^{22}} \end{pmatrix} = \begin{pmatrix} E^{11} & E^{12} \\ E^{21} & E^{22} \end{pmatrix} \tag{2.21}$$

The total energy requirements by industries in the regions are therefore composed of four sets. For region 1 we can state that the total energy requirement for industry use to produce total domestic output (production perspective), ${}^{prod}E^{1}$, is stated as:

$${}^{prod}E^{1} = E^{11} + E^{12} \tag{2.22}$$

and by using equations in (2.21) then (2..22) can be written in terms of final demand as:

$${}^{prod}E^{1} = \mathbf{c^{1\prime}M^{*}y^{11}} + \mathbf{c^{1\prime}Q^{*}y^{21}} + \mathbf{c^{1\prime}M^{*}y^{12}} + \mathbf{c^{1\prime}Q^{*}y^{22}} \tag{2.23}$$

However, when attributing energy requirement to region 1 based on the responsibility of final users (extended consumption responsibility) what is required is all the energy attributable to satisfying domestic final demand and imported final demand, i.e. for region 1 the final demand elements, $\mathbf{y^{11}}$ and $\mathbf{y^{21}}$. Therefore from a consumption perspective the total energy required by industry to satisfy domestic final demand and imported final demand, ${}^{cons}E^{1}$, can be stated as:

$${}^{cons}E^{1} = E^{11} + E^{21} \tag{2.24}$$

which can be written in terms of final demand by using equations (2.21) and (2.24) to give:

$${}^{cons}E^{1} = \mathbf{c^{1\prime}My^{11}} + \mathbf{c^{1\prime}Qy^{21}} + \mathbf{c^{2\prime}Ry^{11}} + \mathbf{c^{2\prime}Sy^{21}} \tag{2.25}$$

To find the solutions for $\mathbf{M}^{*}$, $\mathbf{Q}^{*}$, $\mathbf{R}^{*}$, $\mathbf{S}^{*}$ explicitly, the rule for inverting partitioned matrices (Johnston 1972: 90) is used giving the solutions:

$$\mathbf{M}^{*} = \mathbf{G}^{*} \qquad [\mathbf{G}^{*} \equiv ((\mathbf{I} - \mathbf{A^{1}}) - \mathbf{B^{12}}(\mathbf{I} - \mathbf{A^{2}})^{-1}\mathbf{B^{21}})^{-1}] \tag{2.26}$$

$$\mathbf{Q}^{*} = \mathbf{G}^{*}\mathbf{B^{12}}(\mathbf{I} - \mathbf{A^{2}})^{-1} \tag{2.27}$$

$$\mathbf{R}^{*} = (\mathbf{I} - \mathbf{A^{2}})^{-1}\mathbf{B^{21}}\mathbf{G}^{*} \tag{2.28}$$

$$\mathbf{S}^{*} = (\mathbf{I} - \mathbf{A^{2}})^{-1}(\mathbf{I} + \mathbf{B^{21}}\mathbf{G}^{*}\mathbf{B^{12}}(\mathbf{I} - \mathbf{A^{2}})^{-1}) \tag{2.29}$$

Following the small country assumption made by Proops et.al. (1993:137) where it is assumed that the exports of region α are negligible, then the condition $\mathbf{B^{12}} = \mathbf{0}$ is imposed. Inserting this condition into the above equations (2.26 – 2.29) we get the results:

$$\mathbf{M}^{*} = (\mathbf{I} - \mathbf{A^{1}})^{-1} \tag{2.30}$$

$$\mathbf{Q}^{*} = \mathbf{0} \tag{2.31}$$

$$\mathbf{R}^{*} = (\mathbf{I} - \mathbf{A^{2}})^{-1}\mathbf{B^{21}}(\mathbf{I} - \mathbf{A^{1}})^{-1} \tag{2.32}$$

$$\mathbf{S}^{*} = (\mathbf{I} - \mathbf{A^{2}})^{-1} \tag{2.33}$$

Using these results in equation (2.25) for each of the consumption components, we can then attribute carbon emission to the relevant final demand as:

$$\mathbf{c^1}'\mathbf{M}^*\mathbf{y^{11}} = \mathbf{c^1}'(\mathbf{I} - \mathbf{A^1})^{-1}\mathbf{y^{11}} \quad (2.34)$$
$$\mathbf{c^1}'\mathbf{Q}^*\mathbf{y^{21}} = \mathbf{0} \quad (2.35)$$
$$\mathbf{c^2}'\mathbf{R}^*\mathbf{y^{11}} = \mathbf{c^2}'(\mathbf{I} - \mathbf{A^2})^{-1}\mathbf{B^{21}}(\mathbf{I} - \mathbf{A^1})^{-1}\mathbf{y^{11}} \quad (2.36)$$
$$\mathbf{c^2}'\mathbf{S}^*\mathbf{y^{21}} = \mathbf{c^2}'(\mathbf{I} - \mathbf{A^2})^{-1}\mathbf{y^{21}} \quad (2.37)$$

Inspection of above equations (2.34 to 2.37) requires data for the emission intensity and economic structure of region 1 (UK) and 2 (Rest of the World). We have $\mathbf{c^1}$ and $\mathbf{A^1}$, but we do not know $\mathbf{c^2}$ and $\mathbf{B^2}$. In order to make progress as suggested by Proops et al. (1993:137), we make the following assumption:

$$\mathbf{c^1}' \cdot (\mathbf{I} - \mathbf{A^1})^{-1} = \mathbf{c^2}' \cdot (\mathbf{I} - \mathbf{A^2})^{-1} \quad (2.38)$$

Substituting this assumption into equations (2.34) to (2.37) gives the total emissions embodied in domestic, imported intermediate and imported final goods as described below. These three components are used to measure the emissions attributed to final consumption within this research.

1.2 Domestic carbon emissions attributed to Domestic final demand:

$$E^{11} = \mathbf{c^1}'(\mathbf{I} - \mathbf{A^1})^{-1}\mathbf{y^{11}} \quad (2.39)$$

which describes the fossil resource required for energy purposes by industries in region 1 to produce output to satisfy region 1's domestic final demand.

Foreign carbon emissions attributed to Domestic final demand:

$$E^{21,i} = \mathbf{c^1}'(\mathbf{I} - \mathbf{A^1})^{-1}\mathbf{B^{21}}(\mathbf{I} - \mathbf{A^1})^{-1}\mathbf{y^{11}} \quad (2.40)$$

which computes the fossil resource required for energy purposes by industries in region 2 to produce intermediate exports (i.e. imports for region 1) which are used as inputs in the domestic production process of region 1 to satisfy domestic final demand of region 1.

Foreign carbon emissions attributed to Imported final demand:

$$E^{21,d} = \mathbf{c^1}'(\mathbf{I} - \mathbf{A^1})^{-1}\mathbf{y^{21}} \quad (2.41)$$

This equation calculates the energy required by industries in region 2 to produce final goods which are imported by region 1 to satisfy imported final demand.

Emission intensity of Commodities

To enable comparison and ranking of commodities, the final demand vector is diagonalised to maintain the disaggregated presentation of final demand. Therefore, equations (2.39) to (2.41) are rewritten below using the diagonalised final demand matrix to produce a total emissions vector described by commodity type (equations 2.42 – 2.44).

1.3 Domestic carbon emissions attributed to Domestic final demand according to Commodity type:

$$\mathbf{E}^{11} = \mathbf{c}^{1\prime} \cdot (\mathbf{I} - \mathbf{A}^{1})^{-1} \cdot \langle \mathbf{y}^{11} \rangle \tag{2.42}$$

Foreign carbon emissions attributed to Domestic final demand according to Commodity type:

$$\mathbf{E}^{21,\mathbf{i}} = \mathbf{c}^{1\prime} \cdot (\mathbf{I} - \mathbf{A}^{1})^{-1} \cdot \mathbf{B}^{21} \cdot (\mathbf{I} - \mathbf{A}^{1})^{-1} \cdot \langle \mathbf{y}^{11} \rangle \tag{2.43}$$

Foreign carbon emissions attributed to Imported final demand according to Commodity type:

$$\mathbf{E}^{21,\mathbf{d}} = \mathbf{c}^{1\prime} \cdot (\mathbf{I} - \mathbf{A}^{1})^{-1} \cdot \langle \mathbf{y}^{21} \rangle \tag{2.44}$$

Where, $\langle \;\; \rangle$ denotes the diagonal of the enclosed vector.

Appendix 2. Data Sources

Data used in the model were taken from the Office for National Statistics website, the Royal Commission on Environmental Pollution, IPCC website, the Department for Trade and Industry website and the Department for Transport website. Each variable is described below.

Carbon emission intensity coefficients, $\mathbf{c}$, were calculated by converting industrial energy demand into the corresponding emission factors. The 2002 energy data were retrieved from the Environmental Accounts sourced from the Office for National Statistics (ONS) website and the emission factors were taken from the Royal Commission on Environmental Pollution and the IPCC revised 1996 guidelines. The emission coefficients were summed across fuel type giving a 122x1 vector in MtC/£m.

The **Leontief inverse**, $(\mathbf{I} - \mathbf{A})^{-1}$, was retrieved from the analytical Input-Output tables (ONS website) based on 1995 data (more recent table do not exist). The table is a 122x122 matrix of inverted technical coefficients categorised according to the 1992 Standard Industrial Classification (SIC).

Monetary expenditure for domestically produced goods by households, government and investment, $\mathbf{y}^{11}$, were taken from the 2002 Supply and Use tables (ONS website), measured in £m.

Import use coefficients, $\mathbf{B}^{21}$, are based on the 1995 structure, which is the last detailed analysis of imports to be published by ONS (ONS website). The assumption made is that the distributional structure for imports has not changed since 1995. The imports coefficient matrix is of dimension 122x122.

Demand for imported final goods, $\mathbf{y}^{21}$, by households, government and fixed capital was taken from the 2002 Supply and Use tables (ONS website) and recorded in £m.

The '**investment carbon coefficients**' were calculated using data from the "Output and Capital Formation: by Industry" table of The Blue Book 2004 publication (ONS website). The table reports the amount of investment in £m undertaken by each broad industry group in 2002.

Distribution sectors: wholesale and retail, are proportioned to end-use categories using the **distribution margins** published in the 2002 Supply and Use tables (ONS website). The distribution margins are allocated to different commodity sectors in £m.

Household demand by '**functional headings**' was retrieved from the 2002 Supply and Use tables (ONS website) measured in £m. The table is 122x16 matrix describing the input-output commodity sectors in terms of functional headings.

Re-allocating delivered fuels in households to specific functional needs required data published by the Department of Trade and Industry (DTI website). Specifically, the proportion of electricity used for lighting, heating, cooking and various appliances (brown, cold, wet) were used.

Re-allocation of transport-related emissions to different functional needs categories was carried out using data from the Department for Transport (DfT website), which describes the miles per year associated with various household activities.