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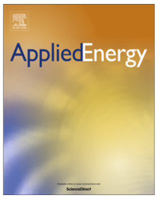

Energy consumption-based accounts: A comparison of results using different energy extension vectors

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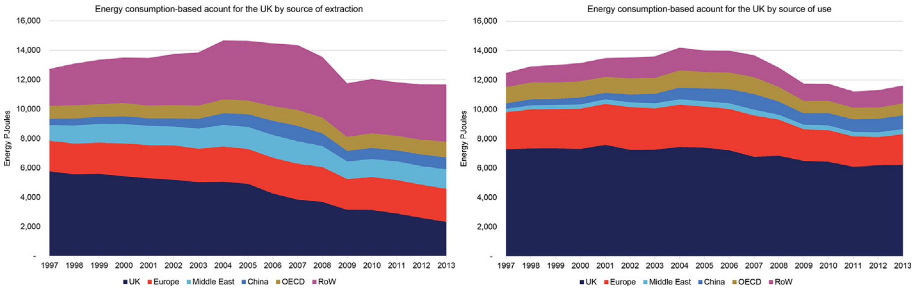
HIGHLIGHTS

- Energy policy increasingly requires an consumption-based accounting (CBA) approach.
- But multi-regional input-output (MRIO) models lack robust input energy vectors.
- In response we complete the first empirical MRIO analysis testing 2 energy vectors.
- Energy-use and energy-extracted vectors give insight to different policy questions.
- MRIO models should provide both vectors to encourage consistent CBA energy analysis.

GRAPHICAL ABSTRACT



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ABSTRACT

Increasing attention has been focussed on the use of consumption-based approaches to energy accounting via input-output (IO) methods. Of particular interest is the examination of energy supply chains, given the associated risks from supply-chain issues, including availability shocks, taxes on fossil fuels and fluctuating energy prices. Using a multiregional IO (MRIO) database to calculate energy consumption-based accounts (CBA) allows analysts to both determine the quantity and source of energy embodied in products along the supply chain. However, it is recognised in the literature that there is uncertainty as to the most appropriate type of energy data that should be employed in an IO framework. Questions arise as to whether an energy extension vector should show where the energy was extracted or where it was used (burnt). In order to address this gap, we undertake the first empirical MRIO analysis of an energy CBA using both vectors. Our results show that both the energy-extracted and energy-used vectors produce similar estimates of the overall energy CBA for the UK—notably 45% higher than territorial energy requirements. However, at a more granular level, the results show that the type of vector that should be employed ultimately depends on the research question that is considered. For example, the energy-extracted vector reveals that just 20% of the UK's energy CBA includes energy extracted within the UK, an issue that is upmost importance for energy security policy. At the other end, the energy-used vector allows for the attribution of actual energy use to industry sectors, thereby enabling a better understanding of sectoral efficiency gains. These findings are crucial for users and developers of MRIO databases who undertake energy CBA calculations. Since both vectors appear useful for different energy questions, the construction of robust and consistent energy-used and energy-extracted extension vectors as part of commonly-used MRIO model databases is encouraged.

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1. Introduction

The 1970s oil crises led to increased attention on energy accounting, with input-output (IO) being one method utilised [1]. Early energy consumption-based accounts (CBAs) [2–4] used Single-Region IO (SRIO) tables, applied to various energy-related topics. For example, in the mid-1970s, Bullard and Herendeen [2] used IO tables to calculate the full energy costs of a car, an electric mixer and the import-export balance of the US. Other energy-related IO topics studied at that time included sectoral energy intensities [5,6] and net energy use [7]. In this respect, Casler and Wilbur's book Energy input-output analysis [8] remains a seminal contribution. Concerns over the environment led to the wider use of IO as a method to study flows of industrial wastes [9] and emissions [10]. However attention is now focussing more on the use of IO for energy accounting, as we face an increasingly uncertain future where energy supply chains are at risk from availability shocks, taxes on fossil fuels and fluctuating energy prices [11,12].

To calculate an energy CBA, an extended energy vector needs to be created which assigns joules of energy to the industrial sectors that match the sectoral breakdown in the IO table. The analyst therefore needs to decide whether the extended energy vector should be based on extracted-energy (i.e. primary energy sources such as oil, coal, natural gas) or used-energy by industry (i.e. final energy such as electricity, diesel). The implications of this choice are highlighted by the SRIO (US) study by Costanza and Herendeen [13]. This 1984 paper is the only study we could find which tests the implications of using both extracted and used energy vectors. Subsequent SRIO studies opt for solely using vectors for energy-extracted (see [14–16]) or energy-used (see [4,17–20]) and the rationale behind the choice has received little attention. It is also uncertain as to whether energy losses are included in any of the energy-used vectors.

By the early 2000s, increased computing power and data availability led to the extension of input-output models that include multiple countries/regions, via multi-regional input-output (MRIO) frameworks. The 'big 5' MRIO models[1] in common use are Eora [21], developed by the University of Sydney; EXIOBASE [22], developed by a consortium of European partners; GTAP [23], the Global Trade Analysis Project; OECD ICIO [24], the OECD's Inter Country Input-Output database; and WIOD [25], the World Input-Output Database. Arguably, the main application of MRIO databases has been to develop robust CBA emissions estimates for countries [26], cities [27,28], individual sectors and products/supply-chains [29]. The advantage of using an MRIO database over the Single-Region IO table is that the original source of the emissions in a country's greenhouse gas (GHG) CBA can then be determined. This means, for example, that it is possible to calculate the GHGs released in China to meet the UK's consumption of goods and services.

The recent development of MRIO databases, coupled to the renewed interest in energy IO analysis, has seen a number of new papers which allow for a more accurate calculation of the energy embodied in traded goods and also the comparison of the energy consumption-based accounts between countries (see [12,30–32]). However, compared to GHG emissions studies, the application of MRIO methods to energy consumption-based accounts (CBAs) has received little attention. Arto et al. (p141, 142) [32] noted that "studies estimating the world energy footprint of nations are scarce". Two key limitations are proposed. The first is related to the quality of available energy extension vector datasets. Arto et al. (p141, 142) [ibid] asserted that there was an "absence of global MRIO databases extended with energy accounts able to assess the energy embedded in the flow of goods and services worldwide". However, of the big 5 MRIO databases, only the OECD-ICIO does not publish an accompanying energy extension data set. Therefore, the real issue is that significant differences exist regarding the nature of the energy extension vectors supplied. In other words, there is a lack of robust, consistent energy datasets across MRIO models.

The second limitation is that there is a lack of guidance to energy modellers in the literature as to which energy extension vector should be used. While this distinction has not been a cause of great concern in single-country studies that estimate the full energy costs of products, when using an MRIO database and taking into account the myriad of information it provides, the distinction becomes crucial. We argue that the use of different vectors ultimately depends on their appropriateness to address different research questions. For example, energy security is becoming a growing focus of research (e.g. [33]) and the decision as to whether to use the energy-extracted or energy-used approach will greatly alter any assessment of the original source of the energy in a country's CBA. Of the big 5 MRIO databases, GTAP and WIOD provide energy-used vectors, Eora provides energy-extracted vectors, and EXIOBASE is the only database to provide both an energy-used and an energy-extracted vector, but there is little documentation as to the difference between them or guidance as to when to use each.

These limitations point to the need for conducting more research into the methodology and implications of using different energy input vectors. This research gap forms the basis for our paper. In this novel analysis, we provide a case study highlighting the implications of using each vector. We first demonstrate how data from the International Energy Agency (IEA) can be used to construct both an energy-extracted and energy-used vector to match the sectors from an MRIO database. The MRIO model, input data and methodology developed to study the two energy vectors are described in Section 2. Secondly, we conduct energy CBA calculations using the energy-extracted and energy-used vectors. Energy CBA results for the UK are presented in Section 3. These results are broken down by source sector and source region to allow a comparison of the two methods[2]. Discussions including implications and modelling uncertainties are also provided in Section 3, before conclusions are drawn in Section 4.

2. Data and methods

Our method is based on the use of an MRIO model, combined with an energy vector input extension. The details of these are given in Sections 2.1 and 2.2.

2.1. The UKMRIO database

The University of Leeds (UoL) calculates the UK's officially reported CBA for CO_2 and all other GHG emissions [34]. To calculate the CBA, UoL has constructed the UKMRIO database. Since the CBA is a National Statistic[3], the MRIO database must be built using IO data produced by the UK's Office of National Statistics (ONS). This data is supplemented with additional data on UK trade with other nations and how these other nations trade between themselves from the University of Sydney's Eora MRIO database [21]. The ONS produces Supply and Use tables (SUT) on an annual basis at a 106 sector disaggregation [35]. The use tables are combined use tables, meaning that the inter-industry transaction table

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[1] For example, refer to http://www.environmentalfootprints.org/mriohome.

[2] Note there is a parallel debate occurring in the GHG emissions literature, for example Davis et al. [45] and Peters et al. [46] discuss the potential for accounting for emissions associated with carbon extraction where the emissions are attributed to the place where the fuel is extracted.

[3] https://www.gov.uk/government/statistics/uks-carbon-footprint.

is the sum of both domestic transactions and intermediate imports, and the final demand table shows the sum of both domestic and imported final products. On a 5-yearly basis, the ONS produces a set of analytical tables where the use table is of domestic use only. Final demand is also split to show domestic purchases separately. Taking proportions of domestic versus imports from the analytical tables, we are able to extract domestic and import data from the annual SUT tables. Imports to intermediate industry is now a single row of data and exports to intermediate and final demand forms a single column of data.

Data from the Eora MRIO database [21] is used to further disaggregate the import and export data to sectors from other world regions. Data from Eora is also used to show how foreign sectors trade with each other, but first the data must be converted to Great Britain Pounds (GBP). The Eora MRIO database is mapped onto the UK's 106 sector aggregation. Eora has a heterogeneous data structure, meaning that different countries' IO data have differing sectoral detail. Where a country has a greater level of sectoral detail than the UK, sectors are aggregated to the UK's 106 sectors. When a country has data at a lower level of detail, sectors must be disaggregated. In the absence of more appropriate data, total UK output is used to disaggregate the sectors. Once this step has been performed, the data can be further aggregated by region. Since Eora contains data from almost 200 countries, we are able to select the most appropriate regional grouping for the trade data. For this MRIO energy study, we construct six regions: the UK, the Rest of Europe, the Middle East (to account for trade with this oil producing region), China, the Rest of the OECD, and the Rest of the World.

2.2. Construction of the energy vectors

2.2.1. IEA energy balance data

The energy data used to construct the energy vectors is obtained from the International Energy Agency (IEA), which collects annual energy data by country [36]. Referring to the example in Table 1, an individual country's energy balance starts with total primary energy supply (TPES) (mainly production plus imports minus exports), and this is traced through to total final consumption (TFC) by industry, transport, non-energy use and other. Energy leaves the system (between primary and final energy) mainly through transformation losses, and the energy sector's own use of energy.

The two energy vectors for the analysis are then constructed from the IEA extended energy balance database. The energy-extracted vector is based on primary energy production by energy carrier (e.g. oil, coal, natural gas). The energy-used vector is constructed via TFC data (e.g. final energy including electricity and road fuel) by industry sectors, and includes energy lost in transformations, transfers and energy industry own-use. Table 1 shows how the two vectors are equivalent in size, since the energy-used vector is created by taking the (smaller) total final consumption data (C), and adding losses and energy industry own use (B) to match the total primary energy supply (A). Whilst the same size, the allocation to industry sector differs: the energy-extracted vector allocates the energy to source sectors (e.g. Mining), whilst the energy-used vector allocates energy to industry end-use sectors. To construct each energy vector, the IEA data is first aggregated by the six regions described in Section 2.1 and then the data is mapped to the UK's 106 sector aggregation using a concordance matrix. We construct two concordance matrices, one for energy-used and one for energy-extracted. Details of this mapping are described in the following section.

2.2.2. The energy-extracted vector

Table 2 shows the mapping procedure used to generate the energy-extracted vector. All energy data is mapped to 7 UKMRIO sectors and the mapping is a many-to-one type mapping, meaning the IEA data must be aggregated into the relevant UKMRIO sectors.

Table 1
IEA energy balance summary for the UK (2013).

Categories of IEA Energy Balance		2013 Energy value (Petajoules)
A, Total primary energy supply	Production	4575
	Imports	6933
	Exports	−2956
	International marine bunkers	−127
	International aviation bunkers	−459
	Stock changes	−21
	Total (TPES)	**7945**
B, Statistical differences, transformation losses and energy industry own use	Statistical differences	−242
	Transformation processes	−1785
	Energy industry own use	−517
	Sub-Total	**−2544**
C, Total Final Consumption (TFC)	Industry	977
	Transport	1635
	Other	2520
	Non energy use	269
	Total (TFC)	**5401**

Table 2
Mapping IEA energy-extraction data to the UK classification system.

IEA production data category	UKMRIO sector
Biodiesel; Biogases; Bio gasoline; Non-specified primary biofuels and waste; Other liquid biofuels; Peat	1. Productions of agriculture, hunting and related services
Primary solid biofuels	2. Products of forestry, logging and related services
Anthracite; Brown coal; Coking coal; Hard coal; lignite; Other bituminous coal; Sub-bituminous coal	4. Coal and lignite
Crude oil; Natural gas; Natural gas liquids; Other hydrocarbons	5. Extraction of crude petroleum and natural gas and mining of metal ores
Additives/blending components	28. Other chemical products
Geothermal; Heat; Hydro; Nuclear; Solar photovoltaics; Solar thermal; Tide, wave and ocean; Wind	52. Electricity, transmission and distribution
Industrial waste; Municipal waste (non-renewable); Municipal waste (renewable)	56. Waste collection, treatment and disposal services; materials recovery services

2.2.3. The energy-used vector

Generating the energy-used vector is more complex. Firstly, the vector includes several parts of the IEA energy balance data as seen earlier in Table 1: the total final consumption (TFC - energy used by industry, domestic, transport and other); the aviation and marine bunkers; the energy sector own use and losses. And, secondly, many of the mappings are one-to-many type mappings meaning that the IEA data must be distributed across several of the UK classification sectors. To distribute an IEA category, additional data at the correct level of detail must be introduced and used to distribute that category into two or more parts (two or more UKMRIO sectors).

We first describe how we generate the weights used to disaggregate one-to-many type mappings. In the absence of more suitable data, it was decided for the majority of IEA sectors to use the distribution of energy-related sectors from the UKMRIO database to split IEA TFC sectors. To do this, we summed the four rows corresponding to the UKMRIO sectors shown in Table 3 for each of the 6 regions in the UKMRIO use table. We then converted this to proportions, giving a single vector showing distribution of all energy to each of the 106 other UKMRIO sectors. This vector can then be used, for example, to split the agriculture TFC energy shown in Table 5 between the two UKMRIO sectors representing agriculture.

Where there was more suitable data at the appropriate level, we used it instead to inform the allocation of IEA data to UKMRIO sectors. We allocate road energy use to different UKMRIO sectors using the carbon dioxide emissions by transport mode data for the UK [37]. Data collected by the ONS reveals that 56% of road CO_2 emissions are from private households (see Table 4) and 20% from land transport services which includes buses and taxis. The remaining impact comes from heavy goods vehicles transporting goods. This vector is used to disaggregate the IEA road sector shown in Table 5 by the sectors in Table 4.

In terms of the allocation of IEA sectors to different UKMRIO sectors, we used the guidance given by the IEA correspondence to NACE 1.1[4] to inform our mapping [38]. Table 5 shows the IEA TFC mapping to the UK MRIO sectors. Note that energy-used vector also includes the direct component –energy used by households to heat the home and drive personal vehicles.

Marine and aviation bunker data from the IEA is simply mapped to the water and air transport services sectors from the UKMRIO sector classification (see Table 6).

Like the TFC data, the energy sector own use data also contains one-to-many mappings (see Table 7). For example, the energy associated with energy sectors' use of crude oil is mapped to the extraction of crude petroleum; the coke and refined petroleum; and the petrochemicals sectors from the UKMRIO database. As above, the total energy supply vector used to distribute the TFC data is used here.

Finally, energy lost through transformation processes is allocated each of the energy using sectors in the 106 UKMRIO classification. Energy is also lost when households burn fuel so we also allocate some losses here. Since household energy use contributes 10% of the total energy use by UK sectors, we allocate 10% of the loss to households and the remainder is proportioned using the energy distribution vector described above.

2.3. Calculation method for UK's energy CBA

We use the standard environmentally extended Leontief method to calculate the UK's energy CBA as briefly described below. The equation,

$$\mathbf{x} = (\mathbf{I} - \mathbf{A})^{-1}\mathbf{y} \tag{2.1}$$

which is known as the Leontief equation, describes total output $\mathbf{x}$ as a function of final demand $\mathbf{y}$. $\mathbf{I}$ is the identity matrix, and $\mathbf{A}$ is the technical coefficient matrix, which shows the inter-industry requirements. $(\mathbf{I} - \mathbf{A})^{-1}$ is known as the Leontief inverse (denoted hereafter as $\mathbf{L}$ and $\mathbf{x} = \mathbf{Ly}$).

Consider, a row vector $\mathbf{f}$ of energy associated with each industrial sector

$$\mathbf{e} = \mathbf{f}\hat{\mathbf{x}}^{-1} \tag{2.2}$$

is the coefficient vector representing energy per unit of output[5]. Multiplying both sides of the Leontief equation by $\mathbf{e}$ gives

$$\mathbf{ex} = \mathbf{eLy} \tag{2.3}$$

and simplifies to

$$\mathbf{Q} = \hat{\mathbf{e}}\mathbf{L}\hat{\mathbf{y}} \tag{2.4}$$

where $\mathbf{Q}$ is the energy in matrix form allowing the full consumption-based energy of products to be determined. $\mathbf{Q}$ is calculated by pre-multiplying $\mathbf{L}$ by energy per unit of output and post-multiplying by final demand. Energy is reallocated from production sectors to the final consumption activities. If $\mathbf{y}$ represents UK final demand, $\mathbf{Q}$ is therefore, the total energy consumption-based account for the UK.

Table 3
Creating a vector to disaggregate IEA data to UKMRIO sectors.

Disaggregator	UKMRIO sector
Energy use	5. Extraction of crude petroleum and gas & mining of metal ores 25. Coke and refined petroleum products 52. Electricity transmission and distribution 53. Gas, distribution of gaseous fuels, steam and air conditioning supply

Table 4
Creating a vector to disaggregate IEA road data to UKMRIO sectors.

Disaggregator	UKMRIO sector	
Energy used by road	59. Wholesale and retail trade	3%
	60. Wholesale trade services	6%
	61. Retail trade services	11%
	63. Land transport services	20%
	66. Warehousing	1%
	67. Postal and courier services	2%
	Direct household travel	56%

The UKMRIO database is an SUT structure based on 6 regions with 106 sectors. The technical coefficient matrix $\mathbf{A}$, is a square matrix with $2 \times 106 \times 6 = 1272$ rows and columns. It follows that the result matrix $\mathbf{Q}$ is the same size. If the columns of $\mathbf{Q}$ are summed, we find the energy CBA of products consumed by the UK by the region purchased from. Similarly, summing along the rows calculates the energy used to satisfy UK consumption by source industry and source region. This data can be aggregated to show totals by industry, product or region.

3. Results and discussion

In this section we present the total energy CBA for the UK when both the energy-used and energy-extracted vectors are used. The CBAs are broken down by source region, source industry and product to study if there is a substantial difference in results from the two vectors. We then broaden our focus to a wider discussion based on the results and then consider modelling uncertainties.

3.1. Total UK energy CBA

Fig. 1 compares the UK's energy CBA, calculated using both the energy-used and energy-extracted vectors, with the total primary energy supply (TPES). The TPES has reduced by 14% between 1997 and 2013. The UK's energy CBA is higher than the TPES and increased by 14% (used) and 15% (extracted) until 2004, before stabilising. During the recession, the UK's energy CBA reduced by 14% (used) and 18% (extracted) and, following the recession, the UK's CBA has stabilised once more. In theory the energy CBA from the two vectors should be the same, and, in fact, the differences (from modelling precision) seen in Fig. 1: UK energy CBA using an

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[4] NACE is the abbreviation of the Nomenclature statistique des activités économiques dans la Communauté européenne. The Statistical classification of economic activities in the European Community.

[5] Denotes matrix diagonalisation.

Table 5
Mapping IEA total final consumption data to the UK classification system.

IEA TFC data category	UKMRIO sector
Iron and steel	36. Basic iron and steel 37. Other basic metals and casting
Chemical and petrochemical	26–32. Chemicals, petrochemicals, pharmaceuticals
Non-ferrous metals	38. Weapons and ammunition 39. Fabricated metal products
Non-metallic minerals	34. Cement, lime plaster and articles of concrete 35. Glass, refractory, clay, other porcelain and ceramic, stone and abrasive products
Transport equipment	43–46. Motor vehicles, trailers and semi-trailers, ships and boats, air and space craft, other transport equipment 49. Repair and maintenance of ships and boats 50. Repair and maintenance of air and spacecraft
Machinery	41. Electrical equipment 42. Machinery and equipment 51. Rest of repair. Installation
Mining and quarrying	6. Other mining and quarrying products
Food and tobacco	8–18, Food and tobacco
Paper, pulp and print	23–24. Paper and paper products and printing and recording services
Wood and wood products	22. Wood and products of wood and cork
Textiles and leather	19–21 Textiles, wearing apparel and leather
Construction	58. Construction
Non specified (industry)	33. Rubber and plastic products 47. Furniture 48. Other manufactured goods
Non-energy use industry/transformation/energy	6, Other mining and quarrying products 8–18. Food and tobacco 26–51. Chemical and petrochemicals, Non-metallic minerals, Iron and steel, Non-ferrous metals, Machinery, Transport equipment. 58. Construction
Domestic aviation	65. Air transport services
Road	See Table 4
Rail	62. Rail transport services
Domestic navigation	64. Water transport services
Pipeline transport	63. Land transport services and services via pipelines
Non-specified (transport)	95. Public administration and defence services; compulsory social security
Non-energy use in transport	62–65. rail, road, water, air transport services 95. Public administration and defence services; compulsory social security
Residential	Direct household non travel
Commercial and public services	7. Mining support services 66–106. All other service sectors
Agriculture	1. Products of agriculture, hunting and related services 2. Products of forestry, logging and related services
Fishing	3. Fish and other fishing products; aquaculture products
Non specified (other)	95. Public administration and defence services; compulsory social security
Non-energy use in other	1–3. Agriculture, forestry and fishing 7. Mining support services 66–106. All other service sectors

Table 6
Mapping IEA bunker data to the UK classification system.

IEA bunkers data category	UKMRIO sector
International marine bunkers	64. Water transport services
International aviation bunkers	65. Air transport services

energy-used and energy-extracted extension vector and TPES (1997–2013) Fig. 1 are small, which is reassuring and adds confidence as to the overall CBA value estimated.

3.2. Energy CBA breakdown

3.2.1. Energy CBA by source region

Comparing Fig. 2 with Fig. 3 reveals that the source of UK energy to satisfy final demand by UK consumers is quite different depending on which vector is used. The energy-extracted CBA in Fig. 2 shows that the share of energy in the UK energy CBA that is extracted domestically (UK) has declined significantly from 45% in 1997, to only 20% by 2013. In addition, the rate of decline is most rapid in the period 2005–2013 versus 1997–2005. Between 1997 and 2005, any reduction in domestic energy extracted was compensated for by increases in the energy extracted abroad to satisfy UK consumption. After the 2008 recession, energy extracted to satisfy UK final consumption decreased in all regions but this decrease was largest in the UK.

In contrast, the energy-used vector results in Fig. 3 highlight three key differences to the results from the energy-extracted vector. Firstly, we see a levelling off of the UK's contribution to the energy-used CBA. Secondly, such contribution of the UK to its energy CBA is noticeably higher compared to Fig. 2, comprising 58% of the total energy CBA in 1997 and 54% by 2013. Thirdly, the energy-used vector results suggest the reduction in the energy CBA post the 2008 recession is met mainly by reductions in the energy used abroad, rather than the energy used in the UK– which is a very different finding to that obtained from the energy-extracted vector results. While the energy extracted in the UK to meet UK final demand has decreased more strongly than the energy extracted in other regions to meet UK demand, the total energy used in the UK to satisfy UK final demand has been more stable than the energy used in other regions.

3.2.2. Energy CBA by source sector

Fig. 4 shows the difference in the source energy for the UK's energy CBA for the year 2013 for the two vectors. The different dis-

Table 7
Mapping IEA energy sector own use data to the UK classification system.

IEA energy sector own use data category	UKMRIO sector
Anthracite; BKB; Bitumen; Brown coal; Coal tar; Hard coal; Lignite; Other bituminous coal; Sub bituminous coal	4. Coal and lignite
Crude oil; Fuel oil; Gas coke; Gas works gas; Gas/diesel oil excl. biofuel; Gasoline type jet fuel; Kerosene type jet fuel; Liquefied petroleum; Lubricants; Motor gasoline; Naphtha; Natural gas; Natural gas liquids; Oil shale and oil sands; Other kerosene; Other oil products; Other recovered gases; Paraffin wax; Patent fuel; Peat; Peat products; Petroleum coke; Refinery feedstocks; Refinery gas; White spirit	5. Extraction of crude petroleum 25. Coke and refined petroleum 30. Petrochemicals
Blast furnace gas; Coke oven coke; Coke oven gas; Coking coal	36. Iron and steel
Anthracite; BKB; Biodiesel; Biogas; Bio gasoline; Bitumen; Brown coal; Charcoal; Coal tar; Electricity; Geothermal; Hard coal; Heat; Industrial waste; Lignite; Municipal waste (non-renewable); Municipal waste (renewable); Natural gas; Other bituminous coal; Other liquid biofuels; Primary solid biofuels; Solar thermal; Sub bituminous coal	52. Electricity transmission
Ethane; Gas coke; Gas works gas; Natural gas; Refinery gas	53. Gas; distribution of gas through mains; steam and air conditioning supply
Industrial waste; Municipal waste (non-renewable); Municipal waste (renewable)	54. Natural water; water treatment and supply services 55. Sewerage services; sewage sludge 56. Waste collection, treatment and disposal services; materials recovery services 57. Remediation services and other waste management services

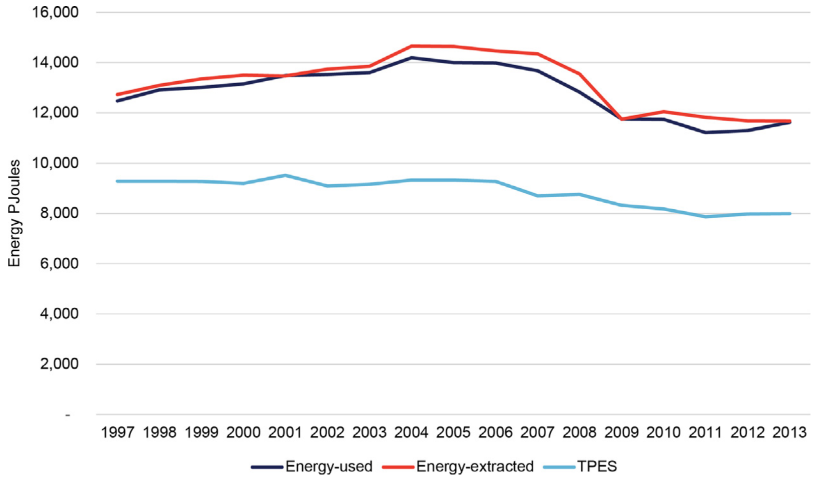

Fig. 1. UK energy CBA using an energy-used and energy-extracted extension vector and TPES (1997–2013).

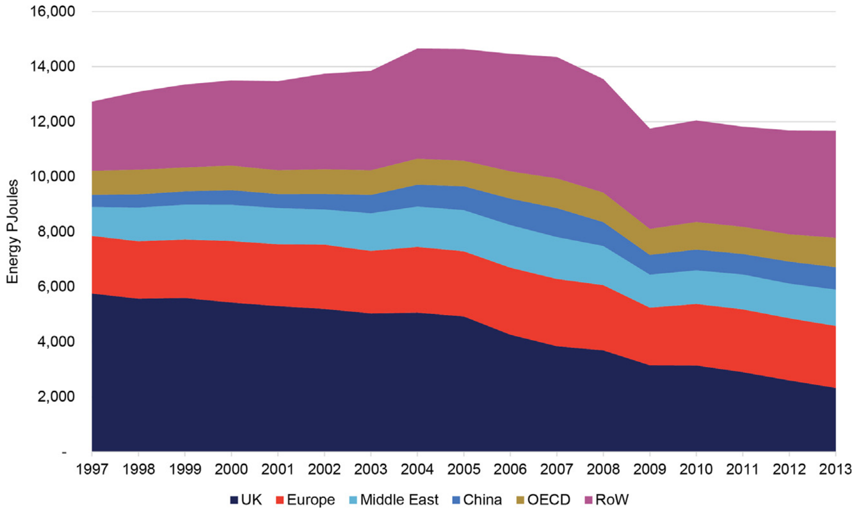

Fig. 2. The UK's energy-extracted CBA from 1997–2013 according to source region.

tribution of energy is very clear with the energy-extraction CBA highlighting the mining sector as the key source, which is to be expected. Note that we have displayed energy used to heat the home (Direct household non travel) next to the 'Power and water' sector and both are shaded in green. Note also that energy used in private transportation (Direct household travel) is displayed next

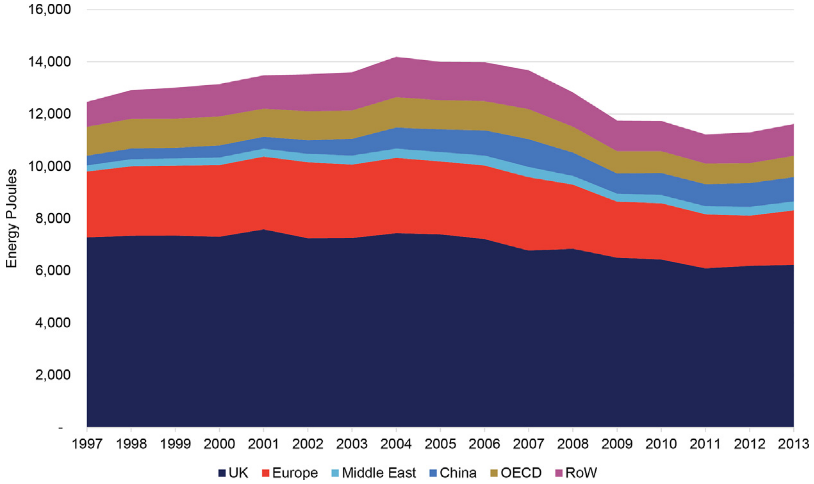

Fig. 3. The UK's energy-used CBA from 1997–2013 according to source region.

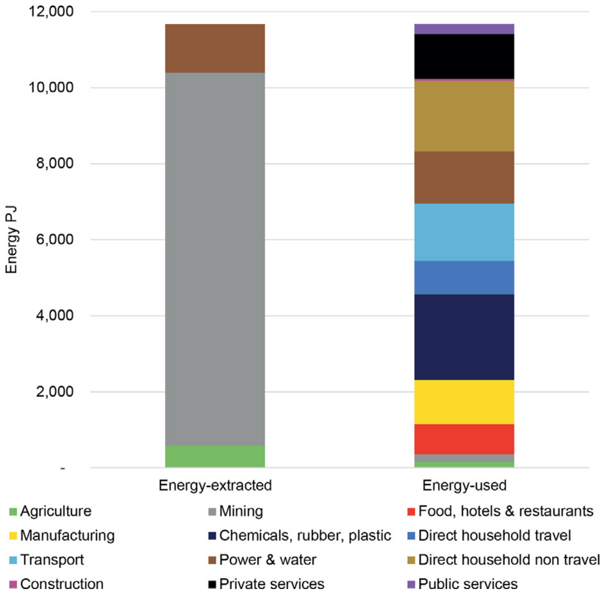

Fig. 4. UK energy CBA by source industry (2013).

to the 'Chemicals Rubber Plastic', which includes refined petroleum products section and both are presented in shades of dark blue.

3.2.3. Energy CBA by end product

Fig. 5 shows the difference in the UK's energy CBA allocated to different end-products for the year 2013 for the two vectors. In theory, the two vectors should be equivalent, since the IO model allocates the extraction-energy to the energy-using sectors as the first supply chain stage of the calculation of the consumption based account. For the energy-used CBA, this stage has already been accounted for in the construction of the energy-used vector.

Fig. 5 shows that although the distribution is close, the two allocations are not identical. Differences occur as the first supply-chain stage using the energy-extracted CBA does not mirror our manual allocation of energy-used when constructing the energy-used vector. There are a number of reasons for this. Firstly, the sectors in the IO tables are not consistent with the IEA sectors leading to allocation uncertainty [39]. We aggregate nine types of coal to a single coal sector when constructing the energy-extracted vector (Table 2). When this is then used to determine energy-use by industry (the first stage in the supply chain), coal is treated as a homogenous sector. Secondly, allocation is based on monetary rather than physical flows of energy giving rise to proportionality assumption uncertainties [39]. For example, the share of coal to each industry in the first stage of energy-extracted CBA will be based on how much coal each sector purchases and assumes that £1 spent on coal by the electricity sector represents the same amount of energy as £1 spent on coal by the textiles industry.

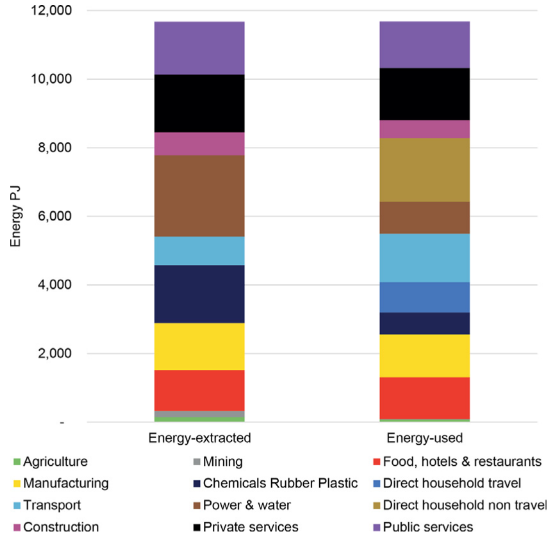

Fig. 5. UK energy CBA by final product (2013).

3.2.4. Comparison of product CBAs from the two vectors

Fig. 6 reveals that the 106 UK product CBAs correlate quite closely, achieving an r-squared correlation coefficient of 63%. The chart is shaded by sector, and the outliers can be seen as products in agriculture, mining, energy and transport sectors[6]. It appears that these are sectors with the least complex supply chains, i.e. the final product is closest to the extraction of energy. Fig. 6 implies that either there is underestimation of these products by the energy-used approach or overestimation by the energy-extracted approach. If the

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[6] Though the logarithmic scale masks some of the mismatch in the CBA of the products with the largest impact (energy products and air travel).

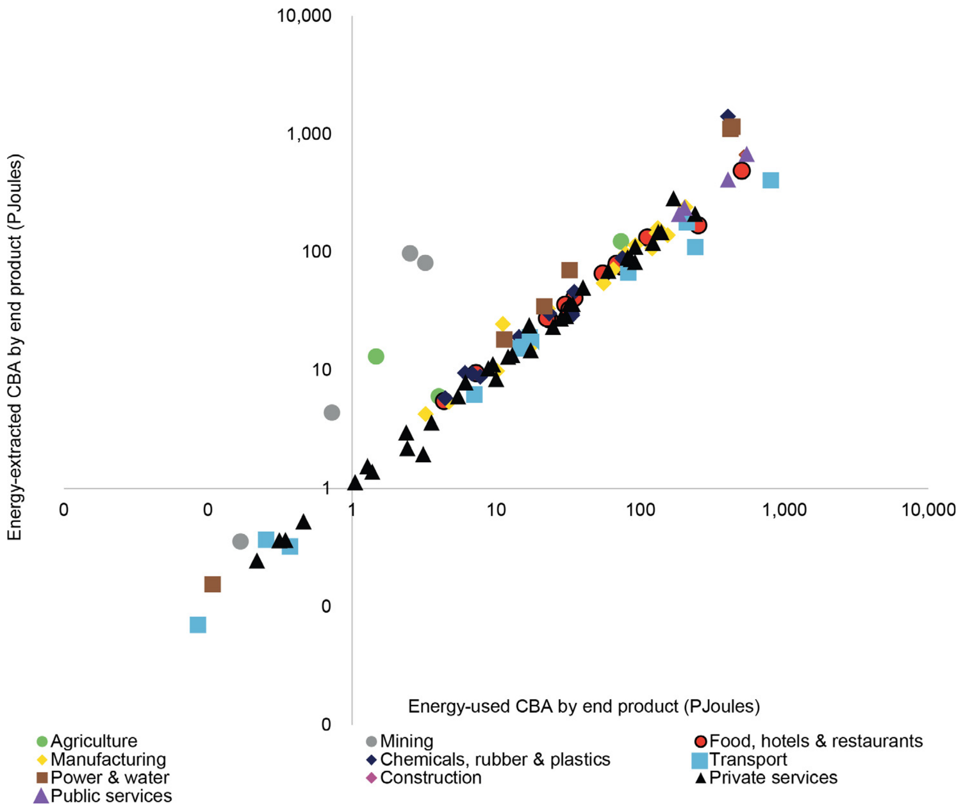

Fig. 6. Correlation between energy-used and energy-extracted product CBAs (2013).

four largest outliers are removed the correlation coefficient for the remaining 102 UK sectors improves to 94%.

3.3. Wider discussion and interpretation

In this section, we discuss the process of constructing the two energy vectors, and consider the appropriateness of each vector for particular research questions, providing numerical examples.

3.3.1. Constructing the energy vectors from IEA energy data

For the energy-extracted vector, the allocation of the IEA extraction data to the 7 UKMRIO sectors (as shown in Table 2) was a straightforward task, and so we are reasonably confident that it has been done accurately. In contrast, the energy-used vector allocating IEA energy use to the sectors in the UKMRIO is a complex task, for two main reasons. Firstly, it required the IEA final energy data to be inflated back to (the higher) primary energy values, by adding back the transformation losses, energy industry own use and statistical differences (shown in Table 1), according to each energy type (i.e. oil, coal, gas, etc.). Secondly, it required complex allocation (via concordance matrix) of energy from 27 IEA TFC sectors to 106 UKMRIO sectors as shown in Table 5.

3.3.2. Are different vectors appropriate for different questions?

We find that the overall energy CBAs from both vectors are very similar, meaning either vector could be used to study time-series of total energy CBA. If ready-to-use energy-used vectors are not available, due to the effort required in their construction, it may be more appealing to use the energy-extracted vector, as the main construction of the vector is already available from the IEA, and the allocation to MRIO sectors is more straightforward. The choice of vector to be used therefore hinges – assuming that both vectors are able to be constructed and hence a choice exists - on whether the research/policy question is focussed on upstream (i.e. energy source/origin) or downstream end-use (i.e. at industry or product) issues.

Let us consider two worked examples to illustrate this. First, there is a growing focus on energy security as part of the energy trilemma – this means not just security of supply but also related to geo-political stability. For example, it may be more important to understand exactly where barrels of oil are sourced from, not just where they are burnt. Taking our UK example (Table 8), the energy-extracted vector reveals that the source of the energy-extracted CBA is concentrated in foreign countries. For example, the energy-extracted data shows that 1323 Petajoules of the energy used to produce the UK's final demand are extracted in the Middle East, whereas the energy-used approach shows just 354 Petajoules of energy is burnt in the Middle East to produce products consumed in the UK.

Second, at the other end of the energy conversion chain lies the need to better understand the energy use at the industry level for energy efficiency policy. In this case, the energy-used vector may be the most appropriate, since it allows for the attribution of actual energy use to industry sectors, thereby enabling efficiency gains by sector to be understood. For example, the effect of the manufacturing industries replacing machines with more energy efficient ones could be explored by reducing the energy used by all manufacturing sectors. Currently, our UK energy CBA for 2013, calculated using the energy-used vector, finds that manufacturing industries contribute 2400 PetaJoules of energy in the supply chain of goods consumed by UK consumers. We are able to calculate that an efficiency improvement of 50% in these sectors would reduce the UK's energy CBA by 10.3%. It is not as straightforward to calculate this type of scenario using the energy-extracted vector since the manufacturing industries do not mine their own energy, and structural path type analysis would need to be applied [40] or fuel substitu-

Table 8
Source of UK CBA for 2013 using both the extracted and used approach.

Source of Energy in UK Energy CBA (2013)	Energy-extracted approach		Energy-used approach	
Region	Energy in PJ	% of total	Energy in PJ	% of total
UK	2325	20%	6229	54%
Europe	2252	19%	2087	18%
Middle East	1323	11%	354	3%
China	815	7%	929	8%
OECD	1071	9%	814	7%
RoW	3889	33%	1219	10%
TOTAL	11,674	100%	11,623	100%

Table 9
Number of extraction sectors in the main MRIO databases.

MRIO database	Number of agricultural sectors	Number of mining sectors	Number of energy sectors
UKMRIO	2	2	6
Eora26	1	1	2
EXIOBASE	18	15	19
GTAP	16	4	7
OECD	1	1	2
WIOD	1	1	2
IEA	6	11	27

tion strategies can be modelled by replacing the industry's supply of electricity from gas with electricity from wind.

3.4. Modelling uncertainties

Mapping energy-extracted vectors involved the aggregation of sectors, whilst conversely disaggregation techniques were required to construct the energy-used vector. This highlights that both of these vectors applied involve uncertainty. In the following sections we discuss the uncertainties in the energy vector construction.

3.4.1. Uncertainties in energy vector construction

There are five issues which we raise. The first is that IO databases lack detail in extraction and energy sectors. In this study we use the UKMRIO database which contains two sectors for agriculture and forestry and two sectors relating to the mining of coal and the extraction of crude oil, natural gas and metal ores. On the other hand, the IEA database has six sectors that can be classified as agricultural (biomass) production sectors and eleven relating to mining extraction. This issue is not unique to the UKMRIO sectoral classification and Table 9 reveals that of the main MRIO databases only GTAP and EXIOBASE contain detailed agricultural data and EXIOBASE is the only database to include more than 4 mining sectors.

In addition to the lack of detail in the extraction sectors, we also find a lack of detail in the energy sectors, meaning that energy sector own use data is highly aggregated. For example in the UKMRIO database, we have eleven sectors that the 27 energy sector own use data can be mapped to. Again, this issue is found when looking at the main MRIO databases and EXIOBASE covers energy sectors in the most detail.

The second issue is that IEA TFC data lacks detail and disaggregation of this data is done using monetary data as a proxy for resource extraction/use. In this study, we disaggregate IEA energy data by the distribution of energy sales. The issue with such techniques is that the figures in the IO table reflect how much different industries spend on energy, not how much energy they use. Thus, in using expenditure data, this may mean we are under/over attributing energy use (in joules) to sectors who pay a lower/higher price for energy.

The third issue is how to best account for household direct energy use. Residential energy use in the IEA data can simply be allocated to household direct non-travel. However, the IEA data that is allocated to household direct travel is the road sector. This cannot be a one-to-one mapping, since road also contains all other vehicles on the roads as well as personal cars. For this study we shared the road energy by the trade, land transport and household direct travel sectors using emissions data from the national travel survey. Clearly, this is an assumption, since it assumes perfect correlation between energy and emissions.

The fourth issue is how to deal with hidden or confidential data. The IEA contains several categories with descriptions that can be described as vague. A pertinent example is 'non-energy use in industry'. Here the only reasonable assumption is to share this total amongst each industry sector. Another example is the 'non-specified other' category. The metadata from the IEA reveals that energy use in defences is usually allocated to this sector. For this study we assumed a one-to-one mapping here and did not allocate this energy to any other sectors.

The fifth issue is the conflict between the residence versus territorial principle. When producing an energy extension vector, the main energy accounting manuals [41,42] recommend that the residence principle should be followed, which is used in a national accounting framework, and states that energy activity of a resident unit (i.e. a person or company) is allocated to the territory of residence [43]. This means that when calculating a CBA, activities of tourists are removed and reallocated to the country of residence of the tourist and any domestic residents' activities abroad are added. However, the IEA energy balances follow the territorial principle, which allocates energy to the country where it is used. Usubiaga and Acosta-Fernandez [44] demonstrate that using the territorial rather than residence principle can lead to differences in CBAs. A further improvement to the energy-used vector should distribute the IEA road energy-use according to the resident principle.

4. Conclusions

This paper has undertaken, to our knowledge, the first empirical MRIO analysis of country-scale energy CBAs using two different primary energy vectors: an energy-extracted and energy-used vector. This is an important analysis and the findings are crucial for researchers working in consumption-based approaches for energy accounting, especially since today's consumption-based energy research questions demand a multi-regional (rather than single region) trade-based IO response. From the results presented and wider discussions, we reach three important conclusions.

Firstly, both our IEA-derived energy vectors produced very similar overall primary energy CBAs, meaning either can be used for construction of aggregated footprints. The key differences between vectors (and thus application) lie in the breakdown and attribution of energy at different stages of the energy conversion chain, i.e. from origin (source) through to end use (industry sector and product). For example, for the UK, the energy-extracted vector attributes much more energy to foreign regions (80% in 2013) versus the energy-use vector (57% in 2013). In short, both vectors appear useful, but they should be applied to different questions.

Secondly, given their potential importance to today's consumption-based research questions, MRIO models (and especially the 'Big 5') should provide both energy-used and energy-extracted primary energy vectors, which are consistent and robust across different MRIO models. This will encourage the uptake of energy-MRIO analysis, and also serve to standardise the energy vector values used in such analyses. This is particularly relevant for the energy-used vector, whose construction (in primary energy values) was not straightforward. Such complexity may act as a barrier for others to independently follow suit, as well as generate the risk of introducing errors between the two constructed vectors.

Third, the growing demand for energy CBAs highlights the need for MRIO database constructors also to be aware of users downstream. Specific issues that the MRIO community should consider include: 1. Greater coverage in the MRIO databases of countries where energy is extracted (e.g. Middle East); 2. Greater disaggregation of agriculture, extraction and energy sectors in MRIO databases; 3. Replacing monetary data with physical data in MRIO models to remove distorting effects of differing energy prices; 4. Exploring how to communicate uncertainty with users and guide best practice, so that the appropriate vector is chosen for the research question at hand.

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