Applied Energy 210 (2018) 632–642

Contents lists available at ScienceDirect

Applied Energy

journal homepage: www.elsevier.com/locate/apenergy

Identifying critical supply chains and final products: An input-output approach to exploring the energy-water-food nexus

Anne Owen*, Kate Scott, John Barrett

Sustainability Research Institute, School of Earth and Environment, University of Leeds, Leeds, UK

HIGHLIGHTS

- Global supply chains demonstrate complicated energy-water-food relationships.
- Multiregional input-output analysis maps global connectivity and resource use.
- Use structural path analysis to identify supply chains with high EWF resource use.
- Identify policy intervention points and the potential for UK food waste policy.

ARTICLE INFO

Keywords:
Multiregional input-output databases
Global value chains
Consumption-based accounting
Structural path analysis
Energy-water-food nexus

ABSTRACT

Recent advances in detailed multiregional input-output databases offers new opportunities to use these environmental accounting tools to explore the interrelationships between energy, water and food–the energy-water-food nexus. This paper takes the UK as a case study and calculates energy, water and food consumption-based accounts for 1997–2013. Policies, designed to reduce the environmental impact of consumption of products, can intervene at many stages in a product's whole life-time from 'cradle to gate'. We use input-output analysis techniques to investigate the interaction between the energy, water and food impacts of products at different points along their supply chains, from the extraction of material and burning of energy, to the point of final consumption. We identify the twenty most important final products whose large energy, water and food impacts could be captured by various demand-side strategies such as reducing food waste or dietary changes. We then use structural-path analysis to calculate the twenty most important supply chains whose impact could be captured by resource efficiency policies which act at the point of extraction and during the manufacturing process. Finally, we recognise that strategies that aim to reduce environmental impacts should not harm the socioeconomic well-being of the UK and her trade partners and suggest that pathways should be targeted where the employment and value added dependencies are relatively low.

1. Introduction

Since the middle of the last century it has been recognised that multiple interlinked factors contribute to environmental change and argued that suites of composite indicators can be used to measure socio-economic and environmental wellbeing. From Boulding's Spaceship Earth essay in 1966 [1], Daly's work on steady state economies [2], Wackernagel and Rees' ecological footprint [3] and Rockström et al.'s planetary boundaries concept [4], scientists have attempted to measure humanity's relationship to and impact on the environment. Lately, the term 'nexus' has been used to describe the dynamic linkages and interdependencies [5] between two or more earth systems—for example the Bonn 2011 conference titled 'The Water, Energy and Food Security Nexus' [6].

The concept of a nexus emerged in recognition of increasing societal pressures competing for natural resources [7]. Numerous authors have studied the interrelationships and dependencies between energy, water and food since these resources are limited and depleting, whilst at the same time being fundamental for human-natural systems [8–13]. Traditional sector and country-bound governance structures often leaves energy, water and food in competition [14] but adopting a multi-centric nexus lens means that we are able to consider a system as a whole and not as a subset of isolated resources, productive sectors and consumers [5,8].

The liberalisation of trade has made the relationships between energy, water and food more complex as materials and resources are traded globally along multifaceted supply chains. Such challenges

* Corresponding author.
E-mail address: a.owen@leeds.ac.uk (A. Owen).

http://dx.doi.org/10.1016/j.apenergy.2017.09.069
Received 24 October 2016; Received in revised form 17 August 2017; Accepted 10 September 2017
Available online 21 September 2017

require innovations in accounting methods and governance practices that recognise global interconnectedness. Multiregional input-output (MRIO) analysis has been suggested as one such accounting method that could prove beneficial in understanding these global interconnectivities, including the role of trade, industries, products and final consumers. The MRIO databases centre on the evaluation of trade flows between regions and industrial sectors, using a flow matrix approach. MRIO analysis is capable of quantifying the full environmental impact of a product's supply chain, (regardless of where in the world production processes take place) consequent on a nations' final demand for goods and services. In the past decade, advances in data availability and computational power have led to the development of several MRIO databases. Using MRIO databases to understand the role of trade in greenhouse gas (GHG) emission accounts is by far the most prominent area of research [15–17] in this field, but in this paper, we argue that consumption-based approaches, calculated using MRIO analysis, have great potential in understanding and quantifying energy-water-food nexus relationships.

The latest audits of MRIO databases [18] show numerous environmental and socio-economic extension data is now available for calculating consumption-based accounts[1] (CBAs). The four main environmentally-extended MRIO databases, Eora, EXIOBASE, GTAP and WIOD, contain emissions, employment, energy, resource use and water extensions. Consequently analysts have calculated consumption-based accounts from each of these indicators. While many studies focus on single indicator carbon [19], material [20], labour [21] or water [22] 'Footprint of Nations' type studies, there are a number of examples of where two or more indicators are analysed together. Galli et al. [23] introduce the concept of a 'footprint family' of indicators comprising the ecological, carbon and water footprint and present the OPEN:EU MRIO database based on GTAP. The authors argue that by providing evidence to monitoring the biosphere, atmosphere and hydrosphere allows for a more comprehensive approach to measuring the environmental element of sustainability. However they also note that "several environmental, economic and social issues are not tracked" [p108 17]. Fang et al. [24] later add energy to the footprint family and discuss how CBAs can contribute to the calculation of planetary boundaries.

Studies linking footprint calculations from input-output analysis and 'nexus' include Vanham [25] who investigates if the water footprint concept can be used to address the water-food-energy-ecosystem nexus. Vanham argues that by tracing both the volume of water involved in the supply chain of agriculture and food products and the water used for industry and energy, important insights into the energy-water-food nexus can be gleaned which might have been missed under other water management studies [25]. Wang and colleagues realise this approach by calculating energy-related water consumption and water-related energy consumption [26] using input-output (IO) approaches and Beijing as a case study. Fang and Chen also use Beijing IO data and linkage analysis to calculate the water and energy directly and indirectly consumed by industrial sectors and find that the real estate sector is an important water-energy nexus node [27]. Holland et al. (2015) use MRIO analysis to trace freshwater consumed to satisfy global energy demands, identifying where, at the river basin level, freshwater is being depleted in areas where water is scarce [13]. Duan and Chen use take a network approach to understand global dependencies between countries for water and energy trade [28]. White and colleagues extend MRIO approaches to also consider food and use the IDE-JETRO MRIO database to find final demand products with high land (food), energy, water and scarce-water footprints [29]. The authors find Construction and Agricultural products to be the largest water-energy-food consumers.

Consumption-based indicators have great potential to measure progress in indicators relevant to the energy-water-food nexus. However, since detailed MRIO databases are relatively new developments [18], few studies have exploited the full wealth of data available. Galli et al. [23] also note that commentary on the socio-economic impacts is often missing from approaches that claim to include a comprehensive suite of indicators. This paper aims to extract information about the energy-water-food related impacts relating to UK consumption that could be used as evidence in policies which are designed to reduce environmental impacts. To do this we use a UK specific MRIO database to calculate the CBAs for energy, water and food materials for the time period 1997–2013. In addition we also calculate employment and gross value-added (GVA) CBAs to provide socio-economic context. Policies, designed to reduce the environmental impact of products, can intervene at many stages in a product's whole life-time from 'cradle to gate'. We therefore use further IO analysis techniques to investigate the interaction between the energy, water and food impacts of products at different points along their supply chains. Whilst there is no commonly agreed definition of a 'nexus' we define it here by considering the points of interaction between a number of environmental and social-economic spheres [5].

In Section 2 we introduce the data and methods used in this study. Section 3 presents the energy, water, food and employment CBAs for the UK between 1997 and 2013. This section then calculates the product-based impacts for the year 2013 to identify those products where the full supply chain impact is large for energy, water and food combined. To start to understand supply-chains, an analysis shows, for each CBA, how far removed from the point of consumption in the UK the impacts lie and where in the world these impacts are felt. This is followed by analysis of individual product value chains with the aim of highlighting those chains with high environmental (energy, water, food) but low socio-economic (employment, GVA) impact. In the discussion Section 4 we argue that policy, while reducing environmental impact, should not hurt the economies of the UK and her trading partners and the high environmental impact low socio-economic value chains should be preferentially targeted. Environmental impacts should be reduced without compromising social wellbeing. Section 5 concludes the study and presents thoughts about future work in this field.

2. Data and methods

2.1. The UKMRIO database

The University of Leeds (UoL) calculates the UK's officially reported CBA for CO_2 and all other GHGs [30]. To calculate the CBA UoL has constructed the UKMRIO database. Since the CBA is a National Statistic,[2] 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 [31]. The ONS produces Supply and Use tables (SUT) on an annual basis at a 106 sector disaggregation [32]. The use tables are combined use tables, meaning that the inter-industry transaction table 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 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 data from the annual SUT tables. Imports to intermediate industry is now a single row of data and exports to intermediate and final demand is a single column of data.

Data from the Eora MRIO database [31] is used to disaggregate the import and export data to further sectors from other world regions. Data from Eora is also used to show how foreign sectors trade with each

[1] CBA are also known as footprints.

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

Table 1
Impact extension data sources and further information.

Impact variable	Source	Description
Energy	International Energy Agency [34]	Take total final consumption data, energy sector own use, shipping and aviation bunkers and losses and map to UKMRIO structure. See [35] for full description
Water	Eora [31]	Sum of blue and crop water mapped from Eora structure to UKMRIO structure
Food	Material flows database [36]	Food biomass categories from WU [36], mapped to UKMRIO structure
Employment	UK data from ONS, other regions from Eora	Eora data mapped to UKMRIO structure
GVA	UK data from ONS. Other regions from Eora	Eora data mapped to UKMRIO structure

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 nexus study, we construct eight regions: the UK, China, France, Germany, the Netherlands, the Rest of Europe, the Rest of the OECD, and the Rest of the World since these are the UK's largest trade partners.

In order to calculate the size of the individual paths contributing to consumption-based accounts, structural path analysis (SPA) techniques are used (see Section 3.2). SPA works best on input-output tables, so the SUTs are converted to this format prior to further calculation using the fixed product sales structure assumption to form an industry-by-industry input-output table (IOT). Details on the technique can be found in the Eurostat manual of supply, use and input-output tables [33].

2.2. Extension data

Table 1, below, describes the impact variables used in this study. Since this is a UK focused study, many of the variables are sourced from the UK's ONS. The advantage of this data is that it is collected at the same sectoral detail as the input-output tables. Where data cannot be sourced from the ONS (i.e. industrial impacts for other world regions or data not collected by the ONS) data is either sourced from the Eora MRIO database or from additional sources such as Vienna University's material flows database or the International Energy Agency's database.

2.3. Calculating consumption-based accounts

We use the standard environmentally extended Leontief method to calculate the UK's 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 and 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 impact generated by each industrial sector

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

is the coefficient vector representing impact per unit of output.[3] 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 consumption-based impact in matrix form[4] allowing the impact of products to be determined. $\mathbf{Q}$ is calculated by pre-multiplying $\mathbf{L}$ by impact per unit of output and post-multiplying by final demand. Impact is reallocated from production sectors to the final consumption activities. Adding an exogenous environmental variable to an IO framework produces an environmentally extended input-output model (EEIOM).

2.4. Structural path analysis

The Taylor's series expansion shows that $\mathbf{L}$ can be approximated by adding the identity matrix $\mathbf{I}$ to the series of the direct requirements matrix $\mathbf{A}$ raised to increasing powers:

$$\mathbf{L} = \mathbf{I} + \mathbf{A} + \mathbf{A}^2 + \mathbf{A}^3 + \cdots + \mathbf{A}^{\mathbf{n}} \tag{2.5}$$

[37,38]

From (2.5) and (2.4):

$$\mathbf{Q} = \mathbf{eIy} + \mathbf{eAy} + \mathbf{eA}^2\mathbf{y} + \mathbf{eA}^3\mathbf{y} + \cdots + \mathbf{eA}^{\mathbf{n}}\mathbf{y} \tag{2.6}$$

adapted from Peters and Hertwich [39].

This is the environmentally-extended Taylor's expansion where $\mathbf{eA}^t\mathbf{y}$ calculates the impact from the t^{th} stage in production. For example, if $\mathbf{y}$ represents the demand for one car, $\mathbf{eIy}$ is the direct emissions at the site of the car manufacturer. This is known as a zeroth order path. In addition, the car production requires $\mathbf{Ay}$ inputs from other industries – these industries emit $\mathbf{eAy}$ of CO_2. These are known as first order paths. In the next stage of the supply chain, these industries require inputs of $\mathbf{A}(\mathbf{Ay})$ and $\mathbf{eA}^2\mathbf{y}$ of CO_2 is emitted [39]. These are known as second order paths.

(2.4) can also be written as the summation:

$$\mathbf{Q} = \sum_{i,j=1}^{n} e_i(I-A)^{-1}_{ij}y_j \tag{2.7}$$

And applying the Taylor expansion to (2.7) gives:

[3] ∧ denotes matrix diagonalisation.

[4] In this paper, $\mathbf{Q}$ is the sum of the impact associated with the consumption of products and does not include direct household impacts such as the energy burnt in homes or from personal household transportation.

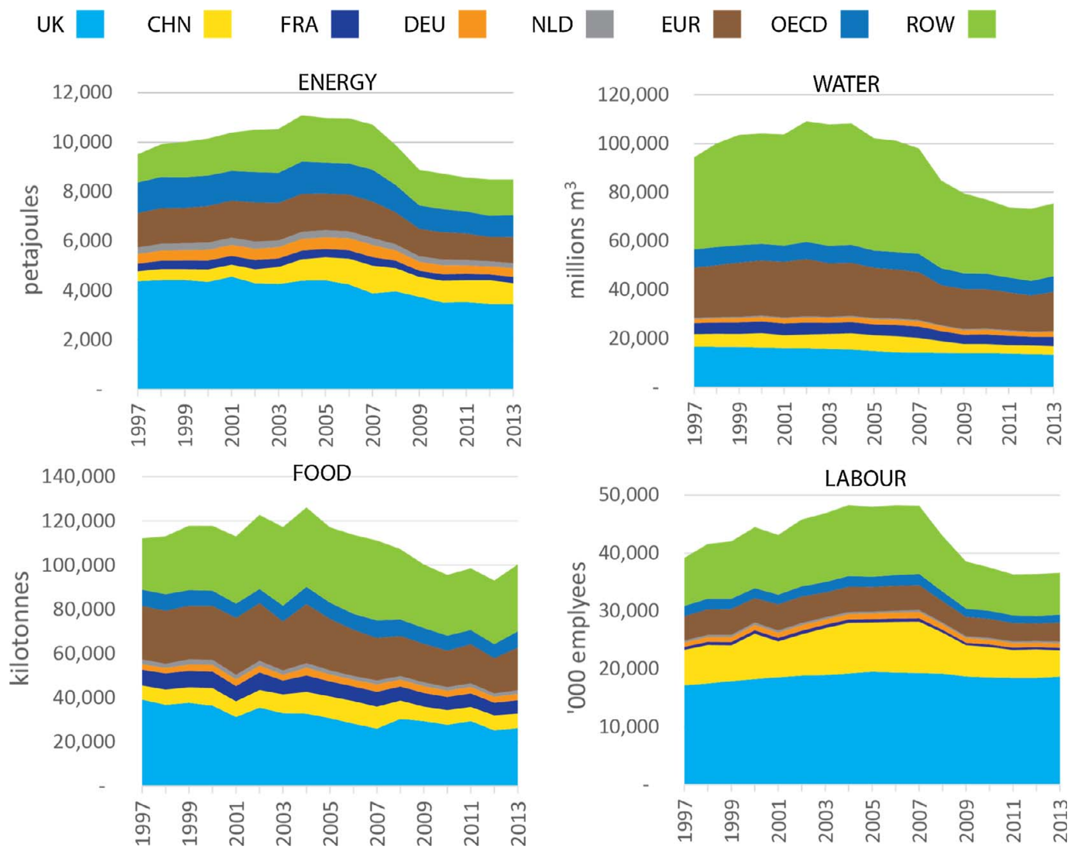

Fig. 1. UK CBA for energy, water, food and labour by source region (1997–2013).

$$\mathbf{Q} = \sum_{i,j=1}^{n} e_i(\delta_{ij} + A_{ij} + A_{ij}^2 + A_{ij}^3 + \ldots)y_j$$

$$\mathbf{Q} = \sum_{i,j=1}^{n} e_i(\delta_{ij} + A_{ij} + \sum_{k=1}^{n} A_{ik}A_{kj} + \sum_{l=1}^{n}\sum_{k=1}^{n} A_{il}A_{lk}A_{kj} + \ldots)y_j$$

$$\mathbf{Q} = \sum_{i=1}^{n} e_i y_i + \sum_{i=1}^{n} e_i \sum_{j=1}^{n} A_{ij}y_j + \sum_{i=1}^{n} e_i \sum_{k=1}^{n} A_{ik} \sum_{j=1}^{n} A_{kj}y_j + \sum_{i=1}^{n} e_i \sum_{l=1}^{n} A_{il} \sum_{k=1}^{n} A_{lk} \sum_{j=1}^{n} A_{kj}y_j + \ldots \quad (2.8)$$

where i,j,k and l are component sectors. A first order path from sector i into sector j is calculated by $e_iA_{ij}y_j$. A second order path from sector i via sector k into sector j is calculated by $e_iA_{ik}A_{kj}y_j$ and so on [40].

2.5. Path interlinkages

To gain an appreciation of the interlinkages between different and competing natural resources we require a technique that can consider the impact types concurrently. In this study we use Structural Path Analysis (see Section 2.4) to identify the top 1000 unique supply chains that rank highly in each of the environmental stressors (energy, water and food). We then calculate the societal impacts (employment and GVA) of these environmentally harmful supply chains. For each environmental impact type, the highest path is scored 1, the second highest 2 and so on. We then find the sum of the three scores for the *same identical* supply chains for energy, water and food and re-rank these sums from smallest to largest to identify the combined highest ranking pathways. Finally we consider the employment and GVA impacts of these supply chains to identify which paths are important for targeted policy.

3. Results

3.1. UK consumption-based accounts

Fig. 1 shows the UK's CBA for energy, water, food and labour for the time period 1997–2013. Each impact is broken down by the source country and clearly shows the UK's dependence on traded goods to satisfy final demand. In 2013, the UK relied on imported sources for 59% of the energy, 82% of the water and 74% of the food material embodied in the products consumed by UK consumers. 49% of the employees required to produce products for UK consumers work abroad but of the GVA[5] generated from UK consumption 74% remains within the UK. The rest of world (ROW) is the source of 30% of the UK's food CBA and 40% of the UK's water CBA. The water, labour and energy CBA show a levelling off of impact from 2003 before reducing due to the recession. The food CBA has been reducing since 2005.

3.2. Final product impacts

The column sum of **Q** (2.4) calculates the footprint of products bought by UK final consumers. There is some cross over in the final products consumed by UK consumers that have high energy, water and food material impacts. For example, the three highest final products for water and food are UK products of agriculture and hunting, UK food and beverages and UK preserved meat and meat products. For the energy CBA, the top three are UK electricity, UK human health services and UK construction.

Table 2 below, finds the top twenty impacts by product across all three systems. The rank of each product is summed for the three

[5] GVA is not shown in Fig. 1 because the data is in current prices and the chart simply shows the effect of inflation.

Table 2
Top 20 Nexus product impacts for the energy, water and food combined UK CBA (2013).

	Product description	Energy rank, % of total	Water rank, % of total	Food rank, % of total
1	UK Food and beverage serving services	6 (3.1%)	2 (6.1%)	2 (6.2%)
2	UK Human health services	2 (6.0%)	5 (3.8%)	5 (3.6%)
3	UK Residential Care & Social Work Activities	9 (2.3%)	4 (4.3%)	4 (3.9%)
4	UK Public administration and defence services; compulsory social security services	5 (4.8%)	6 (2.9%)	7 (2.6%)
5	UK Construction	3 (5.6%)	8 (2.5%)	8 (2.4%)
6	UK Education services	10 (2.2%)	9 (2.5%)	9 (2.3%)
7	UK Preserved meat and meat products	23 (0.9%)	3 (4.5%)	3 (5.2%)
8	UK Products of agriculture, hunting and related services	29 (0.7%)	1 (8.8%)	1 (14.6%)
9	UK Accommodation services	16 (1.3%)	11 (1.9%)	10 (2.0%)
10	UK Owner-Occupiers' Housing Services	7 (2.8%)	23 (0.9%)	21 (0.8%)
11	UK Insurance and reinsurance, except compulsory social security & Pension funding	13 (1.8%)	21 (1.0%)	18 (0.9%)
12	UK Dairy products	45 (0.4%)	7 (2.9%)	6 (3.4%)
13	UK Electricity, transmission and distribution	1 (7.6%)	28 (0.8%)	29 (0.7%)
14	UK Other food products	33 (0.6%)	14 (1.5%)	12 (1.5%)
15	UK Bakery and farinaceous products	37 (0.5%)	18 (1.1%)	17 (1.1%)
16	UK Retail trade services, except of motor vehicles and motorcycles	24 (0.9%)	33 (0.7%)	33 (0.6%)
17	RoW Accommodation services	21 (0.9%)	32 (0.7%)	37 (0.6%)
18	UK Telecommunications services	14 (1.5%)	38 (0.6%)	40 (0.5%)
19	UK Financial services, except insurance and pension funding	19 (1.1%)	36 (0.6%)	39 (0.5%)
20	UK Coke and refined petroleum products	11 (1.8%)	42 (0.5%)	43 (0.5%)

indicators then the table is re-ranked to show the products which appear highest across all systems. In the top-twenty highest ranking, all but one are products that are finished in the UK and are domestic, rather than imported final demand purchases. The twenty products shown capture 47% of the UK's total energy CBA, 49% of the UK's total water CBA and 54% of the UK's total food CBA. Targeting demand reductions for this small set of products can reduce impact within the energy-water-food nexus. We define these 20 products that are ranked highly for energy, water and food as 'Nexus Products'.

UK food and beverages will have part of its supply chain based in the UK but the products' production recipe reveals inputs from many other regions across the world. This means that any changes to the demand for this product, as a result of demand-based strategies, will change the environmental impact in both the UK and abroad. Fig. 2 shows, for the top twenty Nexus Products, where in the world the impact is felt. For example, for product 1, UK food and beverage serving services, 52% of the energy impact is domestically sourced, compared to 21% of the water impact and 28% of the food material impact for the same product. The product ranked ten, UK owner occupiers housing services, has the highest domestic energy impact of the twenty common products. For water and food, this is product eight: UK products of agriculture and hunting.

Fig. 3 shows the proportion of the UK's *territorial*[6] account for energy, water and food that is used in the production of the twenty identified Nexus Products. Just twenty products capture a third of the UK's total energy-use, and three-fifths of the total territorial water and food use. Demand-side strategies focusing on these twenty products would help to reduce environmental impact in the UK.

3.3. Structural paths by path length

Using the Taylor's series expansion from Section 2.4 we can show the impact of stages in the supply chain, where stage 0 represents direct impacts at the point of sale. Fig. 4 shows the impacts from stages 0 to 10 for each of the energy, water, food and labour CBAs. We show the supply chain impacts for 1997, 2007 and 2013 to determine whether there have been any changes during the time period under study. For energy and labour, the highest impact occurs in stage 0 of the supply chain. For food and water, stage 1 contains the largest impact. This is because food use, for example, only occurs in the agriculture, forestry and fishing sectors and so the majority of products need to contain at least one stage in the supply chain to represent the food processing industry, for example, the production of dairy products. Water is concentrated in agriculture-related sectors, whereas energy use and labour are spread over the full 106 sectors. Longer and more complex supply chains lead to the charts moving away from an exponential decay shape. Comparing the shape of the charts in 1997 and 2007 shows that during this decade supply chains satisfying UK demand got longer and occurred in non-domestic territories. Post-recession, we observe little change to the shape of the UK pathways with the majority of the change being a reduction in the contribution from abroad.

3.4. Structural paths

Tables 3–5 show the top 20 largest paths for each of the UK's energy, water and food CBAs for the year 2013. The largest water and food supply chains are similar (Tables 4 and 5), dominated by agriculture and hunting in stage 0 and food and textile products in stage 1. The top 20 pathways contribute to 19% of the total water CBA and 27% of the total food CBA. The top 20 largest energy supply chains are shown in Table 3. The closest energy path that is shared by the food and water is the single stage 'UK products of agriculture, hunting etc' path which is ranked 41st largest for energy, and first for food and water. The energy pathways are dominated by the transportation industry, electricity and gas supply and the petroleum production industry. The 20 largest energy supply chains account for 22% of the total energy CBA for the UK.

The next step is to use the technique described in Section 2.5 to mathematically identify the common highest paths. This results are discussed in Section 3.5 below.

3.5. Path combining

Table 6 shows the 20 most important combined supply chains for the energy-water-food nexus. We defined these as Nexus Pathways. For each path, the energy, water and food impact is shown in terajoules (TJ), millions m^3 and kilotonnes, respectively, and the path's rank from the structural path analysis is shown in brackets. Table 6 shows that the most important Nexus Pathways start with the agriculture and hunting sector. Paths are either producing agriculture and hunting products or food products. The top path is the stage zero UK agriculture and hunting path. This supply chain contributes 15 PJ of energy (0.5% of the total UK CBA), 5.2 billion metres cubed of water (6% of the total UK CBA) and 12 Mt of food material (12% of the total UK CBA). However,

[6] The territorial account is the energy, water and food sourced from the UK.

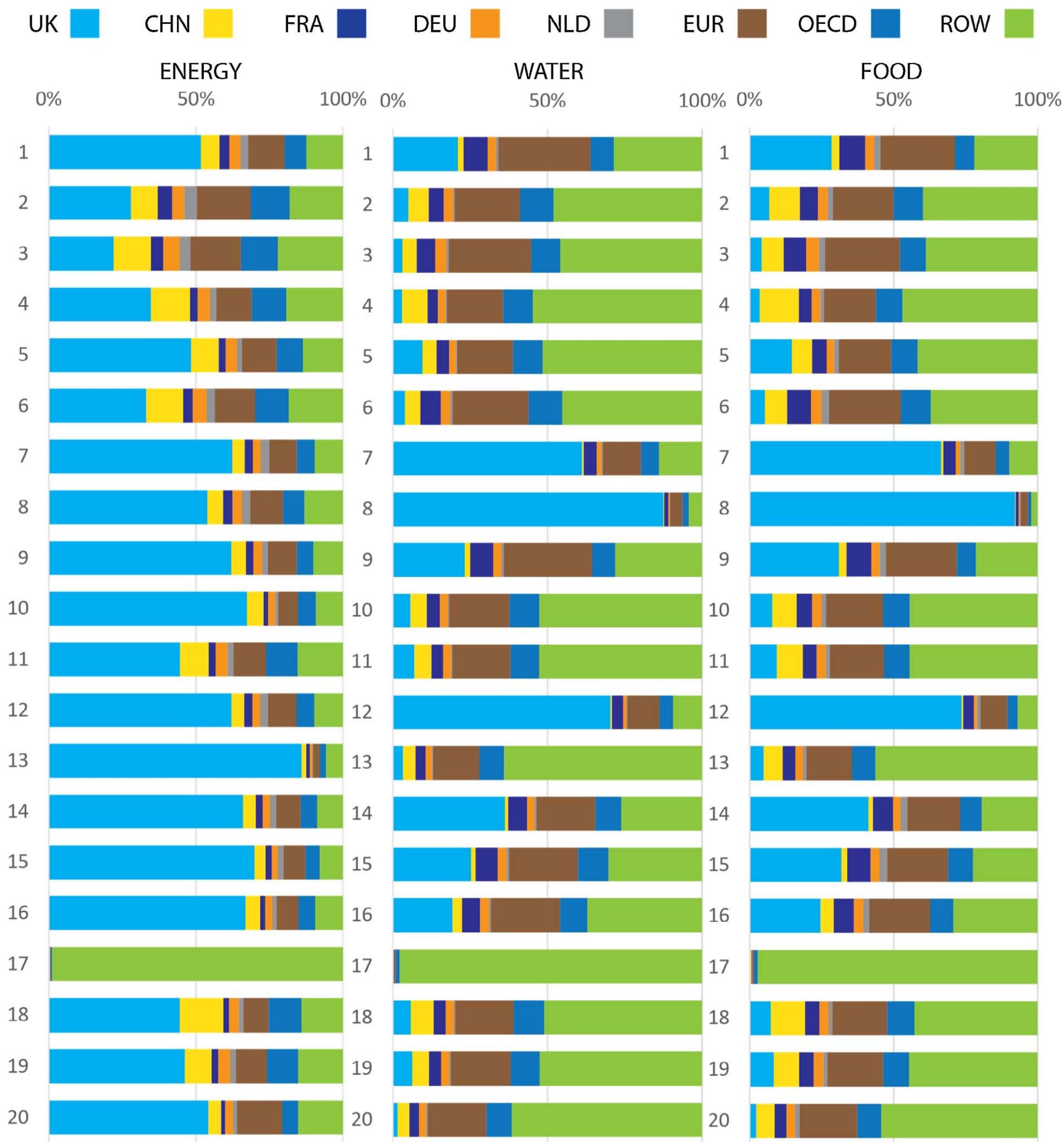

Fig. 2. Impact source (by region) of the top twenty Nexus Products (2013).

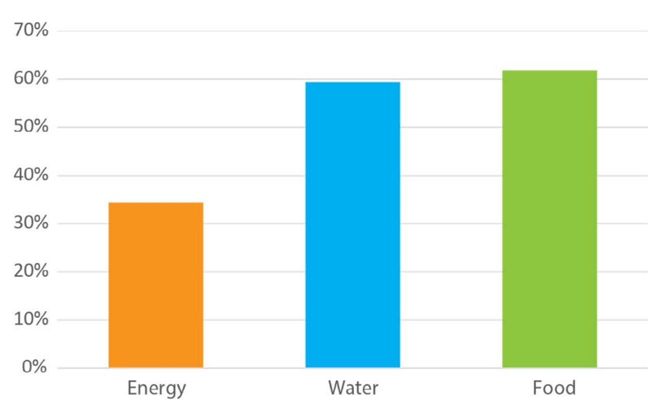

Fig. 3. Proportion of UK territorial industrial Energy, Water and Food captured by the twenty Nexus Products (2013).

this supply chain is also responsible for 55,000 UK jobs and contributes 3.1 billion pounds to the UK economy.

In Fig. 5 we show the proportion of impact captured by the 20 Nexus Pathways within the UK. Just under half of the food used in the UK is identified in the seven identified Nexus Pathways which originate in the UK. These pathways also include two fifths of the UK's territorial water use and 0.4% of territorial energy use. UK industrial efficiency policy, which aims to encourage businesses to use resources in a more efficient manner, will only cover UK industries, so these calculations of the captured impact only include UK based firms.

4. Discussion

In this section we first compare our findings for the UK with the latest state-of-the-art Nexus research. Following this we use a Sankey diagram of energy-water-food flows (Fig. 6) to demonstrate the key

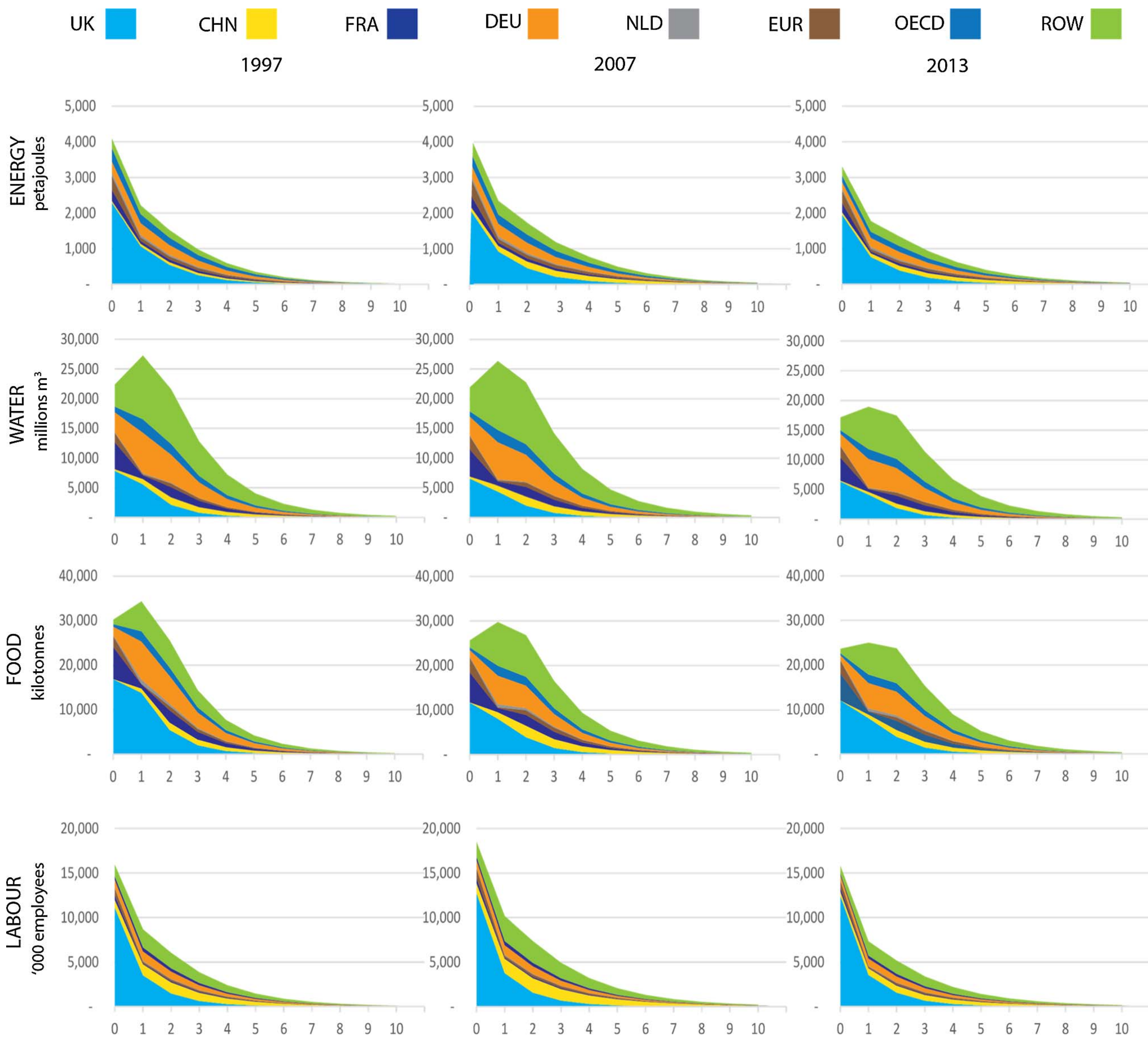

Fig. 4. UK CBA by supply chain stage for energy, water, food and labour by source region and for the years 1997, 2007 and 2013.

supply chain intervention points in a products' whole-life and evaluate the role that evidence from input-output analyses can have on policies designed to reduce impacts relating to the energy-water-food nexus. We then discuss issues around data quality and the uncertainty of results calculated using input-output approaches.

4.1. Comparison with state-of-the-art energy-water-food nexus research

In this section we compare our work with research using input-output techniques to calculate energy-water-food nexus data. Table 2 identifies Nexus Products which interact with all three energy-water-food resource use spheres. Our findings agree with White and colleagues that final consumption of Service sectors, Construction and Agricultural products leads to large energy-water-food footprints [29]. Fang and Chen's calculation of the 'Vertically Integrated Consumption' is the same as the water and energy footprint related to consumption of final products [27]. The authors also identify 'other services' as a consumption category where both water and energy use is high.

Table 6 identifies Nexus Pathways which are individual supply chains where energy-water-food resource use is high. The majority of the pathways identified in our study commence with water extraction, the burning of energy and the harvesting of food biomass by the agricultural industry. The method used in this research is not directly comparable to the work of Duan and Chen who present network data at the country rather that sectoral level [28]. However, many authors have demonstrated the importance of the agricultural sector in various water-energy [10] and water-land use [41] nexus studies.

4.2. Policy intervention points

Fig. 6 is a scaled Sankey diagram such that the total sizes of the domestic extraction and imports[7] of each of the energy, water and food is equivalent. This allows for comparisons between the relative flows to be examined.

Fig. 6 reveals a number of key observations. The majority of the water and all of the food material flows originate from the agriculture and food processing industry (1). The intermediate stage shows the total energy, water and food captured at the penultimate stage in a product's UK supply chain-before it is exported or consumed by UK final demand. We can now see that water and food contribute to the supply

[7] And hence the sum of the UK consumption and exports.

Table 3
Top 20 paths contributing to the UK's energy CBA (2013).

	Stage 0	Stage 1	Stage 2	(TJ)
1	UK Air transport			366,349
2	UK Elect, transmission & distribution			311,309
3	UK Gas			130,200
4	UK Elect, transmission & distribution	UK Elect, trans & distribution		108,811
5	UK Land transport			104,887
6	UK Owner-occupiers housing services			87,028
7	UK Public administration & defence			85,704
8	UK Water transport			75,337
9	ROW Accommodation services			72,703
10	UK Human health services			70,118
11	UK Coke and refined petroleum services			66,676
12	OECD Air transport			64,954
13	UK Food and beverage serving services			60,431
14	ROW Coke and refined petroleum services			43,594
15	EUR Air transport			42,197
16	UK Rail transport services.			41,341
17	EUR Accommodation services			40,897
18	UK Accommodation services			40,366
19	OECD Accommodation services			38,207
20	UK Elect, trans & distribution	UK Elect, trans & distribution	UK Elect, trans & distribution	38,033
	TOTAL CBA			8,490,283
	Top 20 percentage of total			22%

Table 4
Top 20 paths contributing to the UK's water CBA (2013).

	Stage 0	Stage 1	(million m^3)
1	UK Products of agri, hunting etc		5168
2	UK Products of agri, hunting etc	UK Preserved meat & meat products	991
3	UK Products of agri, hunting etc	UK Dairy products	861
4	ROW Products of agri, hunting etc		785
5	EUR Products of agri, hunting etc		667
6	ROW Products of agri, hunting etc	ROW Food and beverage services	487
7	EUR Products of agri, hunting etc	EUR Preserved meat & meat products	478
8	UK Products of agri, hunting etc	UK Products of agri, hunting etc	468
9	UK Preserved meat & meat products		418
10	FRA Products of agri, hunting etc		417
11	ROW Products of agri, hunting etc	ROW Other food products	417
12	ROW Products of agri, hunting etc	ROW Textiles	403
13	UK Dairy products		400
14	ROW Products of agri, hunting etc	ROW Preserved meat & meat products	391
15	ROW Products of agri, hunting etc	ROW Leather and related products	360
16	EUR Products of agri, hunting etc	EUR Other food products	358
17	UK Products of agri, hunting etc	UK Food and beverage services	308
18	OECD Products of agri, hunting etc		304
19	EUR Other food products		277
20	ROW Other food products		265
	TOTAL CBA		75,404
	Top 20 percentage of total		19%

chain of other products besides agriculture and food. However, the majority of the domestic water extracted and domestic food material is used in agriculture and food products and imported water and food makes up a large portion of the production of a service product (6). At this intermediate stage, strategies such as material light-weighting and reducing waste can reduce the amount of product required within the supply chain [42–44]. Finally, at the final demand side we see that products consumed by households contribute most to the UK's water CBA, followed by government and capital demand. Households also contribute most to the UK's energy and food CBA, but for these impacts, capital consumption is slightly greater than government. At the final demand stage, policies such as waste reduction, lifetime optimisation and dietary change will reduce environmental impacts [42,45,46].

An input-output analysis, as explained in this study, can help prioritise areas for action. Fig. 6, clearly demonstrates which areas in a product's supply chain could bring about beneficial reductions in one or more environmental impact spheres.

4.2.1. Food waste policy

As identified in Fig. 6 there is great potential in the UK for applying policies that target the reduction of food waste at both the final demand and intermediate stages of food supply chains. On average, in 2015 19% of food purchased by UK households was thrown away, of which 60% was avoidable (i.e. could have been eaten), worth £13 billion [47]. 18% of all food purchased in the UK hospitality and food service sectors was wasted, of which 75% could have been eaten. This varies by food type and by sector [48]. The UK has had a successful food waste campaign, with avoidable household food waste reducing by 21% between 2007 and 2013, however, since 2012 little progress has been made which can partly be explained by cheaper food prices and increased household earnings. In addition to reducing food material, reducing food waste will also bring about reductions in water and, to a lesser extent, energy. Liu and colleagues [41] find similar results in China and estimate the food loss rate in the supply chain to be in region of 19% and that the greatest savings from avoiding waste are to be made by final consumers

Table 5
Top 20 paths contributing to the UK's food CBA (2013).

	Stage 0	Stage 1	Stage 2	(Kt)
1	UK Products of agri, hunting etc.			12,008
2	UK Products of agri, hunting etc.	UK Preserved meat & meat products		2302
3	UK Products of agri, hunting etc.	UK Dairy products		1999
4	UK Products of agri, hunting etc.	UK Products of agri, hunting etc.		1089
5	EUR Products of agri, hunting etc.			1036
6	ROW Products of agri, hunting etc.			1002
7	EUR Products of agri, hunting etc.	EUR Preserved meat & meat products		742
8	UK Products of agri, hunting etc	UK Food and beverage services		715
9	FRA Products of agri, hunting etc.			669
10	ROW Products of agri, hunting etc.	ROW Food and beverage services		622
11	EUR Products of agri, hunting etc.	EUR Other food products		556
12	ROW Products of agri, hunting etc.	ROW Other food products		532
13	UK Products of agri, hunting etc.	UK Preserved meat & meat products	UK Preserved meat & meat products	5188
14	ROW Products of agri, hunting etc.	ROW Textiles		514
15	ROW Products of agri, hunting etc.	ROW Preserved meat & meat products		499
16	ROW Products of agri, hunting etc.	ROW Leather and related products		459
17	OECD Products of agri, hunting etc.			424
18	EUR Products of agri, hunting etc.	EUR Dairy products		384
19	UK Products of agri, hunting etc.	UK Other food products		356
20	EUR Products of agri, hunting etc.	EUR Bakery and farinaceous products		306
	TOTAL CBA			100,228
	Top 20 percentage of total			27%

Table 6
The top twenty Nexus Pathways and the workforce and GVA dependencies. Numbers in brackets show ranking of each path when each stressor was considered separately.

	Path	Energy (TJ)	Water (millions m3)	Food (Ktonnes)	Labour ('000s)	GVA (millions £)
1	UK Agriculture & hunting	14,695 (41)	5,168 (1)	12,008 (1)	55	3140
2	UK Agriculture & hunting > UK Meat products	2817 (165)	991 (2)	2302 (2)	11	602
3	UK Agriculture & hunting > UK Dairy products	2446 (194)	860 (3)	1999 (3)	9	523
4	EUR Agriculture & hunting	1960 (227)	667 (5)	1036 (5)	10	293
5	EUR Agriculture & hunting > EUR Meat products	1404 (332)	478 (7)	742 (7)	7	210
6	FRA Agriculture & hunting	1420 (327)	417 (10)	669 (9)	1	192
7	UK Agriculture & hunting > UK Agriculture & hunting	1333 (353)	46 (8)	1089 (4)	5	285
8	EUR Agriculture & hunting > EUR Other food products	1052 (438)	358 (16)	556 (11)	6	157
9	UK Agriculture & hunting UK Food & beverages	875 (511)	308 (17)	715 (8)	3	187
10	ROW Agriculture & hunting	789 (558)	785 (4)	1002 (6)	36	132
11	OECD Agriculture & hunting	804 (548)	304 (18)	424 (17)	1	97
12	EUR Agriculture & hunting > EUR Dairy products	725 (604)	247 (21)	384 (18)	4	109
13	UK Agriculture & hunting > UK Meat products > UK Meat products	634 (681)	223 (23)	518 (13)	2	135
14	NLD Agriculture & hunting	1173 (403)	21(275)	145 (52)	1	148
15	EUR Agriculture & hunting > EUR Bakery products	578 (748)	197 (25)	306 (20)	3	87
16	EUR Agriculture & hunting > EUR Alcoholic beverages	547 (787)	186 (29)	289 (21)	3	82
17	OECD Agriculture & hunting > OECD Meat products	538 (798)	203 (24)	283 (23)	0	65
18	ROW Agriculture & hunting > ROW Food & beverages	490 (8 6 8)	487 (6)	356 (19)	22	82
19	EUR Agriculture & hunting > EUR Fish products	515 (8 3 3)	175 (30)	532 (12)	3	77
20	UK Agriculture & hunting > UK Other food products	436 (9 5 3)	153 (32)	514 (14)	2	93

(~7.3%). The authors also demonstrate the potential savings from land use and water footprint. Evidence from the United States [10] suggests that food waste is an increasing, rather than decreasing issue with the availability of fast food a possible culprit. Tackling food waste, in addition to reducing water, energy and food materials, may also have additional health benefits.

4.3. Data uncertainties

The version of the UKMRIO database used in this study is essentially a flow matrix showing the economic transactions between 106 industries in eight global regions. This is a matrix of $(106 \times 8)^2 = 719{,}104$ cells. Whilst much of this data on domestic transactions is provided by national statistical agencies, data on imports and exports is often

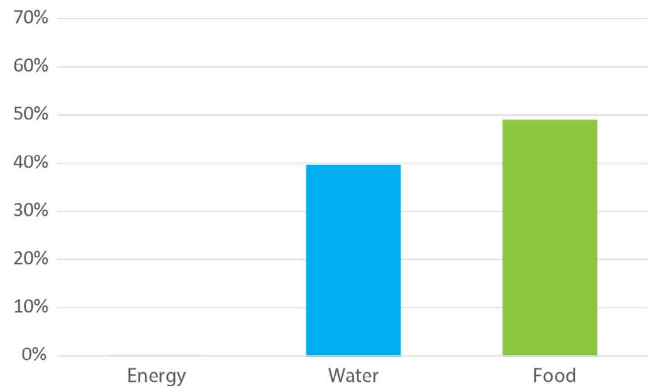

Fig. 5. Proportion of UK territorial industrial energy, water and food captured by the twenty Nexus Pathways (2013).

lacking and has to be modelled (see [49] for further information). In addition countries collect data using different classification systems, in different currencies and the imports of one country rarely match the claimed exports of the trading partners [50,51]. Column and row sums are 'known' figures in MRIO tables since they relate to the total output of a product or industry. It is less certain exactly what the distribution of data in these rows and columns are. This means that analysts wanting to use evidence from MRIO analyses to inform policy must consider the accuracy of the type of data they have calculated.

National level CBAs use the sum of the entire table and have shown have a low uncertainty in the final figure [52]. Product level figures, such as those calculated in Table 2 require the sum of a single column. Since column sums are based on known data, these estimates are considered reasonably accurate. Supply chain analyses, as demonstrated in Tables 3–5 involve calculations at the cellular level of an MRIO table. A recent study has shown that there to be large variations when the same supply chain is extracted from different MRIO databases [53], however this has not prevented the publication of many high impact studies that use this technique (see [54] for example). In addition, supply chains that do not cross a country's boundary, such those presented in Table 6, will actually use original data from the national statistical offices which is not modelled to estimate the effects of trade. We can therefore assume it to be accurate.

5. Conclusion

This paper demonstrates that techniques from ecological economics, namely the calculation of consumption-based accounts using input-output analysis and the identification of critical supply chains using structural path analysis, can be used to quantify and add value to the discussions of the energy-water-food nexus. This research is important because it provides a framework for nexus analysis and shows that quantitative results can be generated using readily available and open source datasets and calculation routines that are well established in a pre-existing economic discipline. The paper provides a UK case study — the first analysis demonstrating the use of structural path MRIO thechniques.

We provide examples as to the type of results that could be used as evidence in environmental policy. Demand-side strategies can reduce the overall consumption of goods and services. We therefore identify twenty Nexus Products which have large impacts in terms of the total energy, water and food used in their production which would be the priority products for reduction strategies. Industrial efficiency policy acts at the start of a product's supply chain so we then identified the twenty corresponding Nexus Pathways. We believe this to be a novel contribution to both the nexus and environmental accounting fields of research.

This type of analyses has only become possible since the recent development of large scale MRIO databases. The limitations of these databases are well documented [55] but it is anticipated that future

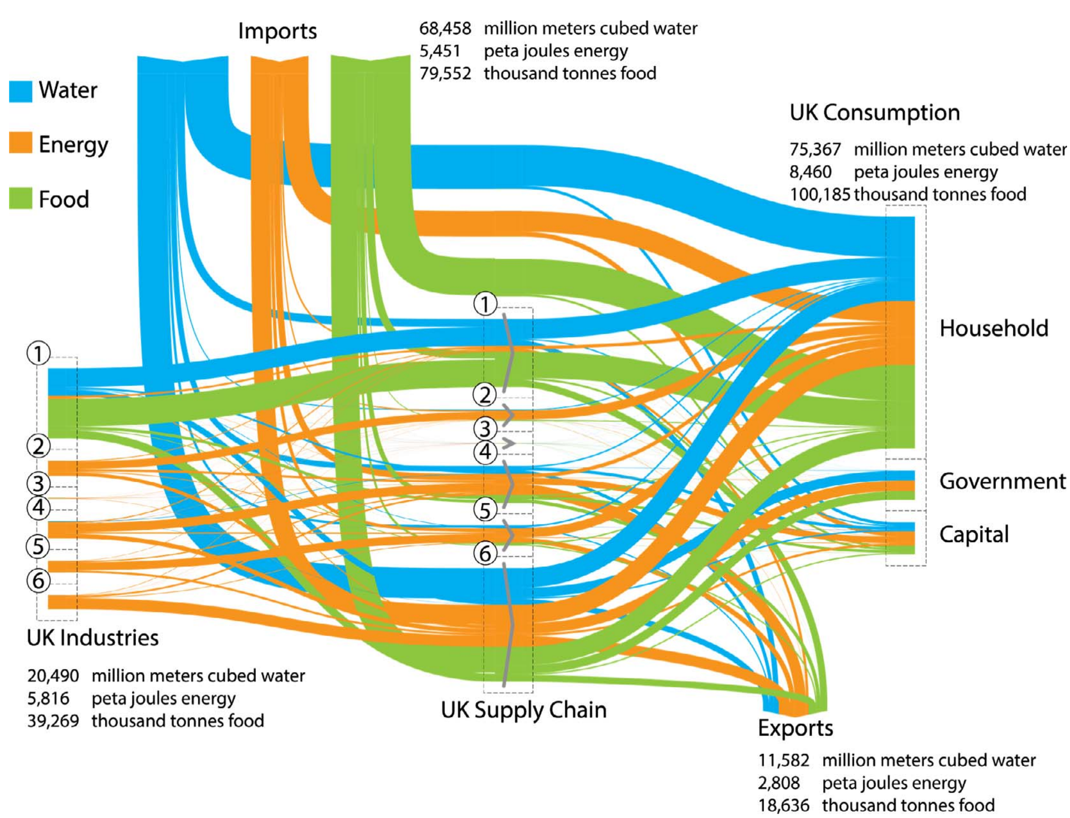

Fig. 6. Sankey diagram showing energy, water and food flows, from industry to final consumption for the UK in 2013, where 1 = agriculture & food processing, 2 = power generation and distribution, 3 = primary materials industries, 4 = manufactured goods & recycling, 5 = transport, 6 = other services.

releases will prove to be more accurate and even more useful for this type of work [56].

Acknowledgments

We would like to thank Simon Arm-Riding for producing the Sankey diagram (Fig. 6) and also the participants at the 23rd International Input-Output Association conference in Seoul for insightful comments on an early presentation of these results. Thank you for the useful comments and suggestions from two anonymous referees. This work was supported by the research programme of the UK Energy Research Centre, supported by the UK Research Councils under [EPSRC award EP/L024756/1] and the RCUK Energy Program's funding for the Centre for Industrial Energy, Materials and Products [grant reference EP/N022645/1].

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