Supplementary information on the construction of the energy extension vector

To article “Structural Change for a Post-growth Economy: Investigating the relationship between embodied energy intensity and labour productivity” in *Sustainability*
Lukas Hardt, Peter Taylor, John Barrett, Timothy Foxon
School of Earth and Environment, University of Leeds

1 Introduction

For our study we construct a global extension vector for EXIOBOASE specifying final energy consumption across sectors and regions. We construct this vector in two steps. In the first step we use data on final energy consumption provided by the International Energy Agency (IEA) in combination with information on monetary output and expenditure from EXIOBASE to construct a complete vector for all countries and regions outside Germany and the UK (described in section 2). In a second step we use national data sources to construct more detailed vectors of energy inputs for the UK and Germany respectively (described in sections 3 and 4).

2 Global energy extension vector

2.1 Data sources

We construct the vector of energy inputs to match the data on monetary flows from the EXIOBASE database. We use the symmetric input-output tables of EXIOBASE version 3.4. The EXIOBASE 3.4 database is available at http://exiobase.eu/index.php/data- download/exiobase3mon. The database covers the period from 1995 to 2011 and represents the global economy in 44 countries and 5 rest-of-the-world regions. Each national/regional economy is disaggregated into 163 sectors based on NACE rev.1.1 classification. However, for our purposes we aggregate the database to a level of 70 sectors, largely by removing detailed sub-classifications in the sectors of agriculture, food production, metal mining and processing and recycling. We perform this aggregation to 70 sectors because our energy data does not provide a similar level of detail and it simplifies computation and analysis (Table S1). The term “EXIOBASE sectors” will be used from hereafter to describe the 70 aggregated sectors and sector numbers will refer to the numbers in Table S1, ranging from 1 to 70.

For the construction of the energy extension vector we draw on data from the Extended World Energy Balances provided by the International Energy Agency (IEA, 2018) to produce information on the final energy inputs for each sector and each country/region in EXIOBASE. However, the energy inputs for the UK and Germany are later replaced by more detailed information from domestic sources. The energy balances provide details on the energy production, transformation and use in more than 140 countries.

Table S1: Sector classification used in analysis

No	Sector	NACE 1.1	No	Sector	NACE 1.1
1	Agriculture	01	36	Production of electricity from nuclear power	40.11
2	Forestry	02	37	Production of electricity from renewables and other sources	40.11
3	Fishing	05	38	Transmission and distribution of electricity	40.12, 40.13
4	Mining of coal and lignite	10	39	Manufacture and distribution of gas	40.2
5	Extraction of crude petroleum and nat. gas	11	40	Steam and hot water supply	40.3
6	Other mining and quarrying	12-14	41	Water collection, purification and distribution	41
7	Manufacture of food products	15.1-8	42	Construction	45
8	Manufacture of beverages	15.9	43	Sale, maintenance, repair of motor vehicles	50
9	Manufacture of tobacco products	16	44	Wholesale and commission trade	51
10	Manufacture of textiles	17	45	Retail trade	52
11	Manufacture of clothes	18	46	Hotels and restaurants	55
12	Manufacture of leather products	19	47	Transport via railways	60.1
13	Manufacture of wood products	20	48	Other land transport	60.2
14	Manufacture of paper and paper products	21	49	Transport via pipelines	60.3
15	Publishing, printing and reproduction of recorded media	22	50	Water transport	61
16	Manufacture of coke oven products	23.1	51	Air transport	62
17	Petroleum refinery	23.2	52	Supporting and auxiliary transport activities	63
18	Processing of nuclear fuel	23.3	53	Post and telecommunications	64
19	Manufacture of chemicals	24	54	Financial intermediation except insurance	65
20	Manufacture of rubber and plastic products	25	55	Insurance and pension funding	66
21	Manufacture of non-metallic minerals	26	56	Activities auxiliary to financial intermediation	67
22	Manufacture of basic iron and steel	27.1-3, 27.5	57	Real estate activities	70
23	Manufacture of non-ferrous metals	27.4	58	Renting of machinery and equipment	71
24	Manufacture of fabricated metal products	28	59	Computer and related activities	72
25	Manufacture of machinery and equipment nec	29	60	Research and development	73
26	Manufacture of office machinery and computers	30	61	Other business activities	74
27	Manufacture of electrical machinery and apparatus nec	31	62	Public administration and defence; compulsory social security	75
28	Manufacture of radio, television and communication equipment and apparatus	32	63	Education	80
29	Manufacture of medical, precision and optical instruments, watches and clocks	33	64	Health and social work	85
30	Manufacture of motor vehicles, trailers and semi-trailers	34	65	Sewage and refuse disposal	90
31	Manufacture of other transport equipment	35	66	Activities of membership organisation nec	91
32	Manufacture of furniture; manufacturing nec	36	67	Recreational, cultural and sporting activities	92
33	Recycling	37	68	Other service activities	93
34	Production of electricity from coal	40.11	69	Private households with employed persons	95
35	Production of electricity from gas	40.11	70	Extra-territorial organizations and bodies	99

Given that we are only interested in final energy data, we only use the information on Total Final Consumption (TFC) in the energy balances, which is subdivided into 27 energy flows (Table S2). We download the data for the 27 flows for all countries available in the energy balances and aggregate the data of individual countries to the 49 countries/regions used in EXIOBASE. We then exclude the two flows of non-energy use and residential energy consumption, because our study focuses on energy inputs into economic production. This leaves us with the relevant final energy consumption in each EXIOBASE country/region disaggregated into 25 IEA flows.

In the following we describe how we map the 25 IEA flows onto the 70 EXIOBASE sectors.

2.2 Industry

Table S2 describes how the 13 industry-related energy flows were mapped onto the relevant 25 industry and construction sectors in EXIOBASE (6-15,19-33,41-42 in Table S1). IEA Flows that only correspond to one EXIOBASE sector are directly assigned to that sector. IEA flows that correspond to multiple EXIOBASE sectors are split in proportion with the total monetary expenditure on energy in each sector. The expenditure on energy of each sector was obtained by summing the intermediate expenditures on the energy-producing sectors (4-5,16-18,34-40 in Table S1) from the EXIOBASE tables.

We used expenditure on energy rather than total sectoral output for splitting the IEA flows, because a comparison of the results of both methods for the UK revealed that the energy expenditure approach produced results that better matched the more detailed information available from domestic data UK sources.

The IEA flow of “non-specified industry” includes both the energy use in industry sectors that are not covered by the other industry flows, as well as any energy use that cannot be allocated to a specific industry due to lack of information. We allocate this flow only to the EXIOBASE industry sectors that are not covered by the other IEA flows (i.e. sectors 25, 32,33,41 in Table S1) in proportion to the energy expenditure in these sectors.

2.3 Transport

2.3.1 Rail, pipeline and non-specified transport

The IEA energy flows for rail and pipeline transport are directly assigned to the respective EXIOBASE sectors. The IEA flow of “non-specified (transport)” is allocated across all transport sectors in proportion to economic output in the sectors.

2.3.2 Road transport

The treatment of the IEA energy flow for road transport is more difficult and poses several challenges. Firstly, it includes the energy used by private households, which we have to exclude for our analysis, as we are only interested in energy used for commercial purposes. Information on the share of non-commercial road transport energy use in total road transport energy use is not available in a single consistent database.

Table S2: IEA energy flows from TFC and corresponding EXIOBASE sectors (sector numbers refer to Table S1).

IEA TFC flow	EXIOBASE sectors	Method for allocation
Industry		
Iron and steel	22,24	EXIOBASE energy expenditure
Chemical and petrochemical	19	Direct
Non-ferrous metals	23	Direct
Non-metallic minerals	21	Direct
Transport equipment	30-31	EXIOBASE energy expenditure
Machinery	25-29	EXIOBASE energy expenditure
Mining and quarrying	6	Direct
Food and tobacco	7-9	EXIOBASE energy expenditure
Paper, pulp and print	14,15	EXIOBASE energy expenditure
Wood and wood products	13	Direct
Construction	42	Direct
Textile and leather	10-12	EXIOBASE energy expenditure
Non-specified (industry)	25,32-33,41	EXIOBASE energy expenditure
Transport		
Domestic aviation	51	See details in text
Road	48	See details in text
Rail	47	Direct
Pipeline transport	49	Direct
Domestic navigation	50	See details in text
Non-specified (transport)	47-51	See details in text
World aviation bunkers	51	See details in text
World marine bunkers	50	See details in text
Other		
Commercial and public services	43-46, 52-68	EXIOBASE output
Agriculture/forestry	1-2	EXIOBASE output
Fishing	3	Direct
Non-specified (other)	1-3,6-15,19-33, 41-68	See details in text
Excluded flows		
Residential	-	-
Non-energy use	-	-

Therefore we rely on different data sources to obtain the necessary information. For those countries that publish greenhouse gas (GHG) inventories under the UNFCCC, we use the share CO_2 emissions produced by cars in the total road transport CO_2 emissions as a proxy for the share of non-commercial road transport energy use. For all remaining countries we tried to obtain estimates from the academic literature or from other statistical sources. Where such sources were not available, we used the shares obtained for different countries

that we considered to be sufficiently similar. For the rest-of-the-world regions we obtained the information for a single country in the region as an estimate for the share of non-commercial transport in the whole region.

Secondly, IEA energy balances are assembled based on a territorial principle, while national economic accounts and EXIOBASE follow a residency principle (Stadler *et al.*, 2018). This is particularly problematic for the transport sector. In the IEA balances, transport energy use is recorded where the fuel is used (or sold), no matter whether the company (or person) using the fuel is resident in the country. In contrast the economic activity is recorded in the country of residency of the company or person. This means that ideally the figures for road transport energy use provided by the IEA need to be adjusted for energy used by foreign vehicles in the country and the energy used by domestic vehicles outside the country. However, such information is not easily obtained and detailed modelling would be beyond the constraints of this study. We therefore do not perform any adjustments of this nature, essentially assuming that energy use by domestic vehicles abroad is similar to energy use by foreign vehicles domestically. This is not the case in many countries and this assumptions therefore adds to the uncertainty of this analysis. However, we consider it unlikely that taking into account such adjustments in road transport would significantly alter our overarching conclusions.

Thirdly, once the total energy use for commercial road transport is estimated, this figure cannot simply be allocated to the EXIOBASE sector for road transport, which only captures the logistics sector. Instead the IEA data captures all road energy by commercial vehicles, many of which are directly operated by companies in sectors outside logistics, for example supermarket distribution lorries. The data on commercial road transport energy use therefore needs to be split and allocated across a range of economic sector. The only country for which we found information of this nature is Germany for the years 1995 to 2001 (see section 3). Therefore we use the German data to estimate the allocation of commercial road transport energy use across the EXIOBASE sectors for all other countries/regions. We achieve this in three steps. Firstly, we obtain the German road transport intensity of each sector by dividing sectoral road transport energy use by industry sector output from EXIOBASE. As the intensities are relatively stable, we obtain the average German intensities over the seven years provided to apply them to all other countries and years. Secondly, we multiply the average Germany road transport energy intensities for each sector with total output in each sector and each year in the other countries. Thirdly, we scale these results in each country so that the sectoral road transport energy use adds up to the total energy use for commercial road transport in the country.

2.3.3 Aviation and marine transport

The energy use of internal aviation and marine transport (i.e. international marine and aviation bunkers) pose similar challenges to road transport, again due to the fact that the IEA data is reported based on the territorial principle while EXIOBASE is built on the residency principle. A detailed modelling of aviation and marine trade flows to allocate international bunkers to the right countries is, again, beyond the constraints of this study.

For simplicity we therefore assumed that the aviation sectors across all countries/regions have the same energy intensity of output set to the global average. The economic output of the aviation sector in EXIOBASE does not distinguish between domestic and international aviation, as the IEA data does. To obtain the global average intensity we therefore add international aviation bunkers and energy use for domestic aviation across all countries to obtain the total global energy use for aviation. We then divide the total aviation energy use by the sum of economic output in the aviation industries across all countries/regions in EXIOBASE to obtain the

global average energy intensity. The global aviation energy use is then reallocated to the aviation industries in the individual countries based on their economic output and the average global intensity. For marine transport energy use we adopt the same process.

Our process of allocation therefore relies on very simplified assumptions, but we considered that they represent the best possible solution within the constraints of this study. Aviation and marine transport each make up about 5% of commercial global final energy consumption in 2011 (i.e. excluding residential, private transport and non-energy use). The assumptions therefore add a degree of uncertainty to our results.

2.4 Other flows

Of the remaining flows, the energy use for fishing and construction are assigned directly to the respective EXIOBASE sectors. The agriculture/forestry flow in the IEA balances was split according to sector output as reported in EXIOBASE.

The IEA extended energy balances only feature a single flow describing all final energy consumption in the commercial and public service sectors. We split this flow into the relevant EXIOBASE sectors (43-46, 52-68 in Table S1) in proportion to the total output in these sectors as reported in EXIOBASE. In contrast to the industry sectors, we use total output and not energy expenditure for the service sectors because the energy expenditure approach produces unrealistically low values of energy consumption in some sectors.

Finally, the energy balances include a flow labelled as “Non-specified (other)” which includes all energy use that is not assigned to other categories (including for military use). Values for this category are mostly between 0 and 2% of overall final energy use (excl. non-energy use) for most countries/regions but can reach higher values (up to 10%) in some years and some countries/regions. The category is therefore non-negligible but there is no information on what the energy is used for. In the absence of better information we distribute the flow across all energy-using sectors in proportion to sectoral output.

2.5 Sectors without final energy consumption

Some of the 70 EXIOBASE sectors were not assigned any final energy use from the IEA flows. This includes those sectors that produce primary energy carriers (e.g. coal mining) or transform them into final energy carriers (e.g. electricity production). By definition, these sectors (4-5,16-18,34-40 in Table S1) are not users of final energy and therefore do not feature a final energy consumption in the IEA balances. In addition we also did not assign any final energy consumption to the sectors “Private Households with Employed Persons”, because we consider that the sector does not have energy use separate from private residential use. We didn’t assign any energy consumption to the sector “Extraterritorial bodies and organisations” as this sector does not feature any monetary flows in EXIOBASE.

3 Energy extension vector for the UK

In our study we focus on the energy and labour footprint of final demand in the UK or Germany. To reduce some of the uncertainty associated with the IEA data, we construct more detailed extension vectors for these two countries drawing on domestic data sources describing energy use.

3.1 Data sources

For the UK we make extensive use of the 2018 version of the Energy Consumption in the UK (ECUK) dataset, published by the Department for Business, Energy and Industrial Strategy (BEIS, 2018). This was complemented by monetary flows from the EXIOBASE database if necessary.

3.2 Industry

For industry sectors, the ECUK dataset provides data on energy consumption at the 2-digit level of the SIC2003 classification. This classification mostly matches the industry and construction EXIOBASE sectors (6-15,19-33,41-42 in Table S1). The only exception is the aggregated food and beverages sector which we split into food and beverages according to EXIOBASE energy expenditure. For the years 2010 and 2011 the ECUK database provides data in SIC2007 classification (corresponds to NACE rev. 2) which we transformed into NACE rev1.1 classification to match our EXIOBASE sectors.

The industrial energy use listed as “unclassified” in ECUK provides a difficult choice for allocation. We decided to add it to the sector “Manufacture of furniture; manufacturing nec” because the sectors featured unrealistically low values of energy intensity otherwise. However, some of the unclassified energy are also likely to be used in other sectors. As a result our estimates of embodied energy intensity for the sector “Manufacture of furniture; manufacturing nec” is an overestimate, while the intensities in the other manufacturing sectors are underestimated.

3.3 Transport

We do not recalculate energy use for marine transport and aviation for the UK but instead take it from the global extension vectors (described in section 1.3) to make sure that it is consistent with our global assumptions.

The ECUK dataset provides separate information on road transport energy use for passenger and freight transport as well as for different transport modes. This allows an estimation of the commercial road transport energy use. However, there is no information provided on the sectors in which the transport energy is used. We therefore estimate the allocation of road transport energy use to EXIOBASE sectors using the German data as described in section 1.3.

Data on rail transport energy use is provided in the ECUK. We obtain energy use for pipeline transport (which is very small in the UK) from the IEA data, as no information is provided in ECUK.

3.4 Other energy users

The ECUK dataset provides information on the aggregate energy use for the sectors agriculture, forestry and fishing. We split this energy use according to sector proportions in EXIOBASE output to obtain the energy use in the three individual sectors.

For the commercial and public service sectors the ECUK dataset provides the aggregate energy use for all years covered in this study as well as a more detailed breakdown for the years 2010 and 2011. Table S3 describes the sub-categories for which data is provided in 2010 and 2011 and the EXIOBASE sectors we assigned to these sub-categories. We estimate the energy consumption in each sub-category for the years 1995-2009 from the data for 2010/2011 using the following steps. Firstly, we obtain the total economic output for each sub-category by summing the output of the relevant sectors from EXIOBASE. Secondly, we use the output figures to calculate the average energy intensity of output in each subcategory for the years 2010 to 2011. Thirdly, we multiply the average energy intensity with the economic output in the sub-categories for the years 1995-2009. Finally, we scale these results so that the sum of energy use in all sub-categories matches the aggregate energy use in the services sectors reported. In essence this process assumes that the relative energy intensities in the sub-categories stay constant at their 2010/2011 value for the whole time period.

Once we have obtained the energy use in each sub-category and each year, the sub-categories are allocated to the relevant EXIOBASE sector in proportion to EXIOBASE sector output (Table S3).

Table S3: ECUK energy use in service sector sub-categories and corresponding EXIOBASE sectors (sector numbers refer to Table S1).

ECUK service sector sub-category	EXIOBASE sectors	Method for allocation
Commercial offices	54-61	EXIOBASE output
Communication and transport	52-53	EXIOBASE output
Education	63	Direct
Government	62	Direct
Health	64	Direct
Hotel and Catering	46	Direct
Other	65-66, 68	Direct
Retail and warehouses	43-45	EXIOBASE output
Sport and Leisure	67	Direct

4 Energy extension vector for Germany

4.1 Data sources

To create a more detailed extension vector for Germany we draw on three important data sources. To obtain energy use in the industrial sectors as well as aggregate energy use in commercial and public services we use the data provided in the German energy balances (AG Energiebilanzen, 2019). In addition, we use statistical

reports on energy use in the sector “Gewerbe, Handel, Dienstleistungen” (GHD), which provides detailed estimates of energy use in the non-industrial and non-transport sectors for the year 1994 (Geiger, Gruber and Megele, 1999) and the years 2001-2011 (Schlomann *et al.*, 2004, 2009, 2013). In combination these reports will be referred to as GHD reports hereafter. Finally, the Berichtsmodul Verkehr und Umwelt (Adler, 2005) provides information on the transport energy use allocated to different sectors for the years 1995 to 2001.

4.2 Industry

We obtain information on energy use in industry for the years 1995 to 2011 from the Germany energy balances. Table S4 outlines the energy flows provided in the balances and the EXIOBASE sectors to which we allocate them. As the disaggregation in the energy balances is less detailed than in our EXIOBASE sectors, we allocate the energy use to the relevant EXIOBASE in proportion to EXIOBASE energy expenditure. Contrary to the IEA and UK energy data, the construction and water sectors are not treated as part of the industrial sectors. They are instead allocated to the GHD category treated in the reports mentioned above.

Table S4: Energy use in the industrial sectors from German energy balances and corresponding EXIOBASE sectors (numbers refer to Table S1).

German energy balance flow	EXIOBASE sectors	Method for allocation
Gewinnung von Steinen und Erden, sonst. Bergbau	6	Direct
Ernährung und Tabak	7-9	EXIOBASE energy expenditure
Papiergewerbe	14	Direct
Grundstoffchemie and Sonstige chemische Industrie	19	Direct
Gummi- u. Kunststoffwaren	20	Direct
Glas u. Keramik and Verarbeitung v. Steine u. Erden	21	Direct
Metallerzeugung	22	Direct
NE-Metalle, -gießereien	23	Direct
Metallbearbeitung	24	Direct
Maschinenbau	25-29	EXIOBASE energy expenditure
Fahrzeugbau	30-31	EXIOBASE energy expenditure
Sonstige Wirtschaftszweige	10-12,15,32-33	EXIOBASE energy expenditure

4.3 Transport

We do not recalculate energy use for marine transport and aviation for Germany but instead take it from the global extension vectors (described in section 1.3) to make sure that it is consistent with our global assumptions.

The German energy balances provide information on the total road transport energy use in Germany. We obtained estimates of the proportion of commercial road transport energy for the years 1994 to 2001 from Adler (2005) and for the year 2016 from Statistisches Bundesamt (2018). We obtain the value of the proportion

of commercial road transport energy use for the years 2002 – 2011 using linear interpolation and use the values to estimate total commercial road transport energy use for the whole time period covered in this study.

Adler (2005) also gives the allocation of road transport energy use to different economic sectors for the years 1994 to 2001. The sector shares in transport energy use remain relatively stable. Therefore we assume constant sector shares for the years 2002 to 2011, set to the values for 2001, and use these shares to estimate sectoral transport energy use from total commercial road transport energy use. The resulting values are then aggregated to EXIOBASE sectors and the energy use added to non-transport forms of energy use in the sectors.

Data on rail transport energy use is provided in the German energy balances. We obtain energy use for pipeline transport from the IEA data, as no information is provided in the German energy balances.

4.4 Other flows

In the German energy balances all other flows are covered in a single category labelled “Gewerbe, Handel, Dienstleistungen” (GHD). The GHD reports provide a more detailed investigation of energy use split into 37 different sub-sectors for the years 1994 (Geiger, Gruber and Megele, 1999) and 2001-2011 (Schlomann *et al.*, 2004, 2009, 2013) in a mostly consistent format. Sectoral energy use for the 37 sectors and years 1995 to 2000 was obtained using linear interpolation. The GHD reports produce results that are not completely consistent with the total GHD energy use reported in the energy balances, although differences between the totals are small. To make the energy extension for Germany as consistent as possible with the German energy balances, we scale the sectoral energy use in the GHD reports to match the total GHD use in the energy balances.

We then transform the energy use in the 37 GHD sectors for the years 1995 to 2011 into the relevant EXIOBASE sectors. Where energy use had to be split from one GHD category into multiple EXIOBASE sectors we allocated the energy use in proportion to EXIOBASE output. The GHD category mostly covers the non-transport public and commercial service sectors (41, 43-46, 52-68 in Table S1), as well as construction (42) and agriculture, forestry and fishing (1-3). However, it also contains small amounts of energy use in small enterprises (less than 20 employees) in the industry sectors (e.g. artisan bakeries), as well as some energy use that is used in the transport sector for non-transport purposes (e.g. energy use in airports).

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