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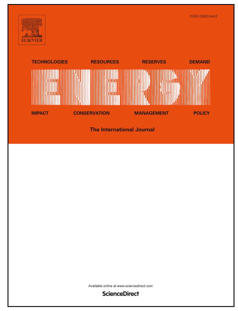

Double accounting in energy footprint and related assessments: how common is it and what are the consequences?

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Double accounting in energy footprint and related assessments: how common is it and what are the consequences?

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Abstract

The number of input-output assessments focused on energy has grown considerably in the last years. Many of these assessments combine data from multi-regional input-

output (MRIO) databases with energy extensions that completely or partially depict the different stages through which energy products are supplied or used in the economy.

The improper use of some energy extensions can lead to double accounting of some energy flows, but the frequency with which this happens and the potential impact on the results are unknown. Based on a literature review, we estimate that around a quarter of the MRIO-based energy assessments reviewed incurred into double accounting. Using the EXIOBASE MRIO database, we also analyse the effects of double accounting in the absolute values and rankings of different countries' and products' energy footprints.

Building on the insights provided by our analysis, we offer a set of key recommendations to MRIO users to avoid the double accounting problem in the future. Likewise, we conclude that the harmonisation of the energy data across MRIO databases led by experts could simplify the choices of the data users until the provision of official energy extensions by statistical offices becomes a widespread practice.

Acronyms

COICOP	Classification of individual consumption by purpose
EEU	End energy use
EREU	Emission-relevant energy use
GES	Gross energy supply
GEU	Gross energy use
IEA	International Energy Agency
IO	Input-output
MRIO	Multi-regional input-output
NEU	Net energy use
PES	Primary energy supply
SEEA	System of environmental-economic accounting
TPES	Total primary energy supply

Variables

f	Direct energy use by industries
geet	Gross energy embodied in trade
gef	Gross energy footprint
geu	Gross energy use
i	Country
j	Industry and final consumption category
k	Energy product
h	Direct energy use by final consumers
L	Leontief inverse
neet	Net energy embodied in trade
nef	Net energy footprint
neu	Net energy use
s	Direct energy intensity
y	Final demand

1. Introduction

There is a growing volume of literature using input-output (IO) techniques to calculate energy footprints and related metrics (e.g. Arto et al. (2016); Wood et al. (2018)). A Google Scholar search of the terms "energy footprint" and "input-output analysis" yields 104 results in 2019 at the moment of writing these lines, compared to 11 in 2010.

The so-called consumption-based accounting makes use of IO and energy data to compute both the direct and indirect energy flows induced by the final demand (i.e. the energy footprint). Within a multi-regional framework, this method allows not only the calculation of the total energy footprint caused by products consumed within a country in a given year, but also the estimation of the energy use induced by trade between countries. Such exercises require two elements: i) a multi-regional input-output (MRIO) table mapping the monetary flows of goods and services between the different users (industries and final demand) and countries of the global economy; and ii) the corresponding energy extensions that record the direct supply and/or use of different energy products by the industries and final demand components represented in MRIO tables.

Most of the major MRIO databases (see Inomata and Owen (2014) for an overview) contain information on energy flows that can be used for energy footprinting, decomposition analysis and other policy-relevant exercises. In general, the energy extensions available in those databases represent a variety of indicators that differ depending on the database. However, this diversity of indicators can be a source of confusion for users that are not familiar with the methodological concepts underlying the construction of such extensions. This can ultimately lead to the selection of an energy extension that is unsuitable for the intended analysis, which has implications for the results.

Three main issues that need to be considered when selecting an energy extension have been documented in the literature: i) methodological choices in the construction of the extension, ii) supply vs. use perspective, and iii) double accounting of energy flows. In this vein, Usubiaga and Acosta-Fernández (2015) showed that the use of different accounting principles affects considerably the air emission extensions – and therefore the energy extensions – of multiple countries. Owen et al. (2017) and Wieland et al. (2019), on the other hand, investigated the potential uses of energy supply and use extensions, and quantified the numerical differences resulting therefrom. Last, Arto et al. (2016) warned that using an extension that represents gross energy (i.e. that accounts for both primary and secondary energy products) as opposed to net energy (i.e. that omits the fraction of energy products that is transformed into other energy products) would lead to accounting twice for certain energy flows, but did not elaborate on how this could affect the results.

Against this background, this paper seeks to shed light on how common the double accounting problem is and on its potential consequences. Thus, in section 2, we introduce the key indicators represented through energy extensions and describe their availability in different MRIO databases. While doing so, we show the instances that can lead to double accounting when using certain energy extensions. Section 3 explains the methodology used to quantify the frequency with which double accounting occurs and how this can impact the results. Sections 4 and 5 present the results of our analysis and discuss the main findings. Section 6 concludes.

2. Energy extensions and the double accounting problem

2.1. Overview of energy extensions

Energy extensions can be arranged around indicators that cover all or different stages of the supply and use of energy as shown in Table 1. On the one hand, supply-side indicators record the energy flows entering the economy from the environment and the outputs of transformation processes. On the other hand, use-side indicators represent how primary and secondary energy products are allocated between various intermediate and final users.

Table 1: Typology of energy extensions applicable to MRIO databases

Side	**Energy extension**	**Definition**
Supply	Gross energy supply (GES)	Supply of all energy products, primary or secondary, by domestic industries. It does not include imports in MRIO format.
	Primary energy supply (PES)	Supply of energy products extracted from the environment by domestic industries. It does not include imports in MRIO format.
Use	Gross energy use (GEU)	Use of all energy products, primary or secondary by domestic industries and final consumers such as households. It does not include exports in MRIO format.
	Net energy use (NEU)	Use of energy products by domestic end users (*), including the losses incurred during transformation, distribution, transmission and transport, but excluding exports.
	End energy use (EEU)	Use of all energy products by domestic end users (*), excluding exports and the losses incurred during transformation, distribution, transmission and transport.
	Emission-relevant energy use (EREU)	Use of all energy products that lead to air emissions by domestic industries and final consumers such as households.
	Direct household energy use by purpose	Direct use of energy products by households, split by type of end use (e.g. heating, cooking, lighting and appliances, transportation, etc.).

Source: own elaboration.

Note: This table is not meant to capture all the energy indicators that can be represented through energy extensions. Instead it shows the main energy indicators currently available in MRIO databases.

(*): End users represent the activities by industries and households where energy is used but not transformed into other secondary energy products.

Gross energy extensions record separately all the flows of primary and secondary energy products supplied and consumed by domestic industries and final consumers such as households. In this context, primary energy refers to the energy resources captured or extracted directly from the environment (e.g. crude oil, coal, natural gas, renewable energy, biofuels and waste, etc.), while secondary energy covers the commodities produced through the transformation of primary sources (e.g. electricity from fossil fuels, refined petroleum products from crude oil, coke-oven coke from coking coal, charcoal from fuelwood, etc.) (OECD et al. 2010). In this sense, the term 'gross' refers to the fact that some energy products are mapped from the extraction to their final use, and some of them are therefore accounted at two separate stages: as an input in the transformation process and as the subsequent use of the resulting secondary product (e.g. the coal used to produce electricity and the use of electricity produced by coal). At the global level, the sum of GES of an energy product *k* matches that of GEU (equation 1 and Figure S1 in the supplementary material). *i* refers to countries and *j* to industries and final consumers.

$$\sum_{i,j} GES_{i,j,k} = \sum_{i,j} GEU_{i,j,k} \qquad (1)$$

Supply can also be recorded in primary terms. Thus, the PES of a country covers the domestic extraction of primary energy by domestic industries, similar to 'domestic extraction used' in the environmental extension required for material footprinting in environmentally extended IO analysis (Giljum et al. 2015) or the 'primary inputs' (e.g. value added) in classical IO applications (Miller and Blair 2009). PES should not be mistaken with total primary energy supply (TPES), an indicator used in the energy balances of the International Energy Agency (IEA) to account for the net energy flows entering the economy of a country either from the environment (i.e. as a domestic extraction) or from other countries (through trade) that is not used as energy extension in environmentally extended IO analysis. TPES covers the domestic production of primary energy, as well as the flows resulting from changes in stocks and from the physical trade balance between the imports and exports (including exchanges with international aviation and marine bunkers) of both primary and secondary energy products.

At the country level, TPES equals NEU, which records the direct energy used (domestically produced and imported) by end users, less exports of energy products plus all losses of energy (during transformation, distribution, transmission and transport) (see equation 2). At the global level, since imports and exports are compensated, PES also matches net energy use, when the latter includes the use of energy associated with international marine and aviation bunkers (see equation 3). These relationships are depicted in Figure S1 in the supplementary material.

$$\sum_{i,j} TPES_{i,j,k} = \sum_{i,j} NEU_{i,j,k} \qquad (2)$$

$$\sum_{i,j,k} PES_{i,j,k} = \sum_{i,j,k} NEU_{i,j,k} \qquad (3)$$

Also from the use side, the end use extension represents the energy used by intermediate and final users for purposes other than transformation, and excluding exports. The direct energy use by households also provides policy-relevant information, especially if disaggregated by purpose (e.g. space heating/cooling, water heating, cooking, electric appliances, transportation, etc.). Last, the EREU extension records the use flows of all the energy products that lead to emissions of air pollutants. For instance, this extension would cover coal combusted in a power plant, but exclude the use of the electricity and heat generated or the use of energy products for non-energy purposes (e.g. feedstock), since the latter two do not lead to emissions. The compilation of EREU extensions is an intermediate step towards the generation of air emission extensions (Eurostat 2015). The main components of supply- and use-side energy indicators are shown in Figure S2 in the supplementary material.

The coverage of these indicators in MRIO databases differs considerably. There are five MRIO databases that are widely used for environmental footprinting exercises: EXIOBASE (Stadler et al. 2018), WIOD (Timmer et al. 2015), EORA (Lenzen et al. 2013), OECD ICIO (OECD and WTO 2012) and GTAP (Andrew and Peters 2013). Most of these databases have energy extensions[1]. EXIOBASE provides GES and GEU data, as well as PES, EREU and NEU data. WIOD covers GEU and EREU; GTAP and EORA include GEU and NEU extensions respectively (see Table S1 in the supplementary material). ICIO does not contain energy extensions.

2.2. Double accounting of energy flows

Double accounting in energy assessments occurs when the footprint of a product group/industry/country incorporates both the inputs and outputs of transformation processes. This gives a biased picture of the upstream energy requirements of the object of study by penalising the use of secondary products. After all, the same energy service can have a different energy footprint depending on whether secondary or primary products were used to provide it.

In practice, this occurs when using GEU and GES extensions to calculate energy footprints, energy embodied in trade, etc. For instance, when using the GEU extension to calculate the energy footprint associated with the acquisition of a product that required electricity produced through a diesel generator, the footprint would not only include the electricity used during the production process (e.g. 0.4 gigajoules, GJ), but also the diesel used as input in the diesel generator (e.g. 0.9 GJ of diesel to produce 0.4 GJ of electricity) and the fraction of crude oil allocated to the diesel production in the oil refinery (1 GJ of crude oil to produce 0.9 GJ of diesel assuming 10% losses). In other words, the energy footprint would account for all the cumulative energy use of primary

[1] GTAP is not published as a MRIO table, but can be converted into one.

(crude oil) and secondary energy (diesel, electricity). In this way the total amount of energy computed as energy footprint (2.3 GJ = 0.4 GJ + 0.9 GJ + 1 GJ) would be greater than the actual primary energy (1 GJ).

As argued before, this situation applies to all energy carriers produced from primary energy products (e.g. refined petroleum products from crude oil, coke-oven coke from coking coal, charcoal from fuelwood, electricity from fossil fuels, heat, etc.).

3. Methodology

The paper has two main objectives. First, it intends to shed light on how often double accounting occurs in MRIO-based energy analyses. Second, it seeks to show how double accounting affects the results and the insights derived from them.
This section describes the methods used to identify the studies incurring in double accounting and to quantify the bias introduced by such practices.

3.1. Search and selection strategy, and identification of studies incurring in double accounting

In order to identify studies incurring in double accounting, we looked for relevant papers in Scopus using the following search terms:

- KEY(energy AND ("input-output" OR footprint OR embodied)) AND ALL(EXIOBASE OR WIOD OR GTAP OR EORA)

This search identified peer-reviewed studies that have the term 'energy' and at least one in the "input-output, footprint, embodied" set of keywords. Since the focus is on MRIO databases, the papers needed to mention at least one of the most widely used ones:

EXIOBASE, WIOD, GTAP and EORA (ICIO OECD was not considered due to the lack of energy extensions). The search was conducted on 12.02.2020 and yielded 273 results.

The set of 273 of studies includes several studies that are not focused on energy, are not peer-reviewed (e.g. book chapters, conference proceedings) and do not use the aforementioned databases. After screening the titles and abstract of the 273 studies, we identified 67 that are peer-reviewed and combine MRIO databases and energy extensions. WIOD is the database most used in the relevant studies (34), followed by EORA (14), EXIOBASE (12) and GTAP (7).

Each of these studies was analysed by two authors independently to identify the energy extension used and whether double accounting occurs. Among the studies that use the GES, GEU or EREU[2] extensions to calculate or decompose the temporal change of energy footprints or energy embodied in trade, we flagged those that consider all the (primary and secondary) energy products included in the extensions. In those cases where the study focuses on a specific energy product or on a set of primary energy products, it was assumed that there is no double accounting. Disagreements over the analysis were resolved jointly by the authors.

3.2. Effects of double accounting

Energy assessments that take a consumption perspective can be used to provide insights on a variety of issues. For instance, they can be used to calculate the energy footprint of a country and to monitor its evolution over time. They can also be used to calculate the net energy embodied in trade at the national level. At a more detailed level, this type of assessments can be used to calculate the energy footprint of specific product groups or consumption clusters and to identify the main energy use hotspots.

[2] While by definition the use of EREU would not lead to double accounting because it only considers energy products that are combusted, the extension in WIOD includes electricity use and heat.

In order to understand how double accounting can affect the results of energy analyses, we computed a number of relevant indicators using the NEU and GEU extensions, and compared the resulting figures. Given that we did not find studies using the GES extension, we restricted the comparison to NEU and GEU. The database selected for this exercise is EXIOBASE v3.7 (Stadler et al. 2018), since it is the only one that contains publicly available NEU and GEU extensions.

The comparison of the results was done at three levels: national, industry and consumption cluster. At the national level, we calculated energy footprints for the years 2000 and 2010, and energy embodied in trade for 2010 for the 44 countries and 5 rest-of-world regions represented in EXIOBASE (equations 4, 5 and 6).

The total GEU/NEU of a country *i* is obtained directly from the environmental extensions by summing the direct energy use (*f*) of all energy carriers (*k*) by national industries (*j*) and the direct energy use by national final consumers (*h*).

$$geu_i = \sum_{j,k} f_{i,j,k}^{GEU} + \sum_{j,k} h_{i,j,k} \qquad (4a)$$

$$neu_i = \sum_{j,k} f_{i,j,k}^{NEU} + \sum_{j,k} h_{i,j,k} \qquad (4b)$$

The gross/net energy footprint (*gef, nef*) of country *i* is the product of the row vector energy intensity (*s*) by industry and country (in TJ per million €), the Leontief inverse matrix (*L*), and the vector of final demand (*y*) of country *i*, plus the energy use by final consumers (*h*) in country *i* [3]. Depending on the energy extension used (NEU or GEU), the expressions for the calculation of the energy footprint would be:

[3] In the equations, bold upper case letters, bold lower case letters and non-bold lower case letters are used to represent matrices, vectors and scalars respectively.

$$gef_i = \boldsymbol{s}^{\boldsymbol{GEU}}\, \boldsymbol{L}\, \boldsymbol{y_i} + h_i \quad (5a)$$

$$nef_i = \boldsymbol{s}^{\boldsymbol{NEU}}\, \boldsymbol{L}\, \boldsymbol{y_i} + h_i \quad (5b)$$

Finally, the gross/net energy embodied in trade (*geet*, *neet*) is a function of the energy footprint and the domestic energy use. These ratios show the extent to which a country is a net importer or exporter of energy. For instance, a value of 100% in equation 6b shows that *nef* is twice as high as *neu*. Under these conditions, the country is a net importer of energy, since the energy use induced by its final consumption is higher than the energy used by the domestic industries and final consumers. Negative values show the opposite, i.e. the energy use induced by the domestic final consumption of goods and services is lower than the energy used by the domestic industries and final consumers, which makes that country a net exporter of energy.

$$geet_i = 100 * \frac{gef_i - geu_i}{geu_i} \quad (6a)$$

$$neet_i = 100 * \frac{nef_i - neu_i}{neu_i} \quad (6b)$$

The energy footprints were also calculated at industry and consumption cluster level. For the latter, we allocated the footprints of industries to the main consumption categories represented in the 'Classification Of Individual Consumption by Purpose (COICOP) using the allocation matrix in Castellani et al. (2019). Given that the allocation matrix was produced for the European Union (EU), we only calculated the energy footprints at COICOP level for the EU28 Member States represented in EXIOBASE.

Differences in the results were analysed using GEF-to-NEF ratios, as well as to Pearson and Spearman rank correlations. Footprint ratios such as GEF-to-NEF shed light on the relative magnitude of the results obtained when using both extensions. Pearson and Spearman rank correlations show the linear relationship of the results and their ranking.

4. Results

4.1. How common is double accounting in MRIO-based energy assessments?

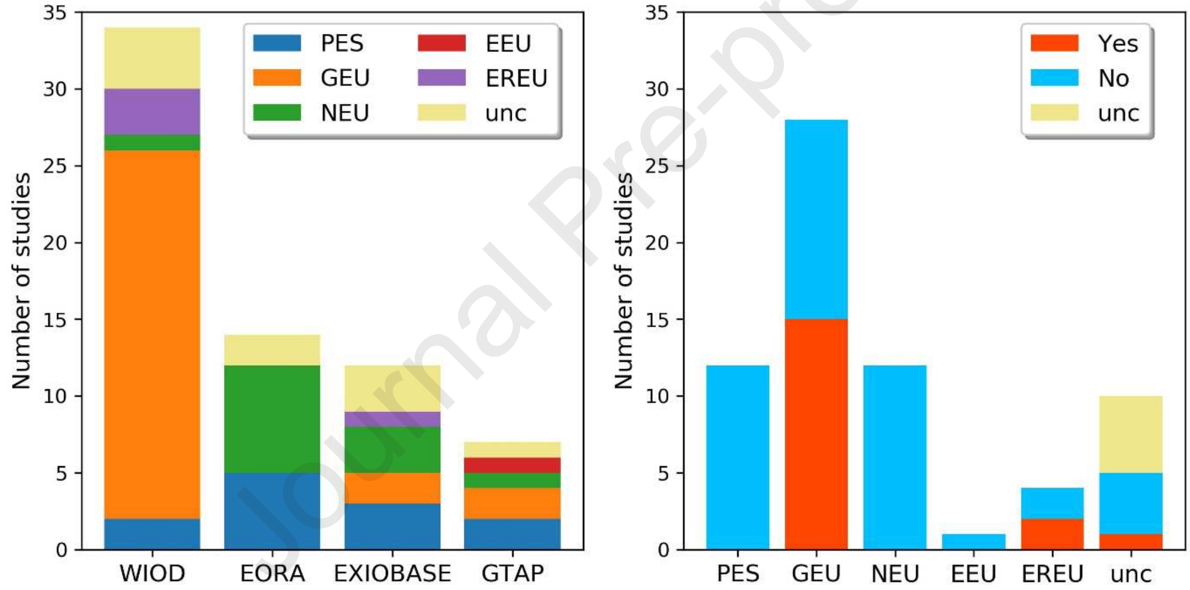
The left side of Figure 1 shows the energy extensions used in the 67 studies identified through the search and selection criteria presented in section 3.1. Most of the studies use the official extensions made available along the MRIO databases. Thus, most WIOD studies use GEU, followed by EREU. In a few cases, the users constructed their own energy extension, which explains the use of NEU and PES. PES is also used in EORA and GTAP despite the data not being part of the official MRIO database. The use of extensions in EXIOBASE is more varied, in line with the wider availability of energy data. In a few cases, it was not possible to identify the extension being used.

The right side of the figure further splits the studies based on whether double accounting occurs or not. As argued previously, in principle, only the use of the GES or GEU extensions can lead to double accounting. In the case of WIOD, the EREU extension also includes electricity and heating, which if not removed when using it, would be problematic. In total we identified 18 studies (27% of total) that seem to incur into double accounting of energy flows. Most of these 18 cases are associated with the misuse of the GEU extension. In four additional cases, we were not able to determine whether double accounting occurs.

Most cases occur in WIOD (16), where an estimated 47% of the studies using the database are potentially problematic (53% if considering the cases where we were not able to determine if double accounting occurred). While many WIOD studies use the GEU extension, many of them have avoided the double accounting problem by focusing on single products such as electricity or primary products such as coal, crude oil, natural gas and renewables. EXIOBASE accounts for the remaining 2 instances. No cases were found in EORA and GTAP. Table 2 sorts the 67 studies reviewed based on the energy extension used and the risk of double accounting. Unclear documentation could lead to misclassification of papers.

Table *2*in the Appendix contains the study-specific information.

Figure 1: Results of the literature review. a) Energy extensions used in selected studies; b) Instances of double accounting per type of extension.



Source: own elaboration.

Note: PES: Primary energy supply; GEU: Gross energy use; NEU: Net energy use; EEU: End energy use; EREU: Emissions-relevant energy use; unc: unclear.

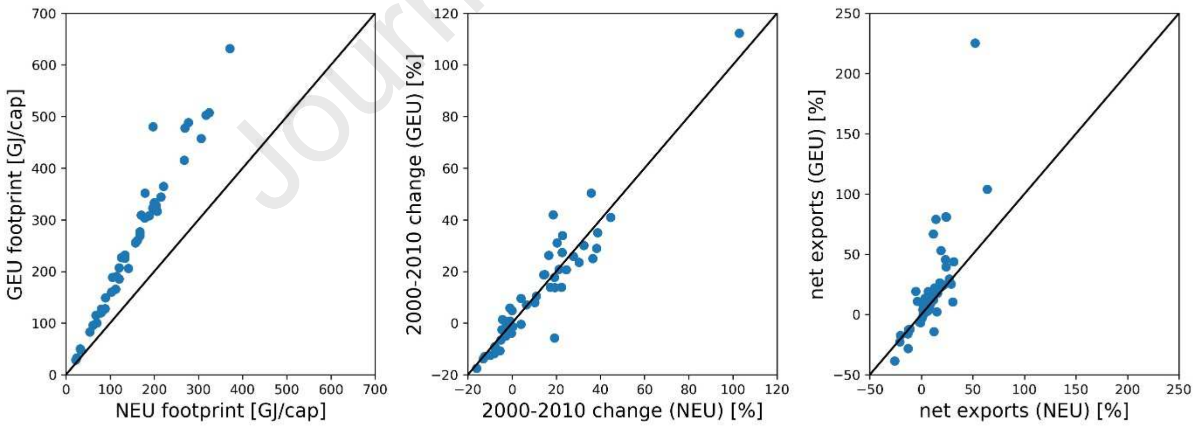
4.2. What are the potential consequences of double accounting?

Figure 2 shows the results of country energy footprints (including temporal change) and energy embodied in trade in 2010 using the NEU and GEU extensions (GEF and NEF respectively). As depicted in Figure 2a, GEF and NEF show high Pearson coefficients in 2010 (R=0.97). Nonetheless, most countries report per-capita GEF values considerably higher than those of NEF. The GEF-to-NEF ratios range from 1.29 to 2.44 depending on the weight of secondary energy products in the supply chains.

The results of the relative change of footprints are also highly correlated (R=0.95), with absolute differences going from -25% to +23% (Figure 2b). In 8 countries (out of 49) relative change shows a different sign depending on the extension used, which gives a conflicting message on whether the country is reducing its energy footprint.

The figures of net energy embodied in trade show a lower correlation than the previous indicators (R=0.77), with differences in absolute differences ranging from -26% to +173% (Figure 2c). In this case, 5 countries switch from being net importers to net exporters (or vice versa) depending on the extension used.

Figure 2: Comparison of country performance using different consumption-based indicators using GEU and NEU extensions. a) Energy footprints, 2010. b) Change in energy footprints, 2000-2010. c) net energy embodied in trade, 2010.

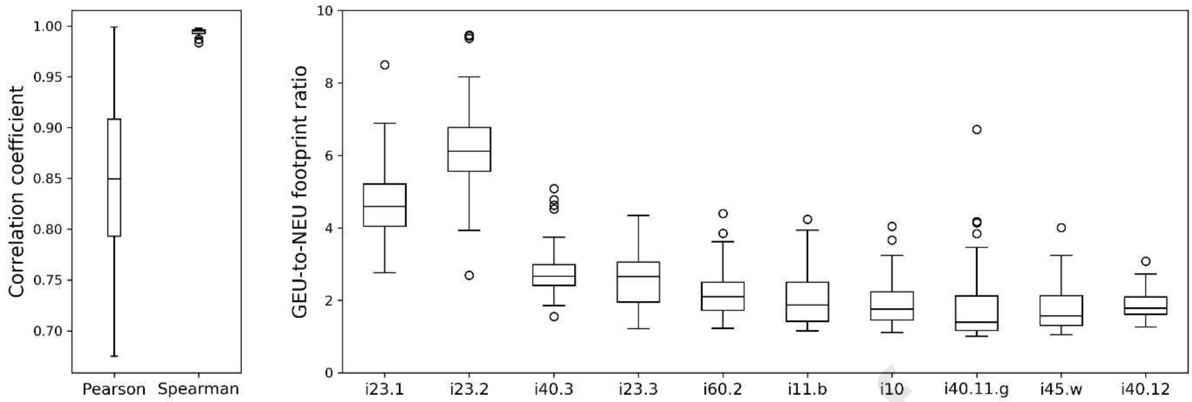


Source: own calculations based on EXIOBASE v3.7.

Footprints by consumption category show a more diverse picture. Consumption categories are represented through the products of 163 different industries, hereinafter referred to as products for readability purposes. Figure 3a shows the Pearson and Spearman rank coefficients of country footprints for each product. Correlations of per-capita GEF and NEF change considerably from country to country, with 29% of countries obtaining R values lower than 0.8 (51% with R<0.85). This indicates that the choice of the extension affects the absolute values of the products differently in some countries. This is, however, not the case with product footprint rankings, which barely differ when different extensions.

Figure 3b focuses on the top 10 products that are most affected by the choice of extension. Not surprisingly, the footprints of coke, refined petroleum products and nuclear fuel (i23.1, i23.2 and i23.3) are among those that are most impacted. In the extension, these industries have low losses when transforming primary energy products into secondary energy products and therefore report NEU values much lower than GEU values. This initial difference in the extension can be offset to a certain extent in the footprint depending on the weight of other energy inputs in the supply chain of those industries. Additional relevant products affected by the selection of the extension are linked to some forms of electricity production and transmission (i40.11g, i40.12), as well as to heat production (i40.3). Other products include terrestrial transportation (i60.2), which relies heavily on refined petroleum products; coal and natural gas (i10 and i11.b), and construction (i45.w). In this context, the GEF of most products in Figure 3b is higher than NEF by a factor of 1.4 to 2.7 (median values). In the case of refined petroleum products and coke the median GEF values are 6.1 and 4.6 respectively.

Figure 3: a) Pearson and Spearman rank correlation coefficients of country footprints at product level, 2010. b) GEF-to-NEF ratio of the top 10 products affected by the change of extension.



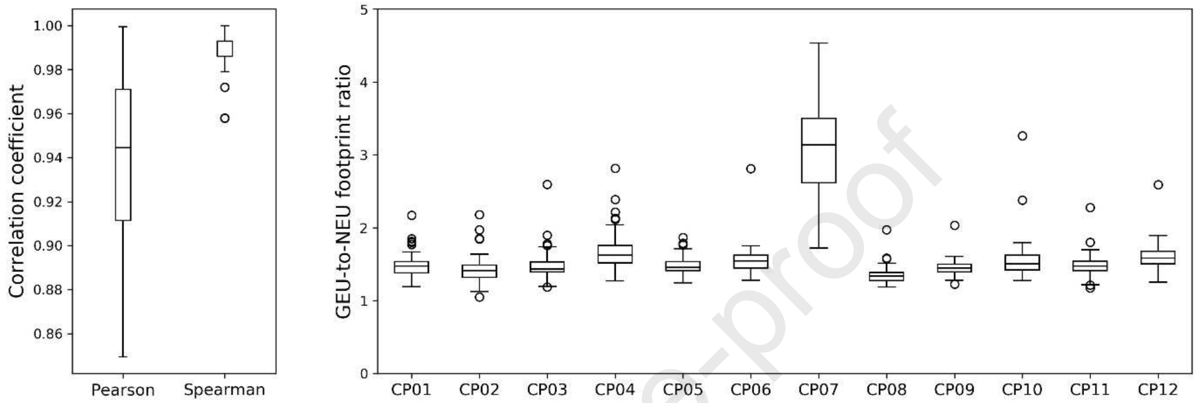
Source: own calculations based on EXIOBASE v3.7.

Note: The selection of the products in figure b is based on the % of countries in which the GEF-to-NEF ratio of a product is among the top 10 affected. This percentage is show within parenthesis after the code in the following lines. i23.1 (100%): Manufacture of coke oven products, i23.2 (100%): Petroleum refinery, i40.3 (88%): Steam and hot water supply, i23.3 (69%): Processing of nuclear fuel, i60.2 (51%): Other land transport, i11b (39%): Extraction of natural gas and services related to natural gas extraction, excluding surveying, i10 (27%): Mining of coal and lignite; extraction of peat, i40.11.g (27%): Production of electricity by biomass and waste, i45.w (27%): Re-processing of secondary construction material into aggregates, i40.12 (24%): Transmission of electricity.

The upper and lower edges of the rectangle represent the 75th and 25th percentiles, while the top and bottom markers represent the maximum and minimum values excluding outliers. The latter are represented with circles.

The ranking of the products that are most affected by the choice of the extension depends on the product resolution of the MRIO database. For instance, if all the products in i23 and i40 were represented in two single groups (as it is the case in WIOD for instance), we would see a different set of products in Figure 3b. To better understand how the results are impacted, we have represented the same information by aggregated consumption categories in COICOP classification (Figure 4). The picture is somehow similar. The GEF and NEF of the COICOP categories show relatively high Pearson coefficients and very high Spearman coefficients (Figure 4a). This suggests that the selection of the extension has limited effects on rankings, but that it affects the absolute values of the COICOP categories differently in some countries. Transport and housing are the categories that show highest GEF-to-NEF ratios (Figure 4b). The former is particularly affected, since the GEF values are 3.1 times higher than NEF values (median value), but can be up to 4.5.

Figure 4: a) Pearson and Spearman rank correlation coefficients of country footprints at COICOP level, 2010. b) GEF-to-NEF ratio of COICOP categories.



Source: own calculations based on EXIOBASE v3.7.

Note: CP01: Food and non-alcoholic beverages, CP02: Alcoholic beverages, tobacco and narcotics, CP03: Clothing and footwear, CP04: Housing, water, electricity, gas and other fuels, CP05: Furnishings, household equipment and routine household maintenance, CP06: Health, CP07: Transport, CP08: Communications, CP09: Recreation and culture, CP10: Education, CP11: Restaurants and hotels, CP12: Miscellaneous goods and services.

The upper and lower edges of the rectangle represent the 75th and 25th percentiles, while the top and bottom markers represent the maximum and minimum values excluding outliers. The latter are represented with circles.

5. Discussion

The previous sections have shown that there are several possibilities to undertake energy footprinting and related analyses with MRIO databases. Users often choose among the databases on the basis of factors such as country and time coverage and/or industry/product resolution. After doing so, they can either use the energy extensions available or produce their own, which is not completely unusual. This offers the users of MRIO databases options beyond those shown in Table S1.

While having more options is arguably good, as we previously hypothesised, it can also lead to confusion among less experienced users, resulting in misleading or, at least, biased messages. Our review confirms that a relevant number of studies has potentially incurred in some type of double accounting of energy flows. Out of the 67 studies included, 27% were flagged as potentially problematic, usually because they used the GEU extension without correcting it to avoid representing the energy inputs and outputs of transformation processes at the same time. Most of the cases of double accounting occurred when using WIOD; EXIOBASE accounted for the rest. These figures could vary slightly due to errors we might have made in the identification of the extensions used or when determining whether a specific study had double accounting. Such errors are most likely linked to poor documentation and inconsistent use of key energy terms in the studies. When possible, we have tried to overcome this situation by comparing the values reported in the studies with those in the original MRIO databases.

The effects of double accounting when using the GEU instead of the NEU extension vary considerably depending on the specific research question to be answered. For instance, rankings of nation and product footprints appear to be very insensitive to the choice of the extension. Nonetheless, there are several cases in which countries move from being net exporters to net importers of energy and from reducing to increasing their energy footprints (or vice versa). This shows the extent to which conflicting messages can arise at the country level when misusing energy extensions. At the product level, absolute footprints are affected differently between countries. This depends on the weight of secondary energy products in the supply chains of the product being assessed. Consequently, refined oil products, heat, coke oven products and road transport are among the most affected products. It is expected that the list of most affected products will differ between MRIO databases, and depending on whether supply and use or IO tables are used to calculate footprints (Lenzen and Rueda-Cantuche 2012). After all, they have different industry/product resolutions and this has been shown to affect the absolute values of product footprints (Steen-Olsen et al. 2014; de Koning et al. 2015). This bias is partially avoided when looking at the energy footprints of consumption clusters such as COICOP categories. What seems clear is that the main insights provided by a MRIO-based energy assessment can be affected if the user incurs in double accounting of energy flows. Our analysis has used EXIOBASE to approach this problem generically, but the specifics will depend on the focus of the assessment (e.g. geographical scope, product resolution, target production category, etc.).

5.1. Recommendations for data users

Data users can do two things to avoid this problem: either choose a MRIO database that contains energy extensions that can be used directly in the analysis or adapt/create the energy extensions for a given MRIO database. Commonly, the first option involves the use of PES or NEU and would therefore be suited for MRIO databases that already contain that information. PES and NEU record energy only once, either at the point of extraction or at the point where it is used or lost. Hence, both PES and NEU extensions are suitable – as opposed to GEU and GES – to calculate energy footprints. This statement is also valid for subsets of NEU such as EEU.

In this context, it is important to bear in mind that PES- and NEU-based footprints provide different insights and are therefore meant to answer different research questions. As explained by Owen et al. (2017), PES can be used as an extension to address energy security and geopolitical issues, since the resulting footprint can be disaggregated to show the origin of the primary energy carrier that has been either used in its original form or as secondary product. NEU, on the other hand, is more suited to explore issues related to energy efficiency in energy and non-energy industries, given that the extension records the direct energy use by industries and the losses incurred during transformation, storage, distribution and so on. While the effects of changes in final demand in consumption-based energy indicators can be modelled using both PES and NEU extensions, the latter represents the direct energy use by households and thus, it allows for a more comprehensive assessment of behavioural change, especially when the direct energy consumption is split by purpose (e.g. cooking, heating, appliances, etc.).

EREU has also been used a few times in energy assessments. EREU also records energy use once – at the point of combustion – and therefore does not lead to double accounting. EREU can be an interesting option if the assessment focuses on the drivers of air emissions, although most users use the air emission extensions directly to compute carbon footprints and other air emission footprints.

The second option is to customise an existing energy extension or to create a new one, although the latter can be challenging and time consuming for less experienced users. We have argued that because GEU records energy both before and after transformation (e.g. coal and electricity, crude oil and refined petroleum products such as diesel, gasoline or kerosene), it should not be used as given to calculate indicators such as energy footprints or energy embodied in trade.

Some users only select the data of primary energy products or focus on single energy products such as electricity or natural gas, thereby avoiding the double accounting problem. This is not to say that GEU and GES as a whole do not provide useful information. In fact, the concept of gross energy is very useful for modelling purposes (Koesler and Pothen 2013; Kratena et al. 2013; Igos et al. 2015; Koesler and Schymura 2015), since it resembles the structure of the supply and use tables in the System of National Accounts and the production functions used in models.

All in all, users should become familiar with the risks associated with using some energy extensions and consider this when selecting the energy data to be used.

5.2. Recommendations for data producers

There is also a role to be played by the producers of data in order to simplify the choices to be made by the users. After all, the environmental extension has been identified as the most relevant explanatory factor of the numerical differences in carbon footprints of different MRIO databases (Moran and Wood 2014; Owen et al. 2014). Because most carbon emissions result from the combustion of energy products, it is reasonable to assume that energy extensions would also be a key contributing factor to different results in MRIO-based analyses.

A relevant – but often overlooked – methodological aspect affecting use-based extensions such as GEU, NEU or EREU refers to the system boundaries adopted when constructing the accounts. Use-based extensions should be fully aligned with the System of Environmental-Economic Accounting (SEEA) (UN 2015). The SEEA is the environmental counterpart to the System of National Accounts (EC et al. 2009), which provides the accounting rules to structure the monetary IO tables. In practice, this means that energy accounts should be based on the residence principle (i.e. cover the activities of the residents of the country) instead of the territory principle (i.e. cover the activities that take place within the country; followed in the energy balances of the International Energy Agency). As shown by Usubiaga and Acosta-Fernández (2015), this affects considerably the air emission extensions – and therefore the energy extensions – of multiple countries. MRIO databases like EORA and GTAP do not seem to arrange their energy extensions according to these rules. How originally misreported industrial energy use data is handled (Fujimori and Matsuoka 2011) can also be relevant when constructing energy extensions.

Because of the technicalities involved in the generation of energy extensions, in the short-term, a harmonisation of the energy data across MRIO databases led by experts – similar to the process facilitated by the International Resource Panel in relation to material flow accounts (IRP 2019) – could benefit the user by simplifying the choices to be made and foster the policy uptake of energy footprints, and by extension of carbon footprints. This could bridge the data gap until the majority of national statistical offices report comparable energy flow account data on a regular basis. Eurostat and the OECD are particularly well suited to lead a process in which the reporting of standardised energy accounts by countries becomes the norm, rather than the exception.

6. Conclusions

The irruption of environmentally-extended MRIO databases produced by academics led to a fast increase in energy footprinting and related studies in the last decade. These studies used a variety of energy extensions. Some of them were made available along these MRIO databases, while others were collated by the users themselves.

The wide availability of data allowed assessing the energy profiles of consumption from different angles, but also resulted in the misuse of some extensions leading to double accounting of energy flows. The problem of double accounting has been referred to in a few publications in recent years, but its extent or the actual effects in the results were so far unknown. To that end, this paper reviewed 67 studies, a quarter of which accounted for some energy flows twice. Most cases where doubling accounting occurred were related to the (mis)use of the GEU extension.

While it is not possible to document the actual implications in the problematic studies without replicating them, this paper adopted a pragmatic approach to understand the effects of double accounting. By calculating a series of footprint indicators using both GEU and NEU extensions, we showed that the double accounting does have an impact on the results, potentially leading to biased conclusions. This is particularly relevant for the sectors that use secondary energy products. Country and sector rankings, on the other hand, seem to be relatively insensitive to double accounting.

Our results show that the effects of double accounting are by no means negligible. Users can avoid potential problems by carefully selecting environmental extensions and/or adapting them when necessary. There is also room for data producers to simplify the choices of the users. Harmonisation of the energy extensions across MRIO databases would be a useful first step.

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Appendix

Table 2 sorts the 67 studies reviewed based on the energy extension used and the risk of double accounting. Unclear documentation could lead to misclassification of papers.

Table 2: Uses of energy extensions in MRIO databases

Database	Energy extension	No double accounting	Risk of double accounting	Unclear
WIOD	Primary energy supply	Rocco and Colombo (2016b, 2016a)	-	-
	Gross energy use	Bortolamedi (2015); Cortés-Borda et al. (2015b, 2015a); Kucukvar et al.	Kucukvar and Samadi (2015); Xia et al. (2015); Andreoni (2017); Kaya (2017);	-

		(2016); Liu et al. (2016); Tang et al. (2016); Zhong (2018); Kucukvar et al. (2019); Wang and Song (2019); Ezici et al. (2020); Wang et al. (2020)	Deng et al. (2018); Liu et al. (2018c, 2018a, 2018b); Chen et al. (2019); Tian et al. (2019); Jiang et al. (2020); Liu et al. (2020b, 2020a)	
	Net energy use	Arto et al. (2016)	-	-
	Emission-relevant energy use	Wang et al. (2017)	Gasim (2015); Zhang et al. (2019)	-
	Unclear	Guevara et al. (2019)	Tao et al. (2018)	Aşıcı (2015); Kaltenegger et al. (2017)
EORA	Primary energy supply	Chen and Wu (2017); Wu and Chen (2017b, 2017a); Hong et al. (2019); Wu and Chen (2019)	-	-
	Net energy use	Schandl et al. (2016); Akizu-Gardoki et al. (2018); Rocco et al. (2018); Lam et al. (2019); Lundie et al. (2019); Wu et al. (2019a); Wu et al. (2019b)	-	-
	Unclear	Chen et al. (2018)	-	Lan et al. (2016)
EXIOBASE	Primary energy supply	Min and Rao (2018); Font Vivanco et al. (2019); Kan et al. (2020)	-	-
	Gross energy use	-	Freire-González (2017); Freire-González and Font	

			Vivanco (2017)	
	Net energy use	Simas et al. (2015); Vita et al. (2019); Usubiaga-Liaño et al. (2020)	-	-
	Emission-relevant energy use	Wood et al. (2018)	-	-
	Unclear	Kan et al. (2019)	-	Lang and Kennedy (2016); Joyce et al. (2019)
GTAP	Primary energy supply	Sato et al. (2017); Kan et al. (2019)	-	-
	Gross energy use	Chen and Chen (2011); Cui et al. (2015)	-	-
	Net energy use	Mi et al. (2018)	-	-
	End energy use	Bordigoni et al. (2012)	-	-
	Unclear	Kharrazi et al. (2015)	-	-

Source: own elaboration.

Note: Unclear documentation might result in the misclassification of some papers.

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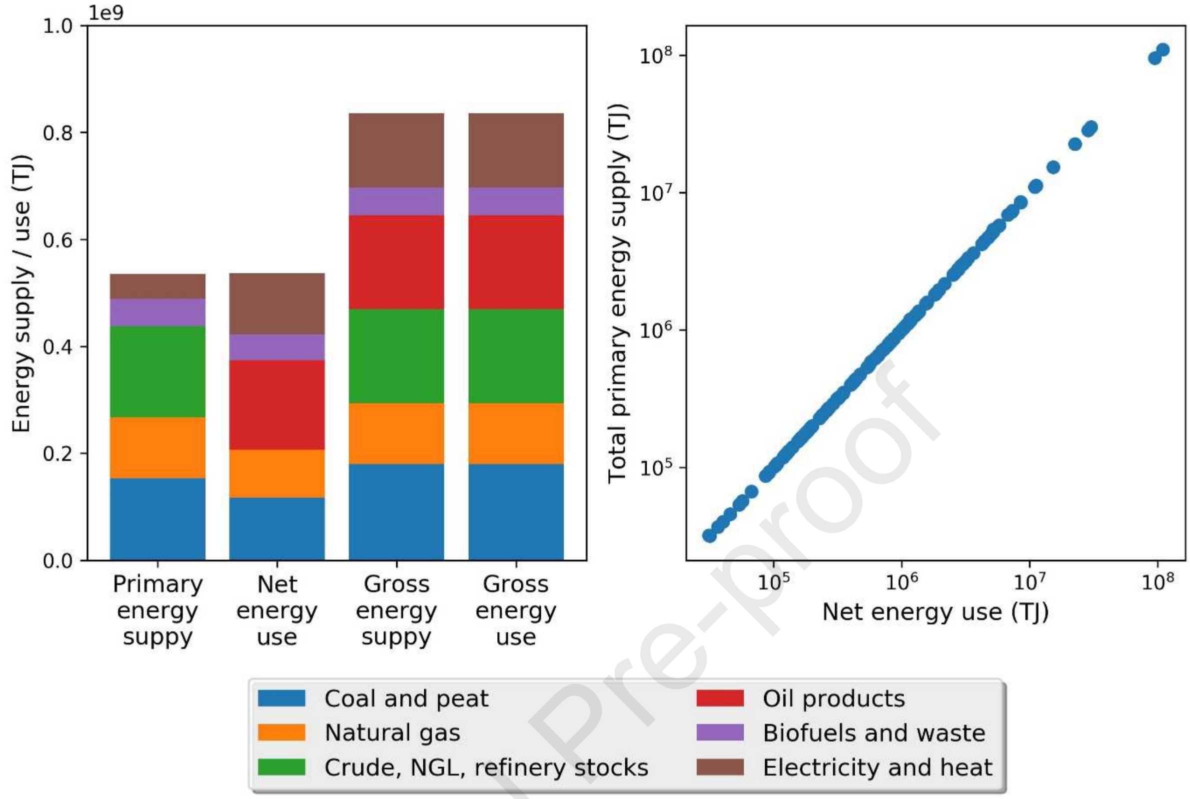
Supplementary material

Energy supply and use indicators

Figure S1 compares selected supply and use indicators at various geographical scales. The left part of the figure shows the global figures for PES, NEU, GES and GEU. Following equations 1 and 3 in the main text, PES equals NEU, and GES equals GEU. The composition of PES and NEU in terms of energy products differs, since the former only comprises primary energy products, while the latter represents the form in which products are consumed by end users (e.g. diesel instead of crude oil, electricity instead of coal). GES and GEU, on the other hand, have the same structure by energy product, since they both account for primary and secondary energy products.

The right hand side of Figure S1 compares TPES and NEU for the 44 countries and 5 rest-of-the-world regions represented in EXIOBASE. As shown in the figure, the total values at country levels match. This equivalence does not happen at energy product level.

Figure S1: Energy supply and use indicators, 2010. (a): Global values for PES, NEU, GES and GEU. (b): Country values for TPES and NEU (*)



Source: own elaboration with data from EXIOBASE v3.7

Note: The left part of the figure represents the world totals for primary and gross energy supply, and net and gross energy use disaggregated by broad energy product groups for the year 2010. The right side of the figure shows the total primary energy supply and net energy use of the 44 countries and 5 'rest of world' regions represented in EXIOBASE.

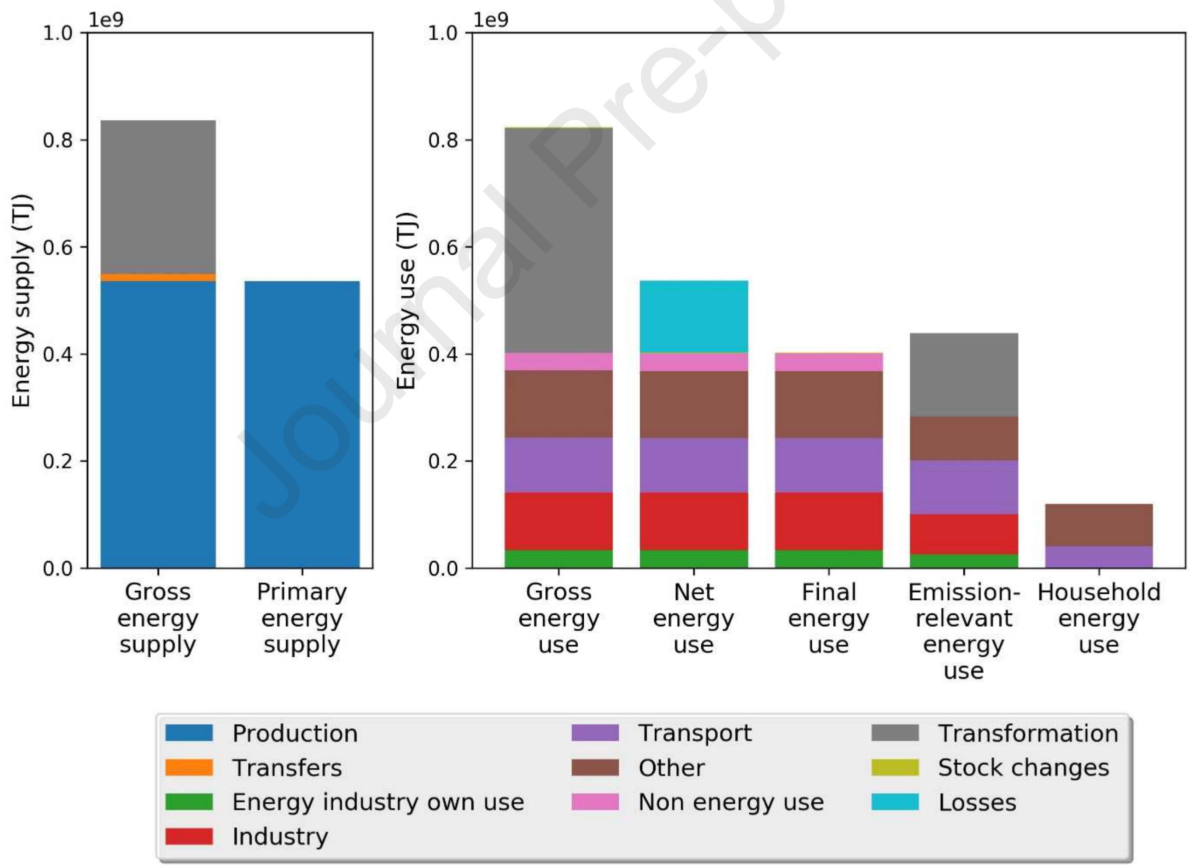
(*): Changes in stocks have been allocated to NEU instead of to TPES.

Figure S2 represents the composition of selected energy indicators in terms of main energy flow categories in the IEA extended energy balances. The figure is based has been extracted from EXIOBASE, which adjusted the IEA data to reconcile trade flows, convert it into the residence principle, etc. There are two main supply-side indicators: PES and GES. PES comprises the (domestic primary) production flow. GES also includes transfers[4] and outputs from transformation processes. As for use-side indicators, GEU

[4] Comprises interproduct transfers (reclassification of products), products transferred (oil products imported for further processing in refineries) and recycled products (finished products which pass a second time through the

covers inputs in transformation process, consumption in the end-use sectors (industry, transport, other) and non-energy uses, as well as energy industry own use. EREU represents a subset of GEU that only considers energy products that are combusted. NEU includes the consumption in the end-use sectors (industry, transport, other) and non-energy uses, as well as energy industry own use and losses. In this line, EEU is a subset of NEU that does not consider losses in transformation, distribution, etc. Last but not least, household energy covers the part of transport and other uses (mainly residential).

Figure S2: Energy use indicators, 2010. (a): Global values for GEU and PES. (b): Global values for GEU, NEU, end use, EREU and household energy use



Source: own elaboration with data from EXIOBASE v3.7

marketing network, after having been once delivered to final consumers).

Note: The left part of the figure represents the worlds totals of supply-side indicators disaggregated by broad energy flow categories for the year 2010. The right part of the figure does the same with use-side indicators. The category 'other' includes energy use in the residential, commercial/public services, agriculture/forestry, and fishing sectors.

Table S1 shows the main indicators that can be calculated from the energy extensions in those five MRIO databases. The table does not cover the industry and energy product resolution, country and time coverage, etc., since this is not deemed relevant for the purpose of the paper. A slightly outdated comparison of the main characteristics of the five MRIO databases can be found in Inomata and Owen (2014).

Table S1: Energy extensions included in MRIO databases

Database	**Energy extensions**	**Source**
EXIOBASE	Primary energy supply Gross energy supply Gross energy use Net energy use [a] End energy use [a] Emission-relevant energy use	Stadler et al. (2018); Mastrucci et al. (2020); Usubiaga-Liaño et al. (2020)
WIOD	Gross energy use Emission-relevant energy use Net energy use [b]	Arto et al. (2016); Corsatea et al. (2019)
EORA	Net energy use [c]	EORA (2017)
GTAP	Gross energy use	McDougall and Lee (2008)
ICIO	None	-

Source: own elaboration.

[a]: Available in the upcoming v3.7 public release.

[b]: Not available in the official release.

[c]: Inadequately termed total primary energy supply in the original source

Double accounting in energy footprint and related assessments: how common is it and what are the consequences?

Highlights

- Overview of energy extensions in multi-regional input-output (MRIO) analysis
- Review of MRIO-based energy assessments
- Identification of double accounting in MRIO-based energy assessments
- Quantification of how results are affected by double accounting
- Recommendations for energy extension producers and users

Declaration of interests

☒ The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

☐The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: