Energy use flows in the supply chains of the world economy: A full account of both primary and intermediate inputs

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Abstract

As an extension of our previous work (Wu et al., 2019b), this study uses a positive accounting manner to track the circulation of energy use via interregional trade, by taking a full account of indirect energy usage related with primary inputs as well as intermediate inputs. The aggregate amount of interregional shift of energy use is about six times larger than that recorded

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in the preceding work, revealing the robust flows of energy use associated with intermediate products traded across global supply chains. The United States is a crucial sink of energy use in the world, serving the leading net importer of energy use in final trade and the second biggest net importer in intermediate trade. Around 60% of the energy use initiated by its final consumption stems from other regions. For Mainland China as the third largest net importer of energy use in intermediate trade and the leading net exporter in final trade, around 60% of local primary energy exploitation sinks into final consumption abroad. For sustainable economic growth and efficient energy management, countries are recommended to be further integrated in the international supply chains by accurately pinpointing their roles in the trading market of energy use.
Keywords: Biophysical support, positive accounting, world economy, trade imbalance, global supply chain

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1. Introduction

Energy products, primarily crude oil, raw coal and natural gas, have long been highlighted as the mostly traded commodities between regions (IEA, 2017b). Following the shocking downfall of international oil price in 2014, policy attention on regional energy security is expanding with the awareness of the increasing dependence on transregional trade in obtaining energy resources (Dixon et al., 2010; Wiedmann et al., 2015). A region with limited energy resources, such as Japan, may rely heavily on importing both energy products and other traded commodities as energy carriers from other regions to satisfy domestic energy demand. Nowadays, all world regions are interconnected in a single economic entity, namely the world economy (Wu et al., 2020). Robust development of technology has significantly accelerated the speed of communication and transport, which largely promotes regional specialization. A global supply chain has come into shape, along with the spatial separation of resources exploitation, product reprocessing, production, assembly and consumption (Meng et al., 2018; Mi et al., 2019). Taking the iPhone product as an example, over 700 suppliers across the 30 countries provide components for an iPhone product before it is ultimately assembled in the Foxconn factories in China, according to Chen et al. (2017). In the near future, more and more products will be made on the globe instead of being manufactured in a single nation or region due to regional specialization.

The high integrity of the world economy will not only result in the high-profile monetary trade imbalance between regions (Groenewold and He, 2007; Trump, 2018), but also the re-allocation of ecological elements (Ji et al., 2020; Mi et al., 2017; Shao et al., 2017; Su et al., 2013; Tian et al., 2020). A region may acquire primary energy use from abroad by outsourcing the energy-intensive industries. To be more specific, apart from the direct imports of energy products, a region may acquire energy use from foreign nations and regions indirectly by importing the energy-intensive products (Tang et al., 2019; Shao et al., 2018; Zhang et al., 2017). By analyzing the drivers of the changes in energy footprints of the world economy, Lan et al. (2016) found out that affluent nations have been constantly receiving imports of energy-intensive commodities from abroad. Due to the highly frequent interregional trade, energy embedded in the traded products could turn out to reach a remarkable amount (Jiang et al., 2020; Yang et al., 2014). According to Chen and Wu (2017), energy embodied in international trade takes more than 90% of the world's total energy use. Similar accountings have been conducted for China (Zhang et al., 2016), the United Kingdom (Tang et al., 2013), Italy (Cellura et al., 2011), South Korea (Park and Heo, 2007), Thailand (Limmeechokchai and Suksuntornsiri, 2007), India (Pachauri and Spreng, 2002) as well as urban regions (Wang et al., 2017; Wang and Chen, 2016; Li et al., 2016) to reveal the cross-border transfer of energy use. Differing from onsite energy accounting that reflects the onsite information only, most of these studies mentioned above assign the onsite energy use to the products used for final demand, thus being able to reflect the flows of energy use via international exchange of final products. A normative accounting manner in terms of final-demand-based framework is adopted in most of these works by considering final demand as the engine of the economic system (Chen et al., 2019).

While the final-demand-based accounting framework is very helpful in establishing point-to-point linkages between direct energy use and the specific agents, the circulating process of the energy use flows across global supply chains is mostly neglected. Objectively speaking, for any sectoral product, energy use is required directly and indirectly in its production processes, whether it is afterwards used for intermediate production or final demand. When the product is traded to another region, the energy use hidden in the product also flows across the borders and keeps circulating along the global supply chains before sinking into final consumption. The final-demand-based framework attaches importance only to the interregional displacement of energy use caused by the exchange of final goods and pays little attention to the energy use flows associated with the traded intermediate goods. The truth is that, with the global supply chain being intricately sliced up, international trade is largely driven by exchange of intermediate products, which are reported to take up around 70% of the total volume of world trade and largely outnumber the trade volume of final products (Johnson and Noguera, 2012). Given that, it is also essential to provide an objective measurement of the circulation of energy use along global supply chains.

Dating back to the occurrence of the first oil crisis in the 1970s, Herendeen (1973) firstly raised a positive accounting framework to objectively depict the circulation of energy use within the economic network, under the support of an established biophysical balance model of energy use. A series of pioneering works on energy accounting supported by national input-output accounts have been then carried out by Bruce Hannon, Robert Herendeen and Clark Bullard (all affiliated to the energy research group in the University of Illinois) for the United States economy for the year 1963, 1967 and 1972, respectively (Bullard and Herendeen, 1975; Hannon, 2010; Herendeen, 1978, 1981). Shortly afterwards, by a combination of ecology and economics, Costanza (1980) examined the total energy requirements of the entire production process and service industry in the United States. During the last decade, Chen and his colleagues has presented a series of energy overviews of the global regions for the year 2004 (Chen and Chen, 2011), 2007 (Chen and Chen, 2013), 2010 (Chen and Wu, 2017) and 2012 (Wu and Chen, 2017) respectively. In these accountings, the direct energy inputs are mostly taken as the primary energy resources exploited as biophysical support from the environment, while energy embodied in the intermediate products is treated as the internal feedback within the economic system and may keep circulating along the supply chains before final use (Brown and Herendeen, 1996; Herendeen, 2004; Wu et al., 2021). Following the demand-pull principle, the primary energy exploited is allocated to those products that are presented to society as final demand, which serve as the sink of energy use.

Whereas, a compromise seems to have been made in the abovementioned embodied energy accountings for the world economy. Final products take inclusion of both the consumer goods, namely the products used for consumptive purposes (namely consumption by households, government and non-profit organizations), and the capital goods. What that could be treated as truly "consumed" and ultimately leaving the economic system are those products used for consumptive purposes, which also corresponds to Adam Smith's classical saying that consumption should be taken as the sole aim of all production (Smith, 1776). For the capital goods, though they are presented to society as final products, they are bound to re-participate in the production system as primary inputs to support the producing process (Wu et al., 2018, 2019a). Actually, capital goods have been long acknowledged by many classical and neo-classical economists, such as Smith (1776) and Mill (1821), as the indispensable means to guarantee economic production. Seeing that the capital goods are not genuinely consumed, Wu et al. (2019b) has previously raised a normative manner in terms of total-consumption-based accounting framework that locates the genuine final consumption as the impetus of the economic system. While that work is appreciated for shedding light on the corresponding relations between direct energy expenditure and the genuine final consumption, it is based on a point-to-point linkage and leaves out the complex production processes across the supply chains of the world economy. To objectively reflect the circulating process of energy utility flows within the economic system, it appears to be necessary to incorporate the whole supply chains by taking into account of indirect energy feedbacks related to not only intermediate inputs but also primary inputs.

As an extension of our previous work (Wu et al., 2019b), this study raises a positive manner to track the process of energy use flows across the global supply chains, with a full account of the indirect energy feedbacks related to both primary inputs and intermediate inputs. Through a positive accounting model aided by energy statistics and a multi-region input-output (MRIO) account, an overall picture for the flows of energy use from the source (extraction) to sink (final consumption) through the channels of interregional trade is depicted. Energy use flows associated with intermediate trade, final trade and trade balance are displayed at length. Besides, sustainability of energy use of regions is discussed by introducing indicators in terms of source-based and sink-based energy self-sufficiency rates.

2. Methodology and data

2.1. Energy accounting model

By giving full attention to the indirect energy usage related to primary and intermediate inputs in the supply chains, a positive accounting framework for energy use is developed in this study based on the one proposed in previous works (Chen and Wu, 2017; Wu and Chen, 2017). A detailed comparison of these two models is described in SI-A (supporting information), together with the schematic diagrams illustrated and the basic mechanisms explained.

For the energy accounting model in this work, the biophysical energy balance for a sector in the global economy incorporates primary energy exploitation (zero for non-energy-exploitation sectors) as the exogenous energy inputs as well as the indirect energy usage related to both the intermediate and primary inputs. The corresponding algorithm is described as below:

For the global economic system as denoted by the multi-region input-output table, it is modelled as a system comprised of m regions, each consisting of n economic sectors. Figure 1 enunciates the detailed energy balance for the i_{th} sector of the r_{th} region. An explanation of the parameters is as follows: $e_i^r \left(= \sum_{k=1}^{t} e_{ki}^r\right)$ denotes the total amount of the different kinds of

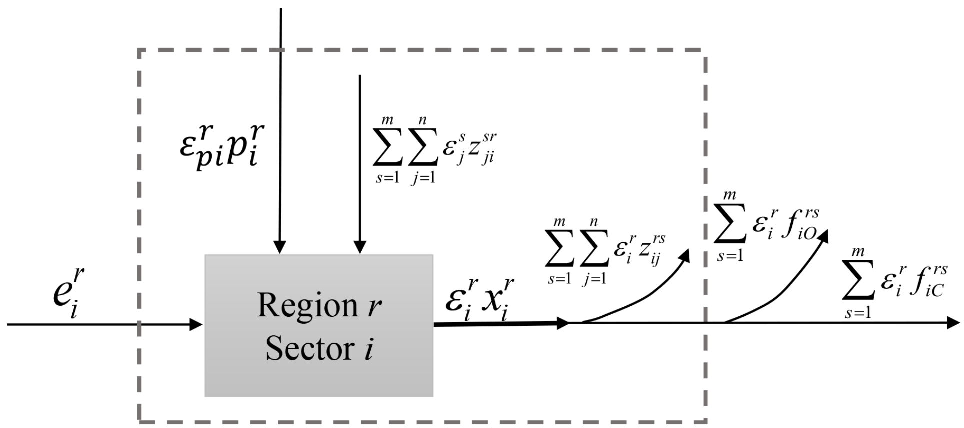


Figure 1: Energy use flows for the i_{th} sector of the r_{th} region in the global economic system

genuine energy inputs provided by the environmental system; p_i^r implies the total primary inputs flowing into the i_{th} sector of the r_{th} region; z_{ji}^{sr} stands for the intermediate inputs, denoting the monetary cost of products flowing from the j_{th} sector of the s_{th} region to the i_{th} sector of the r_{th} region; x_i^r is the total output of the i_{th} sector of the r_{th} region; f_i^{rs} stands for the goods or services produced by the i_{th} sector of the r_{th} region that are used as final demand in the s_{th} region, which comprises f_{iC}^{rs} as the products generated by the i_{th} sector of the r_{th} region that are used for final consumption in the s_{th} region, and f_{iO}^{rs} as the products generated by the i_{th} sector of the r_{th} region that are used in the s_{th} region as the rest of final demand, namely the capital goods such as products used as fixed capital formation and inventory increase; ε_i^r is the energy intensity of the sectoral output by the i_{th} sector of the r_{th} region; ε_{pi}^r is the energy intensity of primary inputs of the i_{th} sector of the r_{th} region.

Hence, the energy balance for the i_{th} sector of the r_{th} region could then be established as:

$$e_i^r + \varepsilon_{pi}^r p_i^r + \sum_{s=1}^{m}\sum_{j=1}^{n} \varepsilon_j^s z_{ji}^{sr} = \varepsilon_i^r x_i^r, \tag{1}$$

where $\varepsilon_{pi}^r p_i^r$ denotes the energy that is embodied in the total primary inputs into the i_{th} sector of the r_{th} region; $\sum_{s=1}^{m}\sum_{j=1}^{n} \varepsilon_j^s z_{ji}^{sr}$ denotes the energy that is embodied in all the intermediate inputs coming from all the economic sectors within the world economy into the i_{th} sector of the r_{th} region.

For the entire economic system covering m world regions and n economic sectors, a matrix equation could be obtained as:

$$\boldsymbol{E} + \boldsymbol{\varepsilon_p}\hat{\boldsymbol{P}} + \boldsymbol{\varepsilon}\boldsymbol{Z} = \boldsymbol{\varepsilon}\hat{\boldsymbol{X}}, \tag{2}$$

where $\boldsymbol{E}$ is the $1 \times mn$ row vector for e_i^r; $\hat{\boldsymbol{P}}$ is the $mn \times mn$ diagonal matrix for $\boldsymbol{P}(=[p_i^r]_{1\times mn})$; $\boldsymbol{Z}$ is the $mn \times mn$ matrix for z_{ij}^{rs}; $\hat{\boldsymbol{X}}$ denotes the $mn \times mn$ matrix for $\boldsymbol{X}$; $\boldsymbol{\varepsilon_p}$ represents the $1 \times mn$ row vector corresponding to ε_{pi}^r; $\boldsymbol{\varepsilon}$ is the $1 \times mn$ row vector for ε_i^r.

For the global economy, energy embodied in the capital goods and that embodied in primary inputs also reach a balance, as clarified in detail in some existing works (Wu et al., 2018, 2019a). The corresponding equation could be established as:

$$\sum_{r=1}^{m}\sum_{i=1}^{n} p_i^r \varepsilon_{pi}^r = \sum_{r=1}^{m}\sum_{i=1}^{n}\sum_{s=1}^{m} \varepsilon_i^r f_{iO}^{rs}. \tag{3}$$

Currently, it is not feasible for us to distinguish the energy intensity of the primary inputs by sector, given the knowledge of the relation between the primary inputs and final demand is lacking. A simplified treatment is therefore made that all the primary inputs, regardless of the type or sectoral difference, are assumed to have the same embodied energy intensity (Wu et al., 2018), ε_{pl} (a scalar). Eq. (3) could be thus reduced as:

$$\boldsymbol{\varepsilon_{pl}} P_{\text{sum}} = \boldsymbol{\varepsilon F_O}, \tag{4}$$

where P_{sum} is a scalar representing the sum of the primary inputs into all the investigated sectors; $\boldsymbol{F_O}$ is the $mn \times 1$ column vector for capital goods.

By integrating Eq. (4) into Eq. (2), the matrix for the energy intensity of sectoral products could be generated as:

$$\boldsymbol{\varepsilon} = \boldsymbol{E}\left(\hat{\boldsymbol{X}} - \boldsymbol{Z} - \frac{1}{P_{\text{sum}}}\boldsymbol{F_O P}\right)^{-1}. \tag{5}$$

The energy use of the r_{th} region as denoted by the energy that is embodied in the r_{th} region's final consumption (EEC) can be generated as:

$$EEC^r = \sum_{s=1}^{m}\sum_{j=1}^{n} \varepsilon_j^s f_{jC}^{sr}. \tag{6}$$

The direct exploitation of energy resources for the r_{th} region could be formulated as:

$$DEE^r = \sum_{i=1}^{n} e_i^r. \tag{7}$$

The energy that is embodied in the imports (EEI) of the r_{th} region is denoted as:

$$EEI^r = EEII^r + EEFI^r = \sum_{s=1(s\neq r)}^{m} \sum_{j=1}^{n} \left[\sum_{i=1}^{n} (\varepsilon_j^s z_{ji}^{sr} + \varepsilon_j^s f_j^{sr}) \right], \tag{8}$$

in which $EEII^r$ $(=\sum_{s=1(s\neq r)}^{m} \sum_{j=1}^{n} \sum_{i=1}^{n} \varepsilon_j^s z_{ji}^{sr})$ represents energy that is embodied in the intermediate imports of the r_{th} region while $EEFI^r$ $(= \sum_{s=1(s\neq r)}^{m} \sum_{j=1}^{n} \varepsilon_j^s f_j^{sr})$ represents energy that is embodied in the final imports of the r_{th} region.

Correspondingly, energy that is embodied in the exports (EEX) of the r_{th} region is denoted as:

$$EEX^r = EEIX^r + EEFX^r = \sum_{s=1(s\neq r)}^{m} \sum_{i=1}^{n} \left[\sum_{j=1}^{n} (\varepsilon_i^r z_{ij}^{rs} + \varepsilon_i^r f_i^{rs}) \right], \tag{9}$$

in which $EEIX^r$ $(=\sum_{s=1(s\neq r)}^{m} \sum_{i=1}^{n} \sum_{j=1}^{n} \varepsilon_i^r z_{ij}^{rs})$ represents energy that is embodied in the intermediate exports of the r_{th} region while $EEFX$ $(=\sum_{s=1(s\neq r)}^{m} \sum_{i=1}^{n} \varepsilon_i^r f_i^{rs})$ represents energy that is embodied in the final exports of the r_{th} region.

As a result, energy embodied in trade balance ($EETB$) of the r_{th} region can be obtained as:

$$EETB^r = EEI^r - EEX^r = EEITB^r + EEFTB^r, \tag{10}$$

where $EEITB^r$ represents energy that is embodied in the intermediate trade balance of the r_{th} region and $EEFTB^r$ stands for energy that is embodied in the final trade balance of the r_{th} region.

It should be emphasized that for the r_{th} region, the following balance exists:

$$EEF^r = DEE^r + EEP^r + EETB^r. \tag{11}$$

Besides, the relationship between the source and sink of primary energy use is shown as:

$$\sum_{r=1}^{m} DEE^r = \sum_{r=1}^{m} EEC^r. \tag{12}$$

2.2. Data sources

While the input-output tables for nations are released by national statistical departments at regular intervals, the global multi-region input-output account is generally constructed by non-governmental organizations. In this work, the MRIO table from Eora database is applied, which provides a time-series of MRIO tables for world economy from the year 1990 to 2015 (Lenzen et al., 2012, 2013). Compared with global MRIO tables from other sources including world input-output database (Timmer et al., 2015), Exiobase (Stadler et al., 2018) as well as global trade analysis program (Aguiar et al., 2016), Eora MRIO table includes an inclusive geographical breakdown of the world economy, with the number of world regions covered reaching 189. The MRIO table from Exiobase, nevertheless, classifies the world economy into 44 nations and 5 ROW (rest of world) regions; the one from world input-output database includes 28 EU countries and other 15 major economies as well as a ROW region. Meanwhile, each region covered under the Eora MRIO table is composed of 26 economic sectors; hence the aggregated number of the sectors of 189 regions are 4914. SI-B and SI-C (supporting information) respectively show the names of the regions and those of the sectors in the global input-output account.

It needs to be especially noted that input-output tables lag behind (sometimes far behind) the present time. For instance, the global input-output accounts in Exiobase are only updated to the year 2011. This is because that the input-output tables for the member nations are mostly unveiled every several years, as the compilation process is a substantial work requiring large quantities of time, labor and money inputs. As known, official input-output tables for Chinese economy (such as the 1997, 2002, 2007 and 2012 input-output tables) are released every five years. Since Chinese economy is one of the main focuses in this work and China's statistics may greatly impact the accuracy of the global input-output account compiled, the 2012 Eora global MRIO table is used to represent the global economy, which could be consistent with the official statistics by Chinese government. Moreover, the data for extraction of energy resources from IEA (2017a) are applied. The primary energy exploited includes fossil fuels, hydro-energy, biomass and the other renewables, the measurement of which is in units of 1,000,000 tonnes equivalent in terms of oil (Mtoe). Detailed information for allocating primary energy resources to the corresponding economic sectors could be resorted to a previous work (Chen and Wu, 2017).

3. Results and discussions

3.1. Energy use of each region

The energy use of each region as captured by EEC is presented in Figure 2. The amount of each region's direct energy exploitation denoted by DEE is also illustrated. SI-D (supporting information) gives the numerical values. As shown, USA, Mainland China, Japan, Germany as well as India are revealed as the top five users, whose EEC respectively reach 3276 Mtoe, 1393 Mtoe, 933 Mtoe, 447 Mtoe and 404 Mtoe. The top five exploiters of primary energy resources are Mainland China, USA, Russia, Saudi Arabia as well as India, whose DEE reach 2360 Mtoe, 1757 Mtoe, 1251 Mtoe, 579 Mtoe and 512 Mtoe, respectively. At witnessed, the energy use of USA denoted by EEC is approximately twice more than that denoted by the direct energy exploitation, while that of Mainland China is in magnitude only 59.04% of the primary energy directly exploited. The gap between EEC and DEE is especially obvious for Japan and Saudi Arabia. The direct energy exploitation by Japan is only 2.97% of its EEC, while that by Saudi Arabia is over eight times as much as its EEC.

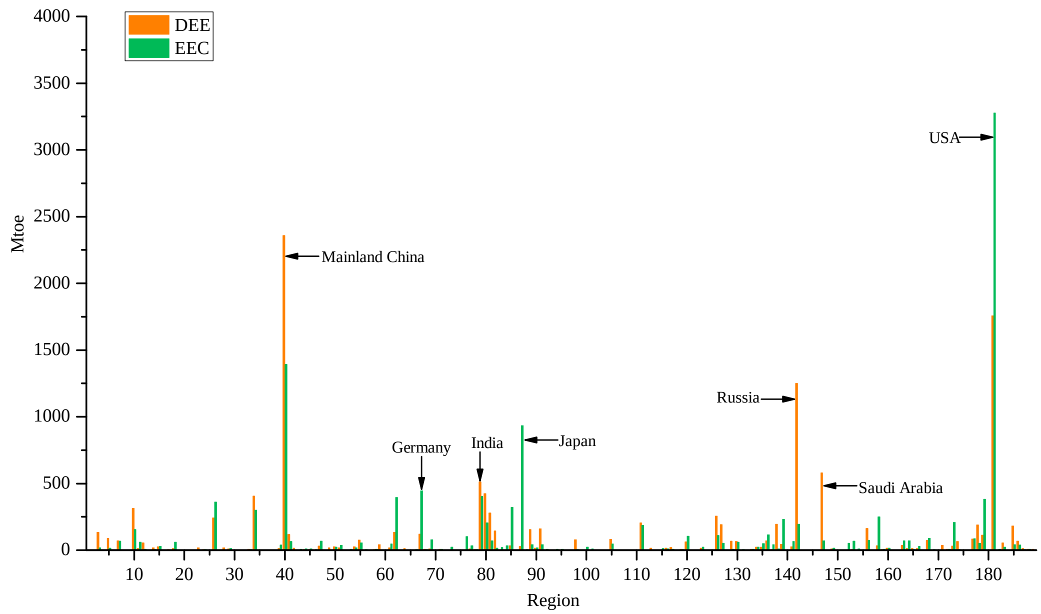


Figure 2: Energy embodied in final consumption (EEC) and direct energy exploitation (DEE) of each region

The components of the EEC for the five leading energy users are presented in Figure 3, as classified respectively by energy type and sector (details for sectoral integration are attached in the supporting information). Service industry is responsible for 53.48% of the EEC of the United States, showing the service-oriented economic structure of the United States. This ratio is 58.06% for Japan, suggesting the resemblance of industrial structure between the United States and Japan. For Mainland China, service industry still remains as a major contributor to its EEC, while the ratio (33.48%) is obviously lower than that of the United States and Japan. This is mainly because that Mainland China as a transitional economy is still on the way of adjusting itself from a low-end-manufacturing-oriented economy to a highend-manufacturing- as well as service-oriented economy. For India, service industry only accounts for 19.66% of its EEC. In addition, it is found that while the contribution by agriculture industry to the EEC is marginal for the United States (0.6%) and Japan (2.04%), it is considerable for Mainland China (13.17%) and India (41.03%), which is due to that these two developing economies have been historically rooted on agriculture and are still on the transitional stage.

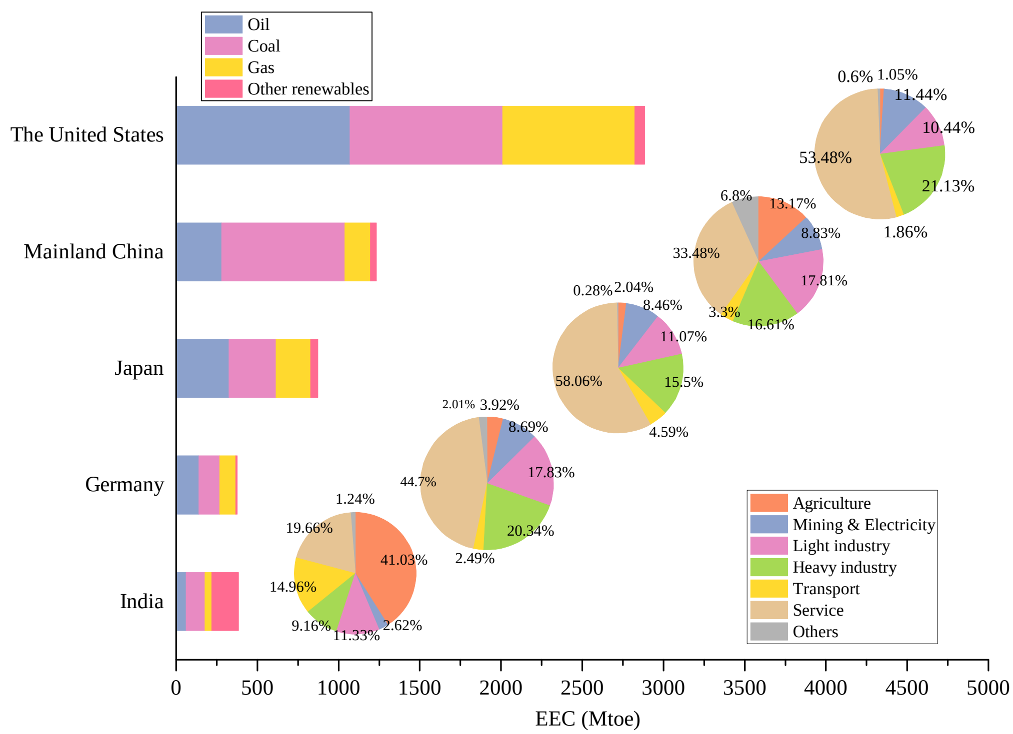


Figure 3: Components of the EEC for the five leading energy users

Figure 4 presents the per-capita EEC of each region and the world average level, which may serve an index to measure the residential living standards of energy use. The per-capita EEC for USA, Japan, Germany and

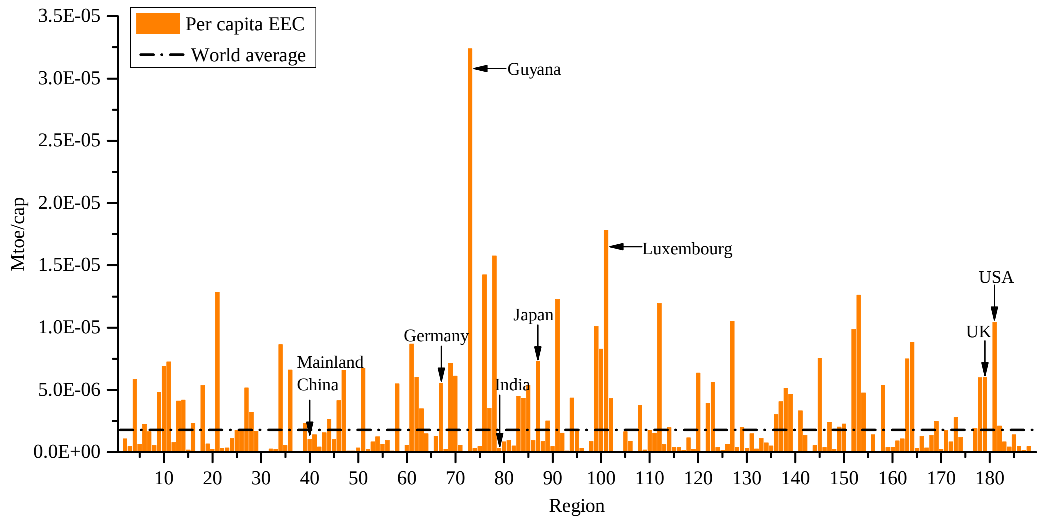


Figure 4: Per-capita energy usage for each region

the United Kingdom are respectively calculated to be 10.43 toe/cap, 7.32 toe/cap, 5.55 toe/cap and 6.03 toe/cap, which are several times higher than the world average level (1.79 toe/cap). Whereas, for Mainland China as the world's second biggest energy user, its per capital *EEC* is merely 1.03 toe/cap, which is in magnitude only around 60% of the world average level, one-fifth of that for Germany, and only 10% of the *EEC* for USA. As revealed, a wide gap lies between the living standards as measured by per-capita *EEC* between Mainland China and the developed economies. Chinese citizens live a frugal life to support consumption in other economies and to create a huge current account surplus.

3.2. Energy use flows in intermediate trade and final trade

Energy use flows across the interregional trade are enunciated in this section. Figure 5 presents the energy use flows associated with the imports, classified by intermediate imports and final imports. While intermediate imports refer to imported products used for intermediate production, final imports represent those used for final demand. As demonstrated, USA, Mainland China, Japan, Germany and South Korea are the five top importers of energy use, whose imports respectively reach 1826 Mtoe, 1127 Mtoe, 1063 Mtoe, 1052 Mtoe and 679 Mtoe. As witnessed, the volumes of energy use imports by Mainland China, Japan and Germany are on the same level. As to USA serving the biggest importer, its import of energy use is twice larger than that of Mainland China. Meanwhile, it could be seen that energy use embodied in intermediate imports for the regions is generally much larger than that in final imports. In total, energy use embodied in global intermediate imports are about five times larger than that in global final imports. As seen, intermediate products contribute dominantly to energy use flows via global trade, reflecting the integrity of the supply chains of the world economy.

With regard to energy embodied in the exports as illustrated in Figure 6, Russia is revealed to be the leading exporter, followed closely by Mainland China, USA, Germany and Saudi Arabia. 1278 Mtoe of energy use are exported from Russia to foreign regions, which are around 1.25 times as much as the exports of Mainland China, 1.38 times as much as those of the United States and over twice as much as those of Saudi Arabia. Meanwhile, energy embodied in intermediate exports of Russia is strikingly around sixty times as much as that embodied in its final exports. More strikingly, for Saudi

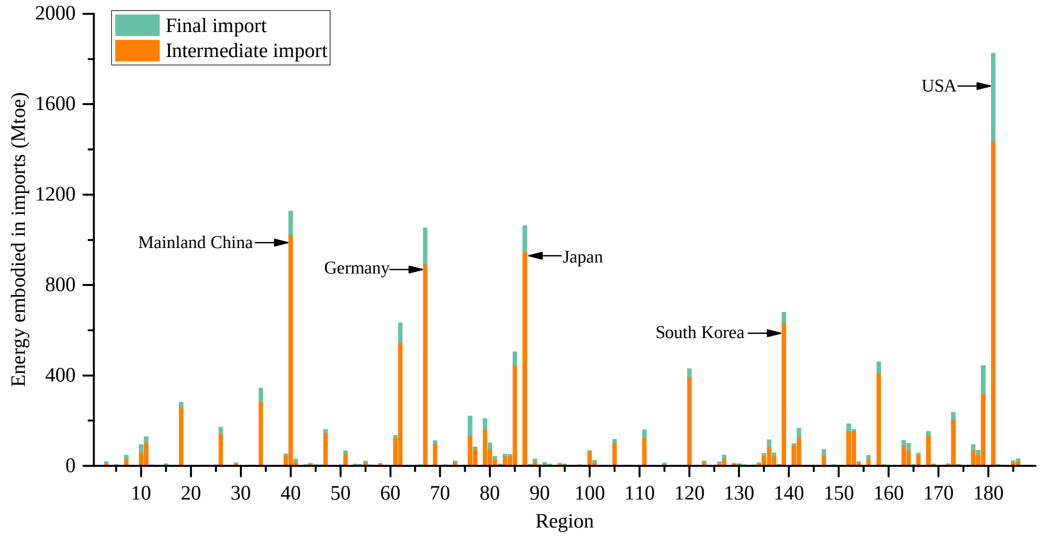


Figure 5: Energy embodied in the imports of the world regions

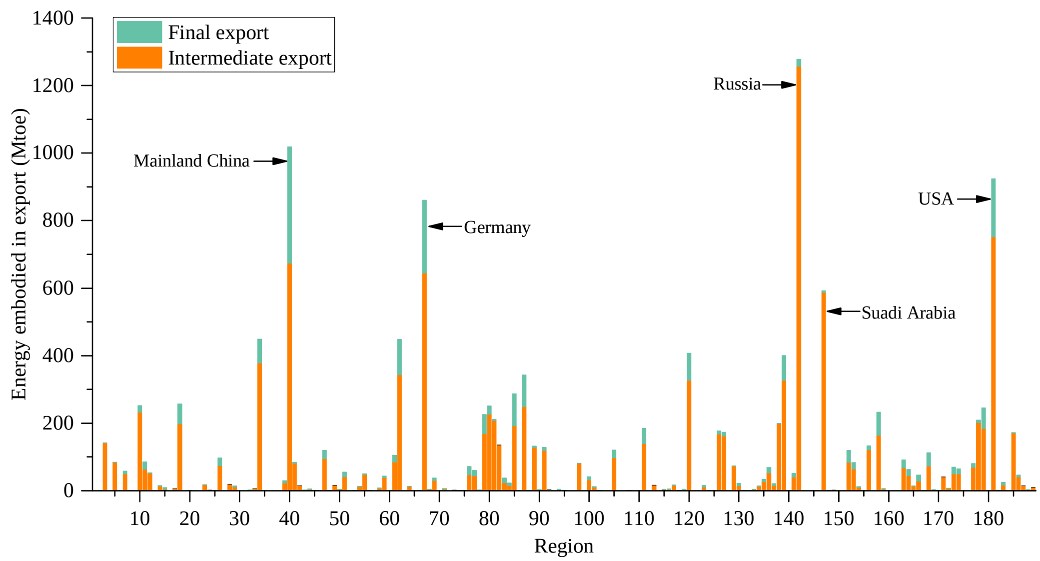


Figure 6: Energy embodied in the exports of the world regions

Arabia that is reliant highly on the exports of intermediate goods (such as oil), this ratio is calculated to be 115.64. While for other leading exporters including the United States, Mainland China and Germany, this ratio turns out to 1.95, 4.36 and 2.98 respectively.

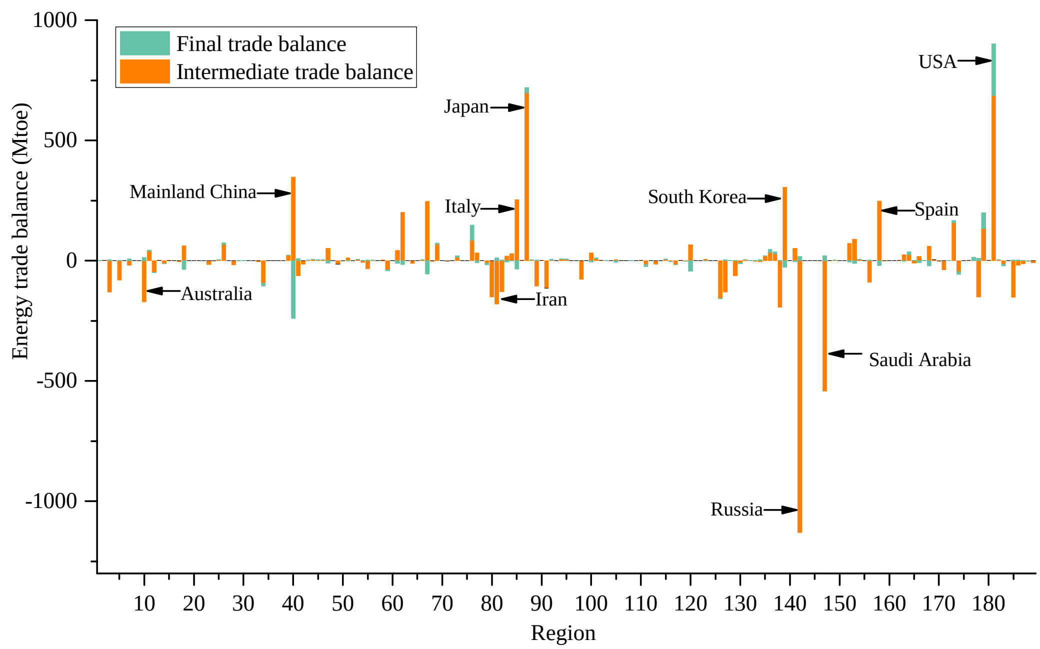


Figure 7: Energy embodied in the trade balance of the world regions

Figure 7 presents energy embodied in the trade balance of different regions in the world, as also classified by energy embodied in the intermediate trade balance and that in the final trade balance. Regarding the countries and regions included in the Eora global MRIO database, 128 regions are illustrated to be net importers of energy use while the rest regions are net exporters. USA, Japan, South Korea, Spain and Italy prove to be the biggest five net importers, receiving a trade surplus of energy use amounting to 902

Mtoe, 720 Mtoe, 278 Mtoe, 227 Mtoe and 218 Mtoe, respectively. Russia and Saudi Arabia, together with Qatar, Iran as well as Australia, are revealed as the leading net exporters of energy use, gaining a trade deficit amounting to 1112 Mtoe, 520 Mtoe, 192 Mtoe, 169 Mtoe, 159 Mtoe, respectively. For Mainland China, the result indicates that it is a net importer of energy use, gaining a trade surplus of 108 Mtoe, which is in magnitude around one-eighth of that for the United States.

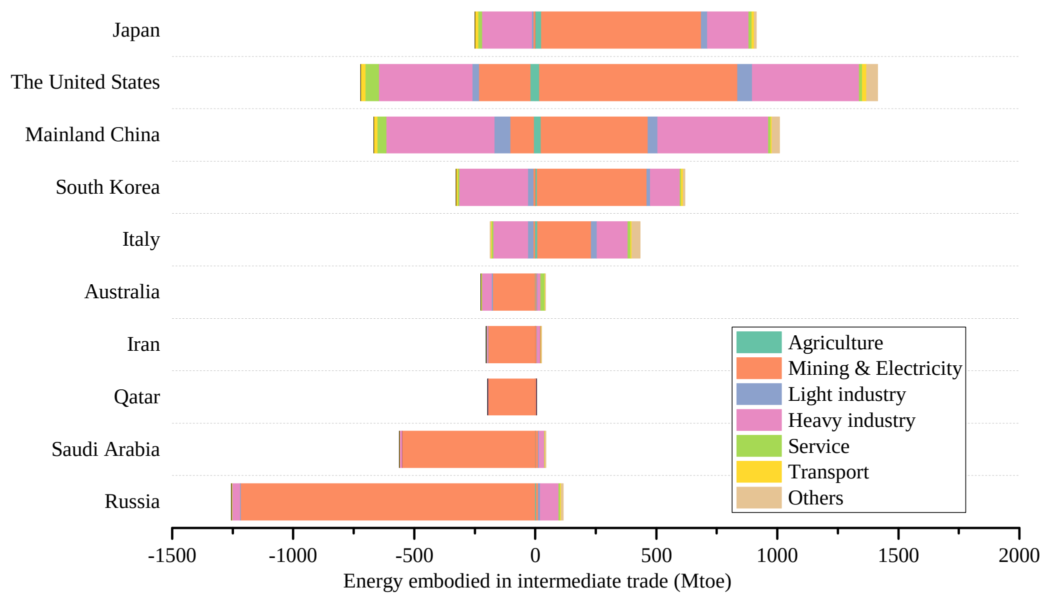


Figure 8: Sectoral components of prominent net importers and exporters of energy use in intermediate trade

Figure 8 presents the major net importers as well as the net exporters of energy use in intermediate trade, with sectoral contributions illustrated. Japan is unveiled to be the largest net importer in intermediate trade, with its intermediate trade surplus reaching up to 698 Mtoe. For the energy embodied in intermediate imports of Japan, 72.31% comes from mining & electricity industry in foreign regions. This is mainly because that Japan as a nation in severe insufficiency of primary energy resources, is heavily dependent on energy products from foreign regions to support domestic industrial production. Japan is followed by the United States (687 Mtoe), Mainland China (348 Mtoe), South Korea (305 Mtoe) and Italy (253 Mtoe). For Mainland China and the United states, imported heavy industry products are respectively responsible for 66.95% and 53.46% of their intermediate imports of energy use. With regard to net exporters in intermediate trade, Russia takes the lead with 1129 Mtoe exported abroad for foreign production activities, followed by Saudi Arabia (542 Mtoe), Qatar (193 Mtoe), Iran (181 Mtoe) and Australia (172 Mtoe). Mining & electricity industry respectively account for 96.80%, 98.10%, and 99.21% of the intermediate exports of Russia, Saudi Arabia and Qatar in terms of energy use.

Figure 9 presents the prominent net importers & exporters in final trade. As witnessed, five leading net importers in final trade turn out to be USA, the United Kingdom, Hong Kong, Japan, and Saudi Arabia; the leading net exporters in final trade turn out to be Mainland China, Germany, Netherlands, Belgium and Italy. For Japan, while heavy industry products from abroad contribute to 42.12% of its final imports of energy use, those exported abroad account for 82.19% of its final exports of energy use. Mainland China is the largest net exporter in terms of final trade, and the heavy industry and light industry respectively hold accountable for 55.05% and 36.00% of its fi-

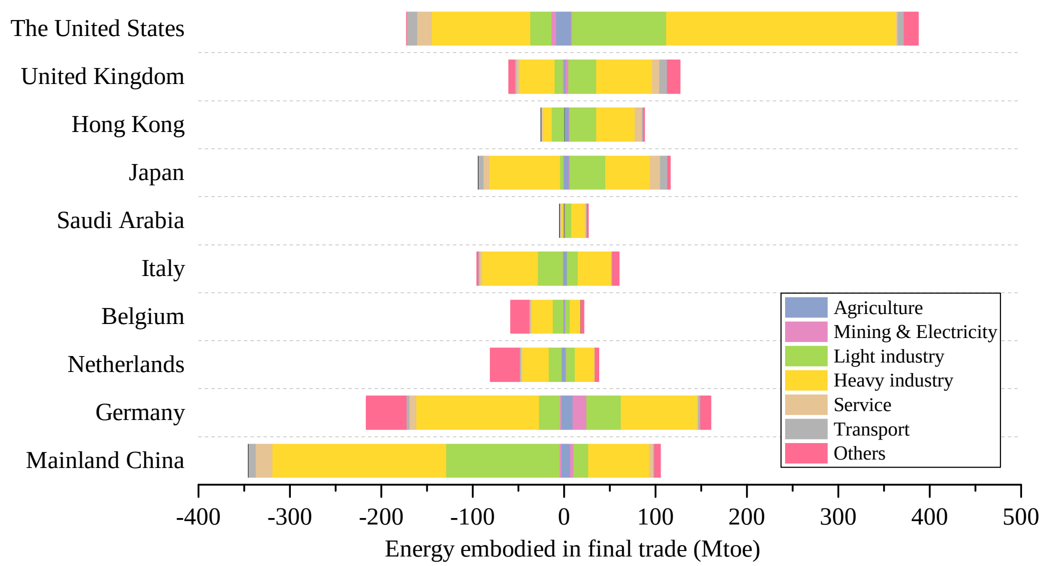


Figure 9: Sectoral components of prominent net importers & exporters of energy use in final trade

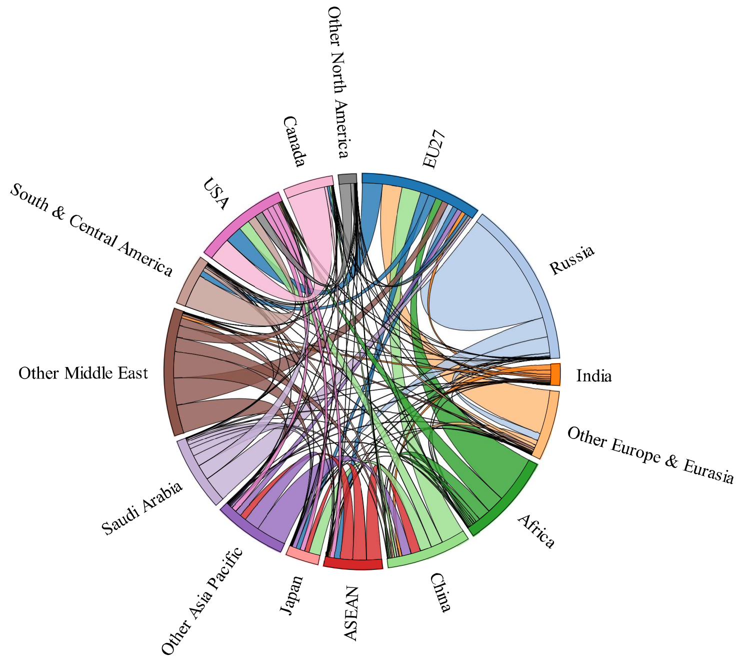
nal exports of energy use. For Germany, heavy industry and light industry respectively contribute 61.95% and 10.54% to its final exports of energy use.

3.3. Trade connections

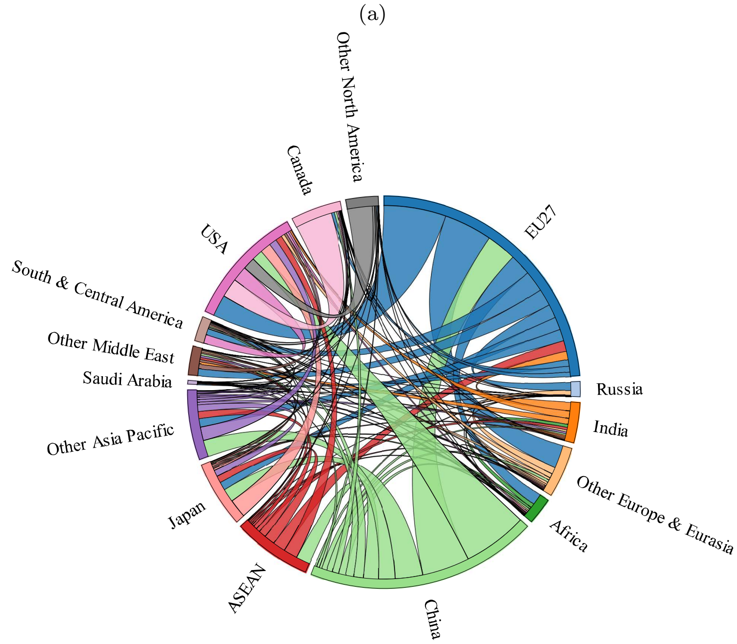
In this section, the energy trade connections between major economies are demonstrated. Figure 10a and Figure 10b respectively depict the intertwisted relations of the major regions in intermediate and final trades. Regions covered in Eora database are integrated into fifteen major regional economies, as could be seen in Figure 10a. SI-B (supporting information) gives the details of the disaggregation of regions. The arc length represents the energy that is embodied in the exports of each region, while the relationship between two regions connected is represented by the chord, the color of which complies with that of the larger exporter.

Regarding intermediate trade as illustrated in Figure 10a, Russia remains the leading exporter of energy use, whose intermediate exports amount to 1256 Mtoe. EU27 and Japan which serve the major contributors are respectively accountable for 73.70% and 12.37% of Russia intermediate exports of energy use. Following Russia and other Middle East, EU27 takes the third place in intermediate exports of energy use. For the intermediate exports of EU27 (920 Mtoe), 17.32% of them flow into the United States, 17.19% to other Europe & Eurasia, 16.57% to China, 4.80% to Russia, etc. While for USA, its intermediate exports of energy use are mainly received by Canada (186 Mtoe), EU27 (135 Mtoe) and China (87 Mtoe). Meanwhile, EU27 and USA are the two most prominent importers of energy use in intermediate trade. Russia, Africa, Saudi Arabia, China and the United States respectively contribute to 35.22%, 14.00%, 7.61% and 5.15% of EU27's intermediate imports of energy use. As for the intermediate imports of energy use for USA, the major contributors are its neighboring regions, namely Canada and South & Central America that altogether account for 39.93% of the total.

For final trade connections as illustrated in Figure 10b, prominent exporters turn out to be EU27, China, USA, ASEAN and other Asia Pacific. Of the 408 Mtoe of energy use in EU27's final exports, 22.72% of them are received by the United States, 10.94% by China, 7.56% by South & Central America, 5.04% by Russia, 4.68% by Japan, etc. For China, the main receivers of its final exports of energy use include USA, EU27 and Japan,



(a)



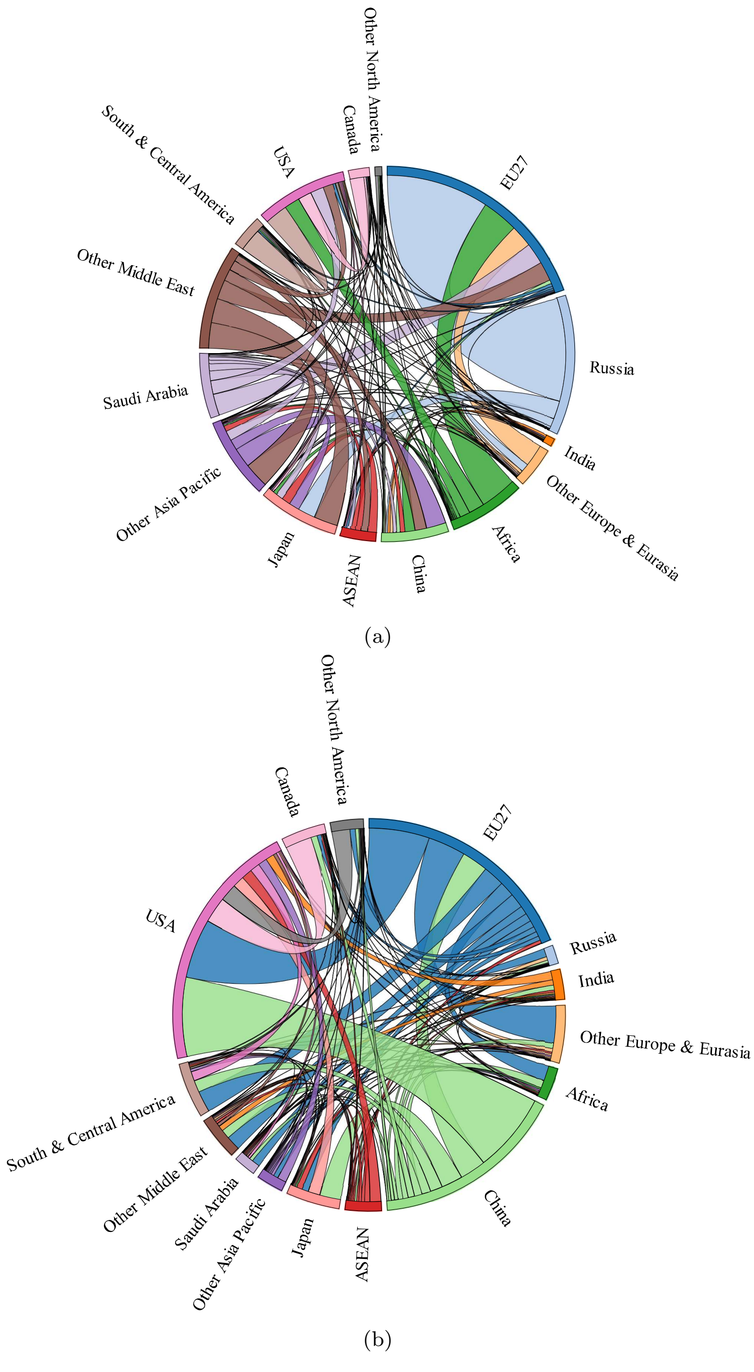
(b)

Figure 10: Energy connections between 15 regional economies in (a) intermediate trade and (b) final trade

which respectively occupy 29.24%, 21.54% and 12.48% of the total. With regard to the receivers of USA's final exports, Canada and South & Central America together hold responsible for 29.61% of the total, followed by EU27 (18.63%), China (9.39%) and Japan (9.23%).

Meanwhile, Figure 11a and Figure 11b respectively map the net intermediate trade and net final trade connections of energy use between some major regional economies. The largest flow of net intermediate trade occurs between the EU27 and Russia. Russia is revealed to have a trade deficit of energy use to EU27 that amounts to 882 Mtoe. Other major couples of intermediate trade imbalance in terms of energy use include EU27-Africa, EU27-Saudi Arabia, EU27-other Middle East, the United States-South & Central America, Japan-other Middle East, China-other Asia Pacific, etc. At witnessed, apart from the intermediate trade imbalance with Russia, EU27 is unveiled to have a big intermediate trade surplus of energy use with Africa, Arabia and other Middle East, respectively amounting to 313 Mtoe, 183 Mtoe and 166 Mtoe. USA is a net importer in trade of intermediate products; it has an intermediate trade surplus of energy use with South & Central America, Canada, Africa and Saudi Arabia, reaching 195 Mtoe, 116 Mtoe, 133 Mtoe and 115 Mtoe, respectively. For Japan that is in severe shortage of natural resource, it absorbs energy inflows mainly from Russia, other Middle East, ASEAN, etc.

As for net final trade of energy use, the largest net trade flow of energy use (80 Mtoe) is from China streaming to USA, followed by that from EU27



(a)

(b)

Figure 11: Energy connections between 15 regional economies in (a) net intermediate trade and (b) net final trade

streaming to USA (60 Mtoe). As witnessed, among these fifteen regional economies, the United States receives the biggest surplus (215 Mtoe) of energy use in final trade, which is around twenty-two times that of Japan (22 Mtoe). Apart from the trade imbalance with China and EU27, the United States appears to obtain a considerable energy surplus in final trade with its geographically adjacent trading partners, including that with Canada (26 Mtoe), that with other North America (18 Mtoe) and that with South & Central America (10 Mtoe).

3.4. Source-based and sink-based energy self-sufficiency rates

Under the global context, when primary energy resource is extracted from Region A, its use may pass through many regions before it finally sinks into final consumption of Region B. The source-based energy self-sufficiency rate and sink-based energy self-sufficiency rate are adopted here to reflect a key aspect of the sustainability of a nation in terms of energy use, which have been defined in a previous work as the ratio of primary energy resources exploited locally to satisfy the local final consumption to the local energy exploitation, and the ratio of primary energy resources exploited locally to satisfy the local final consumption to the energy embodied in the goods that are required by local final consumers, respectively (Chen and Wu, 2017). The source-based energy self-sufficiency rates for the 189 regions are illustrated in Figure 12, while the sink-based energy self-sufficiency rates for these regions are presented in Figure 13.

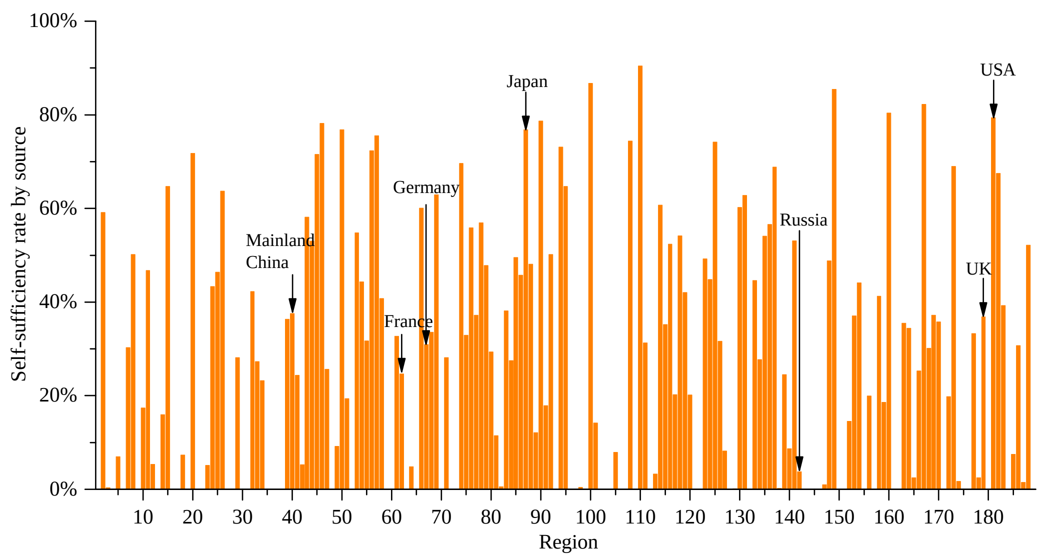


Figure 12: Source-based energy self-sufficiency rates for the world regions

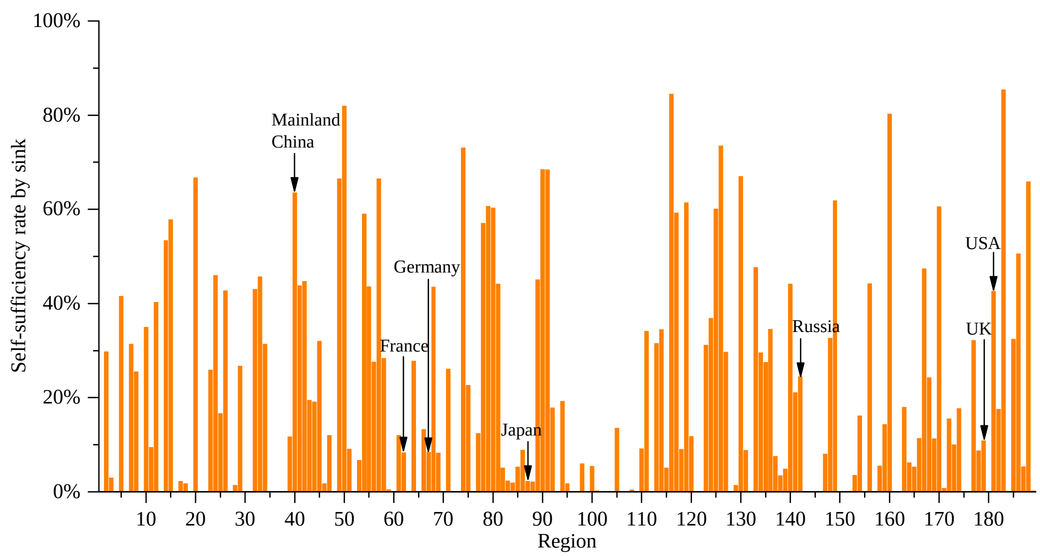


Figure 13: Sink-based energy self-sufficiency rates for the world regions

As witnessed, for economies including USA, Mainland China, Germany, the United Kingdom, Japan, France and Russia, the source-based energy self-sufficiency rates are respectively 79.37%, 37.53%, 30.95%, 36.85%, 76.81%, 24.64% and 3.81%, while the sink-based self-sufficiency rates are respectively 42.57%, 63.57%, 8.41%, 10.83%, 2.28%, 8.34% and 24.44%. For USA that serves the second biggest exploiter, approximately four fifths of the energy resources provided by its local environment finally sink in the products for domestic final consumption. Meanwhile, around 60% of its energy use denoted by EEC is originated from the energy resources that are extracted in other countries and regions. This explains that the United States mainly acts as the ultimate consumer in the global supply chain. For one thing, USA keeps the majority of the energy resources denoted by local environment at home to satisfy domestic final consumers. For another, the use of vast primary energy resources exploited abroad has been brought in to benefit domestic consumers, which has greatly enhanced the domestic living standards.

While for Germany and France, both their source-based and sink-based energy self-sufficiency rates are far smaller than the United States. This implies that Germany and France are actively participating in the world's commodity chains as both receivers and providers of energy use. These countries and regions import massive raw materials from abroad to support domestic producing activities and export massive high value-added goods to foreign regions to satisfy their final consumption. As a result, more than two-thirds of the energy resources by local environment finally sink into other regions.

While it shall also be noticed that, these regions also bring into massive energy use home by importing the consumers products from abroad. Therefore, around 90% of their energy use denoted by EEC stems from energy resources exploited abroad. As seen, these developed regions make full use their comparative advantages to be well positioned in the global commodity chain.

For Mainland China as the country of largest primary energy resource extraction, the picture turns to be quite different. As previously revealed, Mainland China receives a certain quantity of intermediate products from Asian Pacific regions to manufacture massive consumer products that are used to support final consumption of the developed economies. Therefore, among all the primary resources exploited locally, only one-third of them finally sink into the products used for domestic final consumption. Meanwhile, consumption is on a rather low level in Mainland China compared with that in developed economies, thus resulting in the small quantity of final imports from foreign regions. As a result, its energy-sufficiency rate by sink is much larger than that of Germany, France and the United States. Only one-third of its energy use denoted by EEC is originated from foreign energy resources. This implies that Mainland China mainly plays the role of producer in the global supply chain.

3.5. Distinct trading economies

Two distinct trading economies, i.e., Mainland China and the United States, are analyzed in this section by looking into the geographic and sectoral details. Figure 14(a) and Figure 14(b) respectively illustrate the imports and exports of energy use for Mainland China.

As presented in Figure 14(a), heavy industry and mining & electricity industry in foreign regions are the largest two providers of Mainland China's embodied energy imports. While Asia & Pacific contributes the biggest to Mainland China's imports from heavy industry abroad, Middle East remains the largest contributor to those from mining & electricity industry abroad. Meanwhile, of the energy use imports from foreign heavy industry to Mainland China, 67.93% of them go to domestic heavy industry, while only 12.67% of them are used for final demand. With regards to energy use imports from foreign mining & electricity industry, over 90% (93.48% exactly) of them flow into domestic heavy industry to support producing activities. As for exports of Mainland China as presented in Figure 14(b), heavy industry dedicates to over 60% of the total. The biggest three receivers of exports from Mainland China are Asia & Pacific, Europe & Eurasia and North America, respectively contributing to 36.46%, 30.94% and 23.94% of the total. Meanwhile, within the 424 Mtoe of energy use exports from Mainland China to Asia & Pacific, 43.32% of them go to the heavy industry, 30.32% going to the final demand, 9.82% to the light industry, 4.88% to the mining & electricity industry, etc. For the exports from Mainland China to North America, nearly half of them

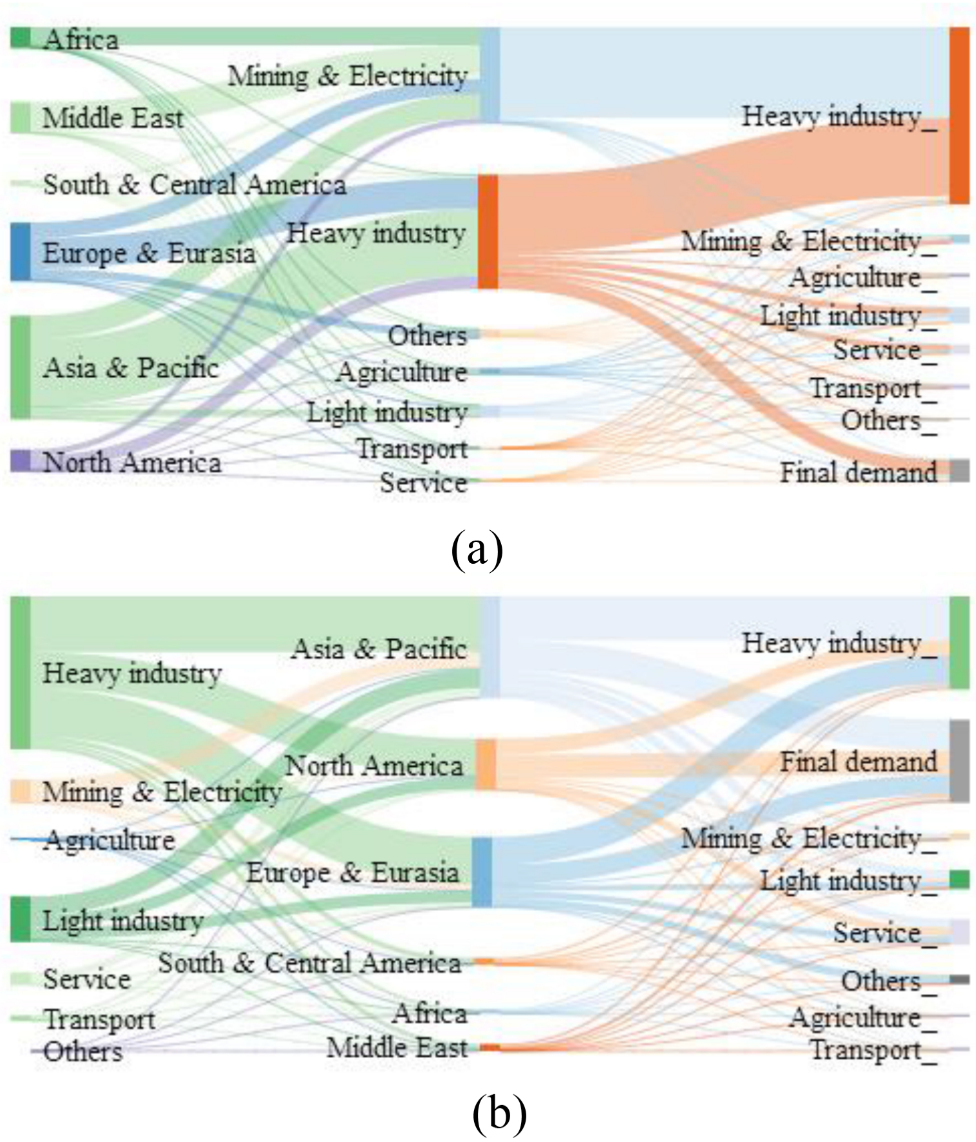


Figure 14: Geographical and sectoral details of the imports and exports of energy use for Mainland China

(46.11% exactly) are used for their final demand.

Figure 15(a) and Figure 15(b) respectively depict the imports and exports of energy use for the United States. At witnessed, North America contributes the biggest to the United States' imports, followed by Asia & Pacific. While North America contributes to 27.89% of the United States' imports from foreign heavy industry and 26.23% of those from foreign Mining & Electricity industry, Asia & Pacific dedicates to 37.35% of those from foreign heavy industry and 45.73% of those from light industry abroad. Meanwhile, for the 693 Mtoe of energy use imports from foreign heavy industry into the United States, 36.29% of them are used as final demand of the United States; 39.26% of them go to heavy industry; 16.62% of them flow to service industry. As for 163 Mtoe of energy use imports from light industry abroad, over 60% (63.24% exactly) of them are used as the United States' final demand. With regards to exports from the United States, domestic heavy industry contributes to over half of the total, followed by Mining & Electricity industry, service industry, etc. Within the 493 Mtoe of energy use exports from the United States, 31.73% of them are received by Asia & Pacific, 29.03% by North America, 26.00% by Europe & Eurasia, etc. In addition, while around one third of the exports of embodied energy from USA to Middle East are used for their final demand, less than one-fifth of the exports of energy use from the United States to Asia & Pacific are used to satisfy their domestic final needs.

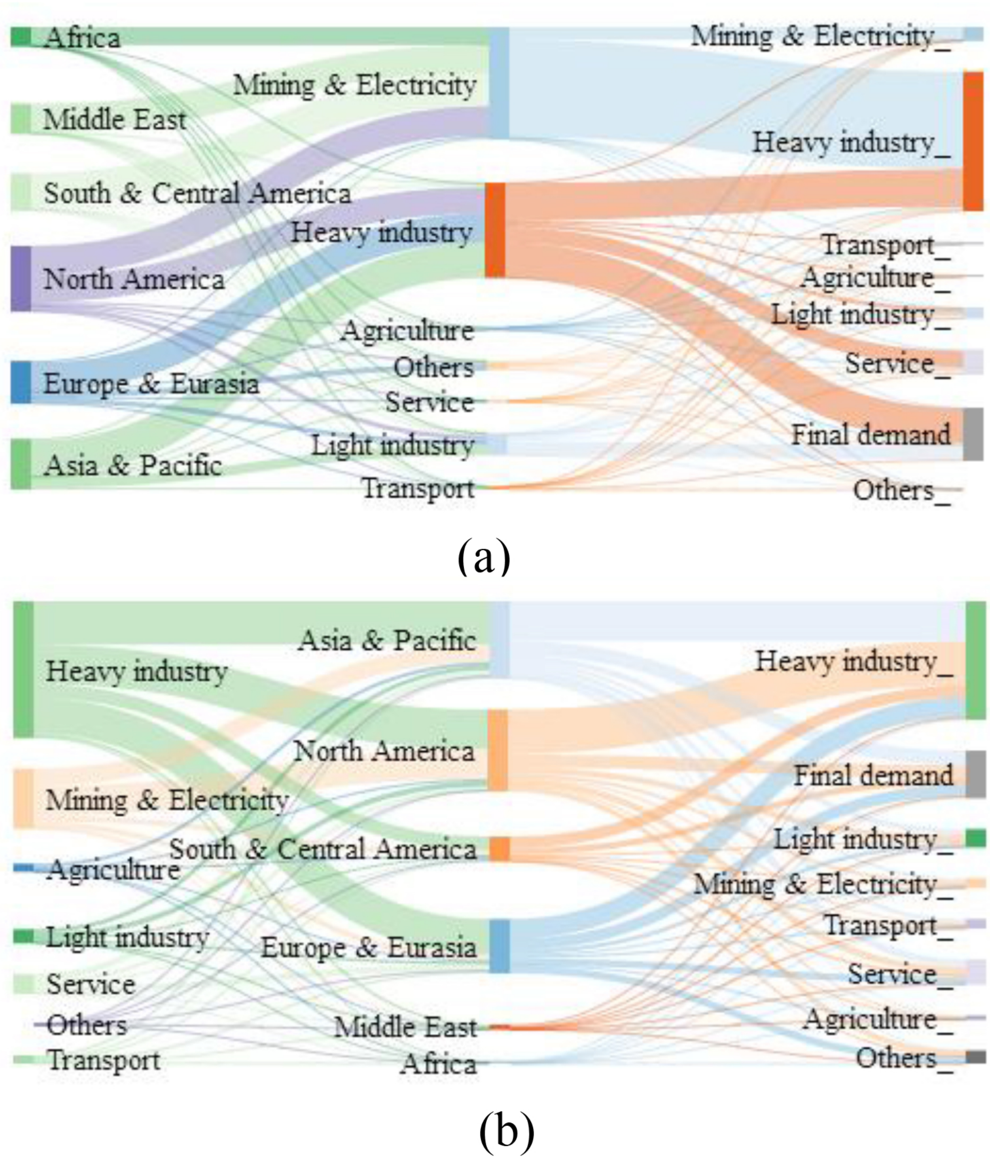


Figure 15: Geographical and sectoral details of the imports and exports of energy use for the United States

3.6. Comparison with existing studies

In this section we compared the results of this work with those obtained in existing studies. Previous efforts seeking to explore energy use of the world economy based on global multi-region input-output analysis are directed full attention (Gasim, 2015; Lan et al., 2016; Simas et al., 2015; Wu and Chen, 2017; Wu et al., 2019b). In the work by Simas et al. (2015) as well as that by Wu and Chen (2017), the result shows that Russia is the biggest exporter and the United States is the biggest importer of energy use, which is consistent with that in this study. However, in the work by Gasim (2015), it was found that China comes as the leading net exporter of energy use while Russia comes the second, differing from the results in this study. An important reason is the selection of different data sources: the study by Gasim (2015) utilized the 2009 MRIO table coming from WIOD database for input-output modelling; the one by Simas et al. (2015) chose the 2007 MRIO table coming from Exiobase; the present study was based on 2012 MRIO table adopted from Eora database. Thus, deviation of the results is generated.

Meanwhile, it is found that the quantity of energy use embodied in international trade obtained in this study is approximately six times larger than that reported in the previous work by Wu et al. (2019b), and also several times higher than that by Simas et al. (2015) and that by Wood et al. (2018). This is mainly because that in these previous works, a normative manner is adopted that assigns the direct energy use to final consumption and only the energy use embodied in traded products for final use is accounted. In the present work, we adopt a positive manner that tracks the circulation of energy use across the whole supply chains, which takes into account of energy use embodied in products traded for both intermediate and final use. As previously mentioned, the economic trade volume of intermediate products is much larger than that of final products. Also, the energy use intensity of intermediate products is generally higher than that of final products which are mostly for consumptive use. Therefore, the amount of energy use embodied in international trade turns out to be largely outpacing that obtained in the abovementioned studies.

3.7. Limitations and future agenda

This study presents a global panorama of energy use of world regions, by means of a developed energy accounting model that gives attention to both primary and intermediate inputs. As a preliminary step, we combine typical statistics for one year to get a global panorama of global energy use and trade connections. The limitation is that the temporal evolution of energy use for world regions is not demonstrated. In future studies, we will make efforts to explore how the embodied energy use and imports/exports of world regions change over time based on time-series investigation. In particular, attention could be paid to how the trade links between regional economies vary during the last several decades, under the context of geo-economic integration of regions. Besides, while the energy accounting model developed in this study may shed new light on the process of how the energy use is sourced from the environment and finally sinking into the social system via final consumption, the energy intensity of primary inputs is not differentiated by sector/type as a preliminary treatment. A future direction is to further develop the energy accounting model by focusing on the feedback mechanism between primary inputs and final demand via social-redistribution matrix.

4. Conclusions and policy implications

In this study, an overview of energy use flows in the world economy is conducted to reveal the highly-integrated relations between world regions, offering a positive accounting framework which covers the indirect energy usage related to primary and intermediate inputs.

Overall, energy use flows associated with global intermediate trade are remarkably over five times more than those of final trade. This means that the utility of primary energy resources will be repeatedly used by a number of regions before it leaves the economic system and sinks into final consumption, implying that regions are becoming more and more integrated in the global supply chain. Under this context, a region is supposed to make itself adapt to the commodity chain in the world economy by precisely pinpointing its role on the global trading market. Moreover, while the top five energy exploiters are Mainland China, the United States, Russia, Saudi Arabia and India, the energy use denoted by EEC of the United States is over twice that of Mainland China, three and a half times that of Japan, and around eight times that of Germany as well as India, which is due to the re-allocation of embodied energy via the world's supply chains by means of interregional trade. Regarding per-capita energy use, it is notably witnessed that the per-capital EEC of Mainland China is only around 60% of the world average and only 10% of that of the USA, implying that Chinese citizens live a frugal life to support consumption in other economies and to create a huge current account surplus.

As revealed in this work, Mainland China is found to be a net importer of energy use in intermediate commodity trade but the largest net exporter of energy use in final commodity trade, obtaining a final trade deficit with nearly each of its trading partners. Therefore, it is like a world factory (or a hub region) which brings in intermediate products from foreign regions to manufacture consumer products that are exported for final demand in developed economies. Though a current account surplus may be achieved by Mainland China, the utility of the energy resources provided by the local environment is mainly exported abroad to benefit foreign consumers instead of domestic residents. As calculated, around 60% of the domestic exploited energy use sinks into foreign regions' final consumption. To maintain more energy use at home, domestic residential consumption is to be quantitatively and qualitatively enhanced in China, since the current consumption level of China is still far lagging behind that of nations such as USA and Japan. Moreover, upgrading domestic industries that are resource-intensive and low value-added to industries that are knowledge-based, service-based, high value-added and energy-efficient is of profound importance for Mainland China to improve the consumption structure, enhance the affluency of domestic residents' lifestyles, relocate itself in the global value chain as well as conserve energy resources.

USA is illustrated to be the leading net importer of energy use, with a tremendous trade surplus with Mainland China and European Union in final trade as well as a surplus with its neighboring countries (Canada, Mexico and Brazil) but a deficit with South & Central America in intermediate trade. Its source-based and sink-based energy self-sufficiency rates are respectively calculated to be 79.37% and 42.57%, revealing USA as a major sink of energy use in the global supply chains. On one hand, the use of the energy resources provided by the local environment is largely kept at home. On other hand, it receives massive imported energy use from all its trading partners. Though this may make its domestic citizens enjoy an affluent lifestyle, the tradeoff is that the United States obtains a massive trade deficit of currency with both European regions and Asia Pacific regions. In retrospect, during the last several decades, the United States has largely transferred its manufacturing industries abroad and pinpointed itself as high-tech- and service-oriented economy. In recent years the United States has promulgated a series of policy packages that aim to move manufacturing industry back home (such as the passing of the reform tax bill that sharply lowers the corporate tax rates), which is deemed to be effective in cutting down its economic trade deficit as well as increasing the domestic employment. Nevertheless, cutting the economic trade deficit by bring back the industries that were once outsourced abroad may be a temporary but not a sustainable solution, which may impede domestic industrial upgrading and also jeopardize the United States' efforts towards climate change mitigation.

Similar to the United States, Japan is demonstrated to be a notable net importer of embodied energy. Featuring a shortage of natural resources, Japan receives large quantities of energy products such as crude petroleum, petroleum gas, coal briquettes, from Russia, Saudi Arabia, and other Middle East nations, thus obtaining a trade surplus in terms of embodied energy with these resource-abundant nations in intermediate trade. In final trade, it is worth noting that by exporting massive high value-added products (such as automobiles and electronical products) to the global market, Japan is revealed to have a considerable deficit of embodied energy with nations such as the United States in final trade. Nevertheless, this deficit is offset by Japan's final trade surplus of embodied energy with Asia Pacific regions, especially with Mainland China by importing the low value-added products such as furniture, toys and textile products, thus making Japan a net importer of energy use in final trade. By expanding its production and consumption beyond its national borders to the whole world, Japan becomes a magnetic hub in the globalized world that absorbs the global resources and products to support both domestic enterprises' industrial demands and local residents' everyday needs.

For Russia, Saudi Arabia and other Middle East regions, they could be regarded as source regions that provide the global market with abundant primary energy sources, thus maintaining a deficit with other regions in intermediate trade of energy use, and a surplus with its trading partners in final trade. Though in the short term these regions may obtain a trade surplus of currency, their economic structure is much too reliant on energy sectors. A shock in energy prices may become a devastation to their economies, as could be demonstrated by the devaluation of Russian ruble in the last few years. Therefore, these economies are supposed to diversify their industrial structure to be more involved in the global market.

Overall speaking, the tide of globalization has been an ongoing and inevitable trend in the long run. In the foreseen future, the binding relations of the economies will be closer and the world economy may grow into a high interdependent community. Therefore, adapting one region's industries to the world's supply chains remains a crucial way to facilitate the sustainable energy use and regional prosperity.

Acknowledgments

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Additional Information

Declarations of Interest: None

References

Aguiar, A., Narayanan, B., McDougall, R., 2016. An overview of the GTAP 9 data base. Journal of Global Economic Analysis 1, 181–208. doi:10.21642/JGEA.010103AF.

Brown, M.T., Herendeen, R.A., 1996. Embodied energy analysis and EMERGY analysis: A comparative view. Ecological Economics 19, 219–235. doi:10.1016/S0921-8009(96)00046-8.

Bullard, C.W., Herendeen, R.A., 1975. The energy cost of goods and services. Energy Policy 3, 268–278.

Cellura, M., Longo, S., Mistretta, M., 2011. The energy and environmental impacts of Italian households consumptions: An input–output approach. Renewable and Sustainable Energy Reviews 15, 3897–3908. doi:10.1016/j.rser.2011.07.025.

Chen, B., Yang, Q., Zhou, S., Li, J.S., Chen, G.Q., 2017. Urban economy's carbon flow through external trade: Spatial-temporal evolution for Macao. Energy Policy 110, 69–78. doi:10.1016/j.enpol.2017.08.010.

Chen, G.Q., Wu, X.D., Guo, J., Meng, J., Li, C., 2019. Global overview for energy use of the world economy: Household-consumption-based accounting based on the world input-output database (WIOD). Energy Economics 81, 835–847. doi:10.1016/j.eneco.2019.05.019.

Chen, G.Q., Wu, X.F., 2017. Energy overview for globalized world economy: Source, supply chain and sink. Renewable and Sustainable Energy Reviews 69, 735–749. doi:10.1016/j.rser.2016.11.151.

Chen, Z.M., Chen, G.Q., 2011. An overview of energy consumption of the globalized world economy. Energy Policy 39, 5920–5928. doi:10.1016/j.enpol.2011.06.046.

Chen, Z.M., Chen, G.Q., 2013. Demand-driven energy requirement of world economy 2007: A multi-region input–output network simulation. Communications in Nonlinear Science and Numerical Simulation 18, 1757–1774. doi:10.1016/j.cnsns.2012.11.004.

Costanza, R., 1980. Embodied energy and economic valuation. Science 210, 1219–1224. doi:10.1126/science.210.4475.1219.

Dixon, R.K., McGowan, E., Onysko, G., Scheer, R.M., 2010. US energy conservation and efficiency policies: Challenges and opportunities. Energy Policy 38, 6398–6408. doi:10.1016/j.enpol.2010.01.038.

Gasim, A.A., 2015. The embodied energy in trade: What role does specialization play? Energy Policy 86, 186–197. doi:https://doi.org/10.1016/j.enpol.2015.06.043.

Groenewold, N., He, L., 2007. The US–China trade imbalance: Will revaluing the RMB help (much)? Economics Letters 96, 127–132. doi:10.1016/j.econlet.2006.12.021.

Hannon, B., 2010. The role of input–output analysis of energy and ecologic systems. Annals of the New York Academy of Sciences 1185, 30–38.

Herendeen, R., 1973. An energy input-output matrix for the United States, 1963: User's guide.

Herendeen, R.A., 1978. Input-output techniques and energy cost of commodities. Energy Policy 6, 162–165.

Herendeen, R.A., 1981. Energy intensities in ecological and economic systems. Journal of Theoretical Biology 91, 607–620.

Herendeen, R.A., 2004. Energy analysis and EMERGY analysis—a comparison. Ecological Modelling 178, 227–237. doi:10.1016/j.ecolmodel.2003.12.017.

IEA, 2017a. Energy balance flow. http://www.iea.org/Sankey/.

IEA, 2017b. Key World Energy Statistics. Technical Report.

Ji, X., Liu, Y., Han, M., Meng, J., 2020. The mutual benefits from sino-africa trade: Evidence on emission transfer along the global supply chain. Journal of Environmental Management 263, 110332. doi:https://doi.org/10.1016/j.jenvman.2020.110332.

Jiang, L., He, S., Tian, X., Zhang, B., Zhou, H., 2020. Energy use embodied in international trade of 39 countries: Spatial transfer patterns and driving factors. Energy 195, 116988. doi:https://doi.org/10.1016/j.energy.2020.116988.

Johnson, R.C., Noguera, G., 2012. Accounting for intermediates: Production sharing and trade in value added. Journal of International Economics 86, 224–236. doi:10.1016/j.jinteco.2011.10.003.

Lan, J., Malik, A., Lenzen, M., McBain, D., Kanemoto, K., 2016. A structural decomposition analysis of global energy footprints. Applied Energy 163, 436–451. doi:10.1016/j.apenergy.2015.10.178.

Lenzen, M., Kanemoto, K., Moran, D., Geschke, A., 2012. Mapping the structure of the world economy. Environmental Science & Technology 46, 8374–8381. doi:10.1021/es300171x.

Lenzen, M., Moran, D., Kanemoto, K., Geschke, A., 2013. Building Eora: A global multi-region input-output database at high-country and sector resolution. Economic Systems Research 25, 20–49. doi:10.1080/09535314.2013.769938.

Li, J.S., Xia, X.H., Chen, G.Q., Alsaedi, A., Hayat, T., 2016. Optimal embodied energy abatement strategy for Beijing economy: Based on a three-scale input-output analysis. Renewable and Sustainable Energy Reviews 53, 1602–1610. doi:10.1016/j.rser.2015.09.090.

Limmeechokchai, B., Suksuntornsiri, P., 2007. Embedded energy and total greenhouse gas emissions in final consumptions within Thailand. Renewable and Sustainable Energy Reviews 11, 259–281. doi:10.1016/j.rser.2005.01.005.

Meng, J., Mi, Z., Guan, D., Li, J., Tao, S., Li, Y., Feng, K., Liu, J., Liu, Z., Wang, X., Zhang, Q., Davis, S.J., 2018. The rise of South–South trade and its effect on global CO2 emissions. Nature Communications 9. doi:10.1038/s41467-018-04337-y.

Mi, Z., Guan, D., Liu, Z., Liu, J., Viguié, V., Fromer, N., Wang, Y., 2019. Cities: The core of climate change mitigation. Journal of Cleaner Production 207, 582–589. doi:https://doi.org/10.1016/j.jclepro.2018.10.034.

Mi, Z., Meng, J., Guan, D., Shan, Y., Song, M., Wei, Y.M., Liu, Z., Hubacek, K., 2017. Chinese CO_2 emission flows have reversed since the global financial crisis. Nature Communications 8. doi:10.1038/s41467-017-01820-w.

Mill, J., 1821. Elements of Political Economy. Baldwin, Cradock, and Joy, London.

Pachauri, S., Spreng, D., 2002. Direct and indirect energy requirements of households in India. Energy Policy 30, 511–523. doi:10.1016/S0301-4215(01)00119-7.

Park, H.C., Heo, E., 2007. The direct and indirect household energy requirements in the Republic of Korea from 1980 to 2000—An input–output analysis. Energy Policy 35, 2839–2851. doi:10.1016/j.enpol.2006.10.002.

Shao, L., Guan, D., Wu, Z., Wang, P., Chen, G.Q., 2017. Multi-scale input-output analysis of consumption-based water resources: Method and application. Journal of Cleaner Production 164, 338–346. doi:10.1016/j.jclepro.2017.06.117.

Shao, L., Li, Y., Feng, K., Meng, J., Shan, Y., Guan, D., 2018. Carbon emission imbalances and the structural paths of Chinese regions. Applied Energy 215, 396–404. doi:10.1016/j.apenergy.2018.01.090.

Simas, M., Wood, R., Hertwich, E., 2015. Labor Embodied in Trade. Journal of Industrial Ecology 19, 343–356. doi:10.1111/jiec.12187.

Smith, A., 1776. An Inquiry into the Nature and Causes of the Wealth of Nations. W. Strahan and T. Cadell, London.

Stadler, K., Wood, R., Bulavskaya, T., Södersten, C.J., Simas, M., Schmidt, S., Usubiaga, A., Acosta-Fernández, J., Kuenen, J., Bruckner, M., Giljum, S., Lutter, S., Merciai, S., Schmidt, J.H., Theurl, M.C., Plutzar, C., Kastner, T., Eisenmenger, N., Erb, K.H., de Koning, A., Tukker, A., 2018. EXIOBASE 3: Developing a Time Series of Detailed Environmentally Extended Multi-Regional Input-Output Tables: EXIOBASE 3. Journal of Industrial Ecology 22, 502–515. doi:10.1111/jiec.12715.

Su, B., Ang, B., Low, M., 2013. Input–output analysis of CO2 emissions embodied in trade and the driving forces: Processing and normal exports. Ecological Economics 88, 119–125. doi:10.1016/j.ecolecon.2013.01.017.

Tang, M., Hong, J., Liu, G., Shen, G.Q., 2019. Exploring energy flows embodied in china's economy from the regional and sectoral perspectives via combination of multi-regional input–output analysis and a complex network approach. Energy 170, 1191 – 1201. doi:https://doi.org/10.1016/j.energy.2018.12.164.

Tang, X., Snowden, S., Höök, M., 2013. Analysis of energy embodied in the international trade of UK. Energy Policy 57, 418–428. doi:10.1016/j.enpol.2013.02.009.

Tian, Z., Fang, D., Chen, B., 2020. Three-scale input-output analysis for energy and water consumption in urban agglomeration. Journal of Cleaner Production 268, 122148. doi:https://doi.org/10.1016/j.jclepro.2020.122148.

Timmer, M.P., Dietzenbacher, E., Los, B., Stehrer, R., de Vries, G.J., 2015. An illustrated user guide to the world input-output database: The case of global automotive production. Review of International Economics 23, 575–605. doi:10.1111/roie.12178.

Trump, D., 2018. Statement by the President Regarding Trade with

China. https://www.whitehouse.gov/briefings-statements/statement-president-regarding-trade-china/.

Wang, S., Cao, T., Chen, B., 2017. Urban energy–water nexus based on modified input–output analysis. Applied Energy 196, 208–217. doi:10.1016/j.apenergy.2017.02.011.

Wang, S., Chen, B., 2016. Energy–water nexus of urban agglomeration based on multiregional input–output tables and ecological network analysis: A case study of the Beijing–Tianjin–Hebei region. Applied Energy 178, 773–783. doi:10.1016/j.apenergy.2016.06.112.

Wiedmann, T.O., Schandl, H., Lenzen, M., Moran, D., Suh, S., West, J., Kanemoto, K., 2015. The material footprint of nations. Proceedings of the National Academy of Sciences 112, 6271–6276. doi:10.1073/pnas.1220362110.

Wood, R., Stadler, K., Simas, M., Bulavskaya, T., Giljum, S., Lutter, S., Tukker, A., 2018. Growth in environmental footprints and environmental impacts embodied in trade: Resource efficiency indicators from exiobase3. Journal of Industrial Ecology 22, 553–564. doi:https://doi.org/10.1111/jiec.12735.

Wu, X., Guo, J., Li, C., Shao, L., Han, M., Chen, G., 2019a. Global socio-hydrology: An overview of virtual water use by the world economy from source of exploitation to sink of final consumption. Journal of Hydrology 573, 794–810. doi:10.1016/j.jhydrol.2019.03.080.

Wu, X., Li, C., Shao, L., Meng, J., Zhang, L., Chen, G., 2021. Is solar power renewable and carbon-neutral: Evidence from a pilot solar tower plant in china under a systems view. Renewable and Sustainable Energy Reviews 138, 110655. doi:https://doi.org/10.1016/j.rser.2020.110655.

Wu, X.D., Guo, J.L., Han, M.Y., Chen, G.Q., 2018. An overview of arable land use for the world economy: From source to sink via the global supply chain. Land Use Policy 76, 201–214. doi:10.1016/j.landusepol.2018.05.005.

Wu, X.D., Guo, J.L., Li, C., Chen, G.Q., Ji, X., 2020. Carbon emissions embodied in the global supply chain: Intermediate and final trade imbalances. Science of The Total Environment 707, 134670. doi:10.1016/j.scitotenv.2019.134670.

Wu, X.D., Guo, J.L., Meng, J., Chen, G.Q., 2019b. Energy use by globalized economy: Total-consumption-based perspective via multi-region input-output accounting. Science of The Total Environment 662, 65–76. doi:10.1016/j.scitotenv.2019.01.108.

Wu, X.F., Chen, G.Q., 2017. Global primary energy use associated with production, consumption and international trade. Energy Policy 111, 85–94. doi:10.1016/j.enpol.2017.09.024.

Yang, R., Long, R., Yue, T., Shi, H., 2014. Calculation of embodied energy in Sino-USA trade: 1997–2011. Energy Policy 72, 110–119. doi:10.1016/j.enpol.2014.04.024.

Zhang, B., Qiao, H., Chen, Z.M., Chen, B., 2016. Growth in embodied energy transfers via China's domestic trade: Evidence from multi-regional input–output analysis. Applied Energy 184, 1093–1105. doi:10.1016/j.apenergy.2015.09.076.

Zhang, B., Qu, X., Meng, J., Sun, X., 2017. Identifying primary energy requirements in structural path analysis: A case study of China 2012. Applied Energy 191, 425–435. doi:10.1016/j.apenergy.2017.01.066.