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Energy use by globalized economy: Total-consumption-based perspective via multi-region input-output accounting

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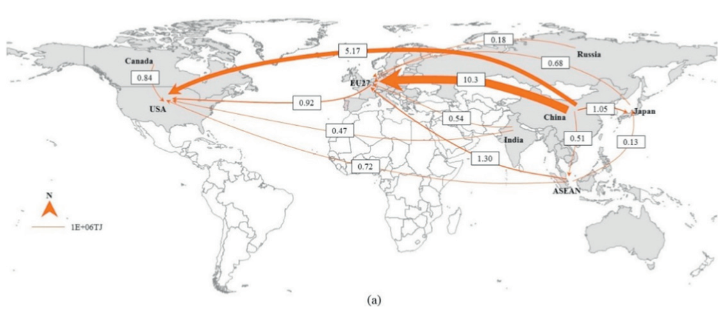
HIGHLIGHTS

- A global energy profile is constructed from the side of genuine final consumers.
- A total-consumption-based multi-region input-output accounting scheme is developed.
- Energy use of the United States is 1.8 times that of mainland China.
- Mainland China accounts for 40% of global total exports of energy use.
- Energy trade imbalance of Mainland China is four times that for the United States.

GRAPHICAL ABSTRACT

Major interregional net trade flows in terms of energy use



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ABSTRACT

Within a single integrated globalized economy featuring robust fluxes of interregional trades, the world economy is like a giant bathtub containing the world inventory of energy use. Based on different norms or ethic percepts, the energy use of the world economy is reallocated to nations and regions via global supply chain using normative accounting schemes. By combining typical statistics for world economy 2012, a new perspective is presented in this study to look into the energy use of regional economies from the side of genuine final consumers. Parallel to the final-demand-based accounting method, a total-consumption-based multi-region input-output accounting method is developed following the norm of consumption being the ultimate end and purpose of all producing activities. From a total-consumption-based perspective, the energy use of the United States economy is shown in magnitude 1.8 times that of mainland China, compared to a ratio of 88% from a territorial-based perspective. The consumer-product-related trade imbalances of major economies in terms of both currency and energy use are analyzed, with major interregional net trade flows illustrated. While the United States and mainland China are respectively revealed as the leading net exporter and net importer of currency, the energy trade deficit of the latter is in magnitude around four times the energy trade surplus of the former. The trade structures by geography and sector are respectively presented for the United States and mainland China as two distinct economies. It is found that around half of the United States' exports of energy use originate from transport and service industries, while nearly 90% of mainland China's exports of energy use come from heavy industry. The findings are supportive for nations to identify their roles in the global supply chain from the perspective of genuine final consumers and adjust the trade patterns for sustained energy use.

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1. Introduction

1.1. Existing energy accounting schemes based on different norms

Quantifying the energy use of national economies remains an essential step to maintain the sustainable use of energy resources as well as to support national policy-making towards mitigating energy-related carbon emissions. In this world featuring increasingly robust fluxes of trans-regional trade that amounts in magnitude to over one-quarter of global GDP (gross domestic product), an integrated globalized supply web has come into shape, making the world economy appears like a giant bathtub absorbing and redistributing resources from almost all nations and regions that are geographically far apart (WTO, 2018; Wu et al., 2018b). As a result, it is necessary to analyze the energy use of each national economy under the global context, since scarcely any nation or region could be isolated from the rest of the world (Nordhaus, 2009). A first question that needs to be firstly addressed is the adoption of the accounting scheme, which identifies the agents and their countries of inhabitation that shall get allocated the energy use within the global bathtub of energy use.

A most common way to establish the energy account of national economies is the territorial-based accounting (Peters et al., 2011), also referred to as production-based accounting (Ghosh and Agarwal, 2014), which treats the energy use of a national economy as the onsite energy use that takes place within its national boundary, as captured by the satellite account. The producers as the agents that technologically consume energy on-site are supposed to be allocated the energy use (Munksgaard and Pedersen, 2001; Su et al., 2013). Therefore, under this accounting scheme, for energy conservation, energy-intensive sectors and their inhabited nations are required to take effective technical measures or propose regulative supervision for improvement of energy efficiency. According to Lenzen et al. (2007), this producer-oriented apprehension of treating the energy use as appendants of the economic industries is mainly due to the inclination of not reaching out a hand to intervene the choices of the customers.

In recent years, extensive attention has been drawn to investigate the resource use or environmental emissions of national economies following a final-demand-based accounting scheme (Davis et al., 2011; Kanemoto et al., 2012; Meng et al., 2018b; Mi et al., 2018; Su and Ang, 2014; Zhang et al., 2016), sticking to premise that final demand serves the driving engine of all industrial production. Compared with the production-based accounting, final-demand-based accounting shifts the point of focus from one side of the coin to the other and arrives at a quite different picture. By means of the final-demand-based accounting that was firstly raised by Leontief (1970) and afterwards extended into a generalized input-output model, the final users as the beneficiaries of production activities are to be allocated the energy use along the supply chain. A global multi-region input-output (MRIO) framework is widely integrated into energy accounting framework, which serves a useful instrument to simulate the global supply chain as well as to reveal the interrelated connections between various industries within the globalized economy (Chen and Wu, 2017; Davis and Caldeira, 2010; Lan et al., 2016; Xia et al., 2017). The final-demand-based MRIO accounting is considered effective in addressing the amount of the energy use or emissions embedded in the goods or services that are ultimately used as final demand in regions outside a nation's jurisdiction (Davis et al., 2011; Meng et al., 2016; Peters and Hertwich, 2008a; Su and Ang, 2017). In addition, it is worth noticing that the final-demand-based accounting has been in recent years referred to as consumption-based accounting, at first by Peters (Peters, 2008; Peters and Hertwich, 2008b) and then widely adopted by other scholars (Bows and Barrett, 2010; Davis and Caldeira, 2010; Lininger, 2015; Meng et al., 2018a; Mi et al., 2017; Steininger et al., 2014; Zhang et al., 2018), in the domain of greenhouse gas emissions accounting that aims at allocating emissions to the nations covered under the United Nations Framework Convention on Climate Change (UNFCCC).

From the perspective of the final users, the final-demand-based accounting redistributes the global total energy use to the nations and regions enveloped in the world economy. Nevertheless, while the final users take the comfort brought about by the consumption of goods and services, the providers of primary inputs earn the income at the same time. The income may come as salaries paid to the employees, or taxes to the government, or revenues gained by the stakeholders, which has always been considered as the driver of the economic activities. Therefore, under the global MRIO model, provided that the primary input suppliers as income beneficiaries are to hold accountable for the enabled energy consumption occurring downstream along the global supply chain, the energy use of a national economy is that assigned to its primary inputs (Liang et al., 2017; Marques et al., 2013; Marques et al., 2012). The national economies that acquire a lot of income by providing primary inputs are supposed to take more duty towards global energy conservation as well as coping with energy-related emissions. Besides, income-based accounting scheme is also helpful for shedding light on energy-conservation measures from the supply-side, such as cutting down the loans received by the industries (mining industries for instance) with intensive income-based energy use.

The abovementioned three allocation schemes respectively present an account of the energy use of national economies, from the producers' side, the final users' side, and the suppliers' side. Besides, it shall be noted that final-production-based accounting (or referred to as sales-based accounting) as another accounting scheme proposed in recent years (Kanemoto et al., 2012), assigns the energy use along the supply chain of the world economy to the finished products by regarding final production as the driving engine of the world economy. Using different accounting schemes, an economy may be allocated quite different amount of energy use, since an economy could be a producer, final user, final producer and supplier of the primary inputs simultaneously. None of them is right nor wrong, just as pointed out by Caldeira and Davis (2011). They merely choose a different way of assignment following different norms and ethical percepts, as noted in normative economics (Paul and William, 2009; Steininger et al., 2016). Meanwhile, the viewpoints based on different allocation principles may well complement each other so as to provide a holistic picture of an economy's performance on energy use, which is helpful to yield an in-depth interpretation of different measures to be taken from various sides for effective energy conservation on the national and global scale.

1.2. A total-consumption-based perspective

The world economy could not only be interpreted as final-demand-driven, supply-driven, final-production-driven, but also final-consumption-driven, or even investment-driven, as acknowledged by normative economics that manifests ideologically prescriptive judgements on economic progress based on different norms or ethical percepts (Paul and William, 2009). To look into the energy use of nations and regions from a consumption-driven perspective, a total-consumption-based MRIO accounting scheme is proposed in this study.

Adhering to the statement of consumption being the sole destination and intrinsic driver of all production, which was initially raised by Adam Smith (1776) and then reinforced by several other influential intellectuals in the history of economics such as James Mill (1824), John Mill (1875), Jean Sismondi (1827) and Alfred Marshall (1895), the total-consumption-based MRIO accounting scheme raised in this study allocates global energy use fully to total genuine final consumption. The term 'total consumption' considered here refers to the total genuine final consumption (including household consumption, government consumption, and consumption of non-profit institutions serving households), which differs from 'final demand' since final demand includes but is not restricted to final consumption (Chen and Chen, 2013; Wu et al., 2018b). Within the global MRIO table as a depiction of the world economy, final demand also comprises other categories, namely gross fixed capital formation and changes in inventory and valuables (Dietzenbacher et al., 2013; Lenzen et al., 2013). While goods and services used as household consumption, consumption by non-profit institutions serving households and government consumption could be regarded as genuinely 'consumed' and do not further come into the production processes, products used as gross fixed capital formation and change in inventories are supposed to re-enter the supply chain as capital goods to facilitate production (Bullard and Herendeen, 1975; Wu et al., 2018b). Hence, from a total-consumption-based perspective, it is natural that the genuine final consumers are to be allocated the energy consumption occurring along the global supply chain. The total-consumption-based energy expenditure of a national economy equals the energy use induced by goods and services that are required domestically and from abroad to satisfy the demands of domestic genuine final consumers.

Within a market-oriented globalized economy featuring increasingly delicate industrial specialization and close inter-dependence of nations and regions, international trade has become a useful tool for some consumption-oriented economies to import massive consumer products from abroad to satisfy domestic final consumption. According to World Integrated Trade Solution, the world's trade volume of consumer products has reached 4.69 trillion US$ in 2016, with several major economies (such as the United States, the European Union, China, Japan, Russia and Canada) being the trading centers (WITS, 2018). Nevertheless, what is generally ignored is that the interregional trade of consumer products synchronizes with the global shift of energy use, resulting in the trade imbalances of major economies in terms of both currency and energy use.

Hence, the aims of this study are as below. First, parallel to the final-demand-based accounting model, a total-consumption-based accounting scheme is proposed to generate fresh ideas from a new perspective by allocating global energy use to the genuine final consumption. Second, from a total-consumption-based perspective, this study seeks to scope into the international transfer of both currency and energy use between regions via trade of consumer products and discuss the related trade imbalances and structures of major economies.

2. Methodology and data sources

2.1. Total-consumption-based MRIO model

Being capable of revealing the intra-and inter-regional connections between the various industries within a meso- or macro-economy, the global MRIO model is applied in this study to supporting the analysis. Initially conceived by Isard (1951) in an attempt to simulate the interwoven economic bonds of a space-economy, MRIO models have in recent years been widely extended into the environmental-extended MRIO model (namely final-demand-based MRIO model) in order to draw a panorama of the trans-boundary transfer of resources use or environmental impacts associated with international trade (Lan et al., 2016; Steen-Olsen et al., 2012; Wiedmann, 2009). Under the environmental-extended MRIO model stemming from a demand-pull perspective, the energy use of the world economy is assigned to the divisions under final demand, supported by the Leontief inverse matrix. A virtual energy intensity specifically corresponding to final products is derived, reflecting the energy use that is initiated to produce one monetary unit of final products (Chen and Wu, 2017; Wei et al., 2018; Wu et al., 2018a). Whereas, under the total-consumption-based MRIO accounting model, products used as household consumption, consumption of non-government institutions serving households, and government consumption are assumed to be fully allocated the energy use. A virtual energy intensity is also defined here, which specially applies to the products used for genuine final consumption. Detail procedures are presented in the next section.

2.2. Algorithm

The world economy is modelled as an economic network comprised of $m \times n$ basic economic units, containing m economies and n basic economic sectors for each economy. F denotes the final demand matrix, including household consumption, consumption of non-profit institutions serving households, government consumption, gross fixed capital formation, changes in inventories and valuables; Z represents the matrix for intermediate inputs; X signifies the matrix for sectoral total output. The correlated relationship between final demand and sectoral total output could be expressed in matrix form as:

$$X = (I - A)^{-1} F, \tag{1}$$

where A is the direct requirement matrix with its element A_{ij}^{st} $(i, j \in (1, 2, \ldots, n)$ and $s, t \in (1, 2, \ldots, m))$ defined as Z_{ij}^{st}/X_j^t, which reflects the direct sectoral output from sector i in economy s needed to generate every unit of output in sector j in economy t; $L(=(I-A)^{-1})$ is the total requirement matrix, or generally expressed as the Leontief inverse matrix, with its element L_{ij}^{st} denoting the total sectoral output by sector i in economy s that corresponds to per unit of final products manufactured by sector j in economy t.

The correspondence between final demand and total genuine final consumption, could be expressed in matrix notion as:

$$F = \hat{\vartheta} C, \tag{2}$$

where
C is the total final consumption matrix, within which the element C_i^s formulates the goods or services produced by sector i in economy s that are consumed by genuine final consumers; $\hat{\vartheta}$ is a diagonal matrix denoting the proportional relationship between final demand and total genuine final consumption (namely the correspondence between final demand and total genuine final consumption), whose element $\vartheta_{ik}^{sd} = \vartheta_i^s = F_i^s / C_i^s$ when $(i = k) \cap (s = d)$ and $\vartheta_{ik}^{sd} = 0$ when $(i \neq k) \cup (s \neq d)$.

Therefore, integrating Eq. (2) and (3) yields:

$$X = (I - A)^{-1} \hat{\vartheta} C, \tag{3}$$

in which $(I-A)^{-1}\hat{\vartheta}$ represents the correspondent relations between the sectoral total output and the total genuine final consumption.

The connection between energy consumption and sectoral output is expressed as:

$$Q = \alpha \widehat{X}, \tag{4}$$

where $\hat{X}$ is the corresponding diagonal matrix for X; α is the matrix denoting the direct energy consumption corresponding to per unit of sectoral output.

The energy expenditure induced by total genuine final consumption could be thus formulated as:

$$Q_c = \alpha (I - A)^{-1} \hat{\vartheta} \hat{C}, \tag{5}$$

where $\alpha_c (= \alpha (I-A)^{-1} \hat{\vartheta})$ is virtual energy intensity matrix for the goods or services used for genuine final consumption, in which the element α_{ci}^s reflects the energy consumption induced to generate one unit of the products that are provided by sector i in economy s for genuine final consumption activities; $\hat{C}$ is the corresponding diagonal matrix for C.

For economy s covered within the world economy, its total-consumption-based energy use is expressed as:

$$TCE^s = \sum_{t=1}^{m} \sum_{j=1}^{n} \left(\alpha_{cj}^t C_j^{ts} \right), \tag{6}$$

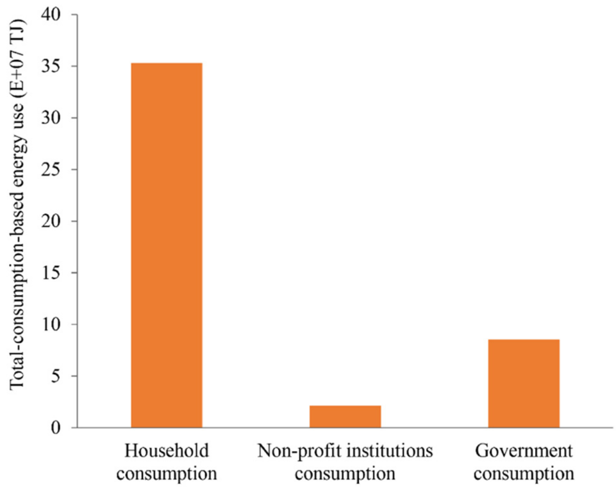

Fig. 1. Energy use induced by genuine final consumption of the world economy.

where C_j^{ts} reflects the goods or services from sector j in economy t to genuine final consumption in economy s; α_{cj}^t is the corresponding virtual energy intensity.

Meanwhile, for economy s, energy use embedded in its imports of consumer products is formulated as:

$$EIC^s = \sum_{t=1(t \neq s)}^{m} \sum_{j=1}^{n} \left(\alpha_{cj}^t C_j^{ts} \right), \quad (7)$$

while that embedded in its exports of consumer products is expressed as:

$$EXC^s = \sum_{i=1}^{n} \sum_{t=1(t \neq s)}^{m} \left(\alpha_{ci}^s C_i^{st} \right). \quad (8)$$

Combining Eq. (7) and (8) produces the energy use embedded in trade balance of economy s, which is expressed as:

$$EBC^s = EIC^s - EXC^s. \quad (9)$$

EBC serves a key indicator to manifest an economy's trading pattern. An economy receives a surplus in energy use when *EIC* outnumbers *EXC*. Reversely, an economy gets a deficit in energy use when *EXC* outstrips *EIC*.

2.3. Data sources

The MRIO table and the direct energy consumption of the investigated sectors are adopted from Eora database (Lenzen et al., 2012; Lenzen et al., 2013). Data for the year 2012 is adopted to reflect recent information for the world economy. The Eora MRIO table divides the world economy into 189 regions and regards each region to be comprised of 26 basic sectors. Regional and sectoral details are respectively presented in Appendices A and B.

As for the population and GDP data for the regions covered under the MRIO table, the statistics unveiled by the World Bank (2016) are applied. Besides, it is worth noting that other existing MRIO databases with quite different regional and sectoral classifications, such as world input-output database (WIOD) (Dietzenbacher et al., 2013; Timmer et al., 2015), global trade analysis program (GTAP) database (Andrew and Peters, 2013), and EXIOPOL (Tukker et al., 2013), are also used in related studies. Among existing MRIO databases, Eora has a coverage of the largest number of nations and regions.

3. Results and discussions

3.1. Energy use induced by genuine final consumption of the world economy

Fig. 1 illustrates the energy use induced by genuine final consumption of the world economy. The energy use induced by global consumer products sums up to the aggregated amount of the onsite energy consumption of all economic sectors. For the elements of final consumption, household consumption is the biggest contributor, dedicating to around three quarters of the global total. This is mainly due to the fact that demands of household consumers have always played a central role in propelling the economic growth, especially in the market-oriented economy. With regard to government consumption, it is demonstrated to account for around one-fifth of the global total energy use.

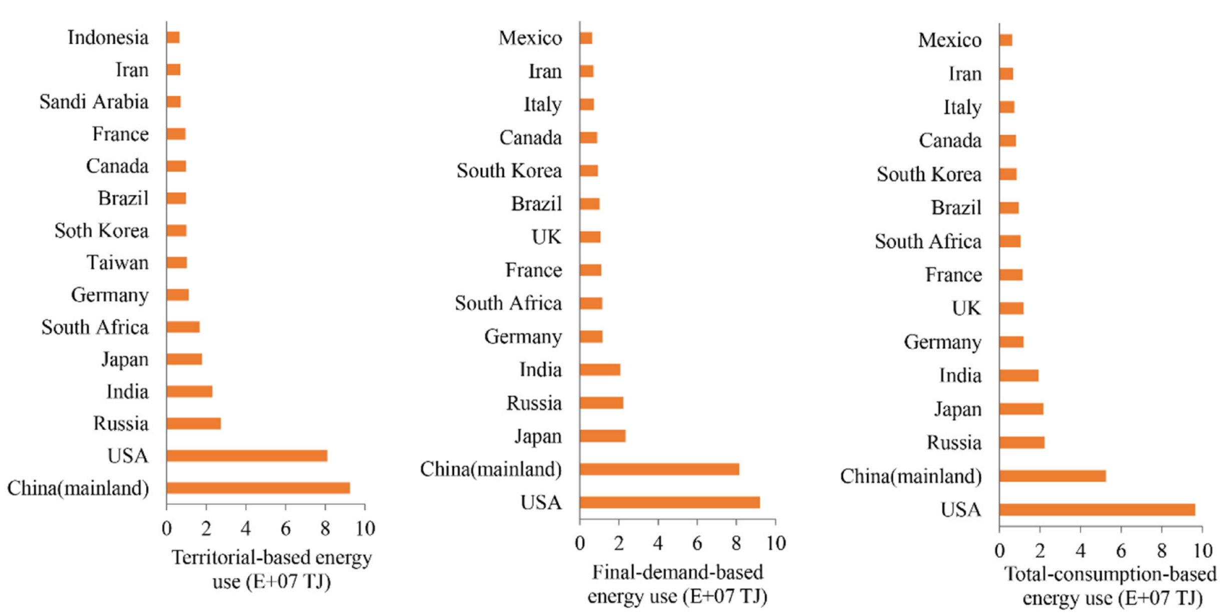

Fig. 2. Energy use allocated to major economies under different accounting frameworks.

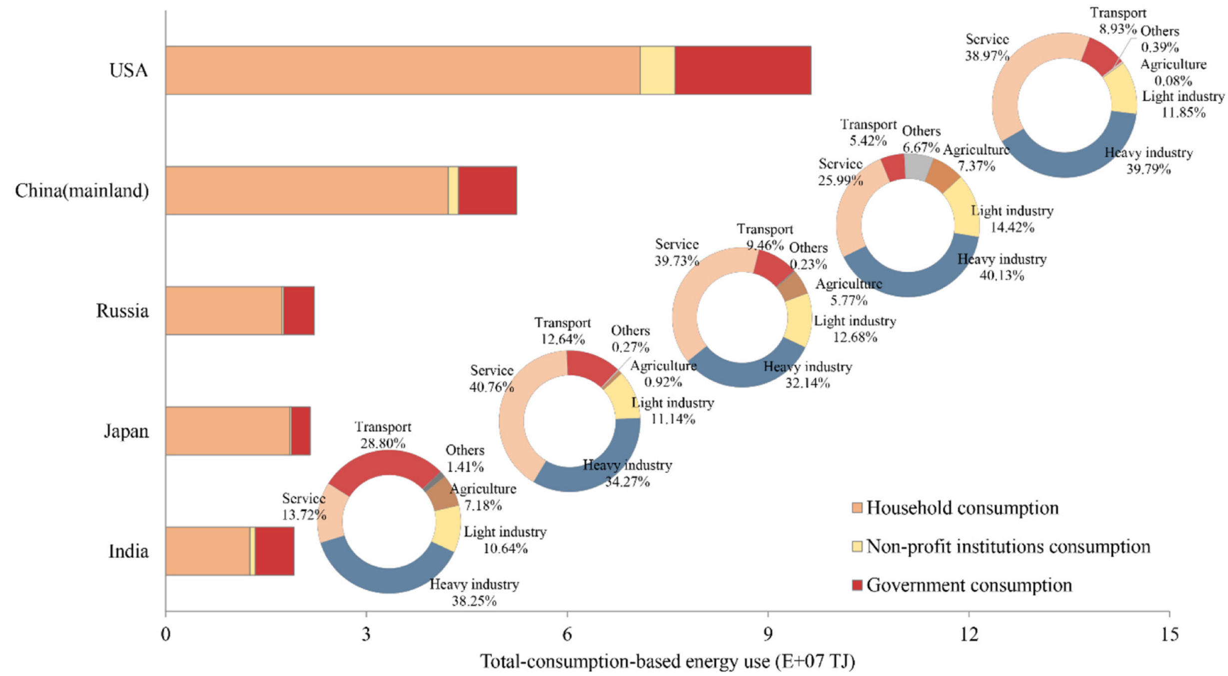

Fig. 3. Sectoral contributions to the total-consumption-based energy use of five leading users.

3.2. Energy use allocated to regional economies

The total-consumption-based energy use of each economy is respectively generated. The United States, mainland China, Russia, Japan, India, Germany, the United Kingdom, France, South Africa and Brazil are revealed as ten leading contributors to the global energy use. As could be observed from Fig. 2, the total-consumption-based energy use of the United States is in magnitude around twice as much as that of mainland China, and over four times that of Russia as well as that of Japan.

The compositions and sectoral contributions to the total-consumption-based energy use of five major energy consumers are presented in Fig. 3. A resemblance of the industrial structure could be observed for the United States and Japan. The consumer products delivered by the service sectors dedicate to around two fifths of the total-consumption-based energy use of the United States and Japan, mainly because that these two economies are characterized by a heavy reliance on the tertiary industry. Besides, the contributions of the agricultural industry could be regarded as negligible for these two economies. For mainland China and India as two distinct developing economies, the service sectors are respectively responsible for one-quarter and one-eighth of their total-consumption-based energy use, much lower than that for the developed economies.

As previously stated, one economy may get allocated different energy use using different accounting methods. Other two metrics, final-demand-based energy use and territorial-based energy use are both taken as references in Fig. 2 to quantify the energy uses of nations and regions, with details attached in Appendix C.1. Regarding final-demand-based energy use, the United States and mainland China still maintain the top two positions, following by Japan, Russia and India. Whereas, as observed, the total-consumption-based energy use of mainland China is lower than its final-demand-based energy consumption by around one-third. This is because that mainland China that is entitled the factory of the world has relied mainly on investment and exports to propel the growth in final demand during the last several decades, and the final consumption rate in mainland China is comparatively low. According the data provided the World Bank (2016), the share of final consumption expenditure in the GDP of China remains steady at round 50% from 2005 to 2015. In comparison, the statistics unveiled by the World Bank suggest that from 2005 to 2015, final consumption expenditure is responsible for steadily around 85% of the GDP for both the United States and the United Kingdom, around 75% of that for both Japan and Germany, and around 80% for France (WorldBank, 2016). As a result, due to the comparatively lower rate of final consumption, mainland China turns out to get allocated less energy use from the global bathtub under the total-consumption-based MRIO accounting framework.

Correspondingly, by grabbing the utility of energy embedded in the great many consumer products imported, some import-oriented economies are allocated more energy use. For instance, the total-consumption-based energy use of the United States, the United Kingdom, Germany and France are revealed to be larger than that their final-demand-based energy expenditures. As for the territorial-based energy expenditures, mainland China outpaces the United States as the leading energy user. Mainland China's territorial-based energy use is nearly twice as much as its total-consumption-based energy use. This has demonstrated that mainland China mainly situates in the upstream part of the global supply chain. A large quantity of onsite energy consumption is essential to support the resource-intensive production processes. Therefore,

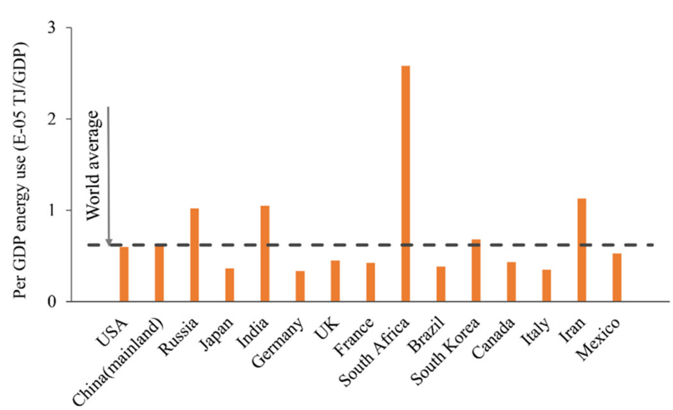

Fig. 4. Per-GDP total-consumption-based energy use for the fifteen major users.

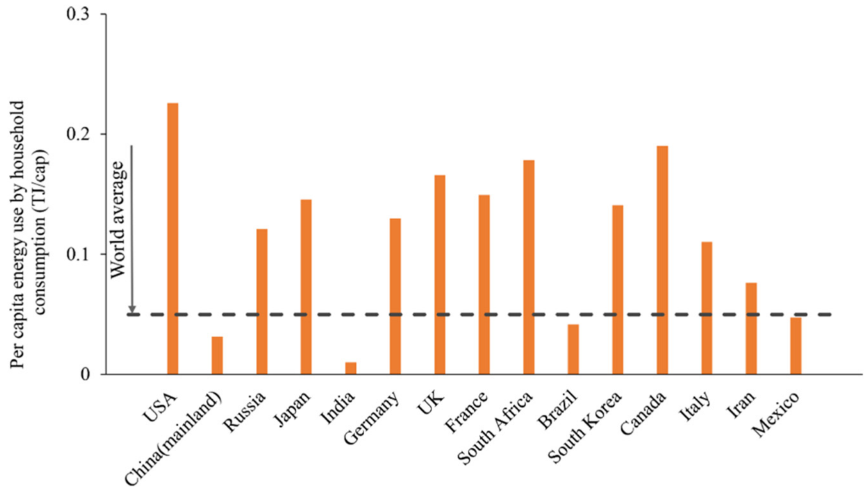

Fig. 5. Per-capita energy use induced by household consumption for the fifteen major users.

though mainland China maintains a trade surplus with some import-oriented economies, challenges towards climate change and sustainable use of local energy resources have appeared.

The total-consumption-based energy use by per-GDP for the major energy users is illustrated in Fig. 4. The South Africa ranks the first place among these economies, followed by Iran, India and Russia. This has reflected a comparatively energy-intensive pattern of the economic growth in these regions. It shall be also noted that mainland China and the United States stay nearly on the same level (around 6 MJ/US$). Besides, the total-consumption-based energy use by per-GDP for some typical developed economies including France, Japan, Italy and Germany generally approach each other.

In addition, to illustrate the energy benefits gained by the households in improving living standards, the per-capita energy expenditures induced by household consumption for these major energy users are depicted in Fig. 5. As witnessed, the United States is revealed to take a leading position among these economies, whose per-capita energy use induced by household consumption is 1.7 times that of Germany, around one and a half times as much as that of Japan, and several times larger than the world average level. Among these fifteen major energy users, the living standards in Mexico, Brazil, mainland China and India as measured by per-capita energy use induced by household consumption lag behind the world average level. Especially, for mainland China and India as the two largest developing economies, the per-capita energy welfares gained by their households are only around 60% and one-fifth of the world average level respectively.

3.3. Energy use associated with the traded consumer products

For the 2012 world economy, 9.64E+07 TJ of energy use is traded inter-regionally along with the exchange of consumer products between nations and regions, in magnitude equivalent to around one-fifth of global total energy use. Some leading importers and exporters of energy use are respectively presented in Figs. 6 and 7, with details attached in Appendix C.2. As shown in Fig. 6, among these major importers of energy use, the United States economy appears to be the

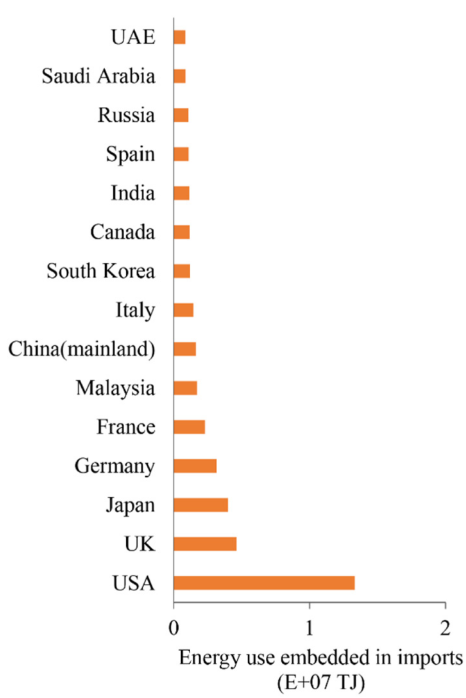

Fig. 6. Major importers in terms of energy use.

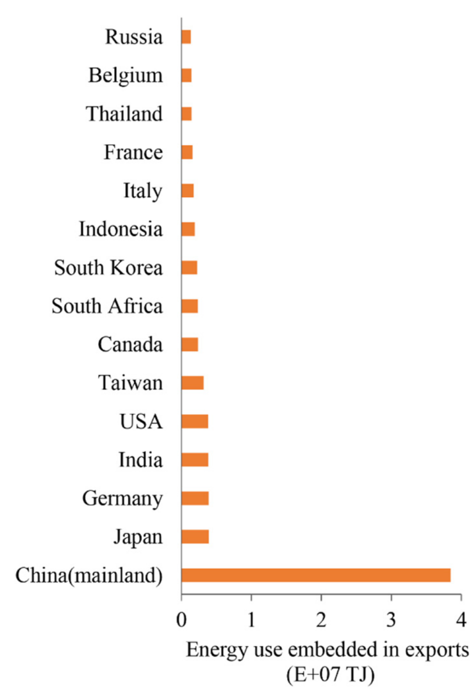

Fig. 7. Major exporters in terms of energy use.

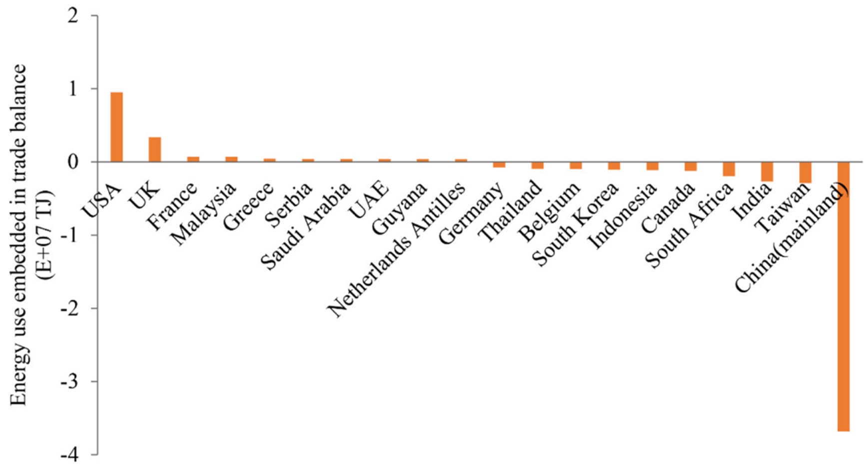

Fig. 8. Trade balance of energy use for ten major net importers and ten major net exporters.

largest receiver. Its imported energy use associated with consumer products is in magnitude equivalent to around one-seventh of the global trade volume (the summation of energy embedded in the traded consumer products). The United Kingdom, Japan, Germany, and France come as the successors. While for mainland China and India as two distinct emerging markets, their imports of energy use are respectively only around one-tenth and one-twelfth of that of the United States.

As for the exporters of energy use, mainland China ranks the first, whose exported energy use far surpasses that of the other exporters. This is mainly due to that the imported-oriented economies situating in the high end of global value chain have for decades outsourced the energy-intensive industries by importing massive amounts of low value-added consumer products produced in emerging markets such as mainland China. In this way, mainland China is integrated into the global supply chain by pouring its abundant natural resources into the global bathtub, which indirectly helps sustain the living standards in the consumption-oriented economies. Japan, Germany, India, the United States and Taiwan follow, the amount of whose exported energy use generally approaches each other but is only in magnitude around one-tenth of that of mainland China. At witnessed, Japan, Germany, the United States are revealed to be both important importers and exporters, which is attributed to the specific industrial specialization of these economies. On one hand, these three economies rely on the imported consumer products, which are mainly low value-added or resource-intensive goods, to satisfy the domestic needs. On other hand, these economies export large quantities of high value-added goods abroad for maximization of their financial revenues. For instance, Japan and Germany are highly dependent on the exports of their world-reputed automatic vehicles to gain economic trade surplus.

The net trade volume of energy use embedded in the traded consumer products is in magnitude around one-twelfth of the global total energy use. The major net importers and net exporters are presented in Fig. 8. Among these economies, while the United States is illustrated to be the largest net importer of energy use, mainland China is revealed to be the biggest net exporter. As observed, the trade imbalance in terms of energy use for mainland China is around four times that for the United States.

3.4. Trade links between major energy users

The interweaved links of world regions in terms of gross trade and net trade of energy use are respectively illustrated in Fig. 9(a) and (b). For clear illustration, the world economy is considered to be constituted by twenty economies, namely EU 27 (including the 27 members of the European Union with Croatia excluded), China (including mainland China, Hong Kong, Macao and Taiwan), ASEAN (the ten members constituting the Association of Southeast Asian Nations), the 16 biggest exporters of energy use within the other 148 regions, and one region

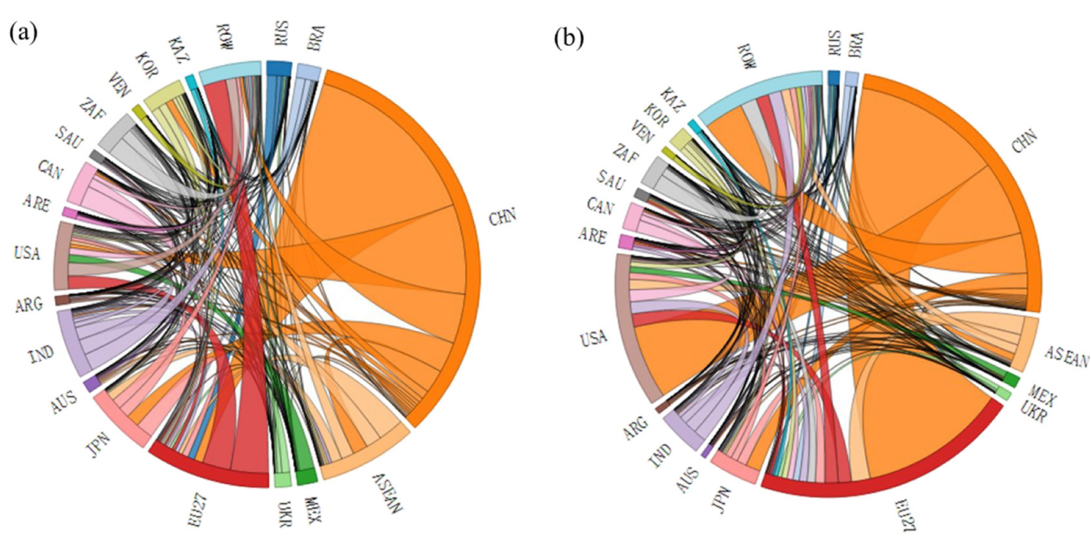

Fig. 9. Energy use connections between twenty world regions by (a) general trades and (b) net trades.

representing the rest of the world (abbreviated as ROW integrating all the rest 132 regions). In Fig. 9(a), there are altogether twenty arc lengths around the circle, corresponding to the export volume of each economy. Within the circle there exist 190 chords, with each chord corresponding to the trade connection between the two economies linked. The sub-arc lengths at the two ends of a chord respectively indicate the general trade flows between the two economies connected, with the color conforming to that of the economy with a larger export volume.

Within the world economy, the largest trade flow in terms of energy use is the export from China to EU27, which amounts to over half of EU27's total imports. The outflow of energy use from China to the United States turns out to be the second largest, equivalent to around 40% of the total imports of the United States. As revealed, massive energy use is embedded in the exported products from China to its two major trading partners, which has been long neglected in existing energy trade statistics that consider the trade of energy products only. Meanwhile, as witnessed from Fig. 9(a), a dominant role is played by China in interregional trade of energy use, the export of which is comparable to the summation of that of the rest economies. Second only to China, EU27 is responsible for around one-tenth of the global total exports of energy use. The United States is demonstrated to be a most important market for EU27's exports. The energy use outflow from EU27 to the United States shares one quarter of EU27's total exports. ASEAN, Japan and India follow as other top exporters. Of all the energy use coming out of ASEAN, 28% of it flows into EU27, 17% to the United States, 17% to China, and 12% to Japan. With regard to the imports of energy use, EU27 becomes the world's largest receiver. Apart from China that contributes most significantly to EU27's inflows of energy use, ASEAN, Japan, the United States and India are also proved to be important contributors.

In Fig. 9(b), the chord shows the net trade relations between the twenty economies linked, with the color of the chord consistent with that of the net exporter. China, India, and ASEAN turn out to be the largest three net exporters, while EU27 and the United States are revealed as the top two net receivers of energy use. Fig. 10(a) and (b) respectively map the major consumer-product-related net trade flows in terms of energy use and currency. As seen, energy use generally moves in the opposite direction with currency. The two significant net trade flows of energy use are that between China and EU27, and that between China and the United States. Besides, apart from EU27 and the United States that are highly dependent on 'China-made' consumer products, Japan and ASEAN are also observed to be important contributors to China's trade deficit of energy use. For Japan, while it receives massive net exports of energy use from China, a considerable amount

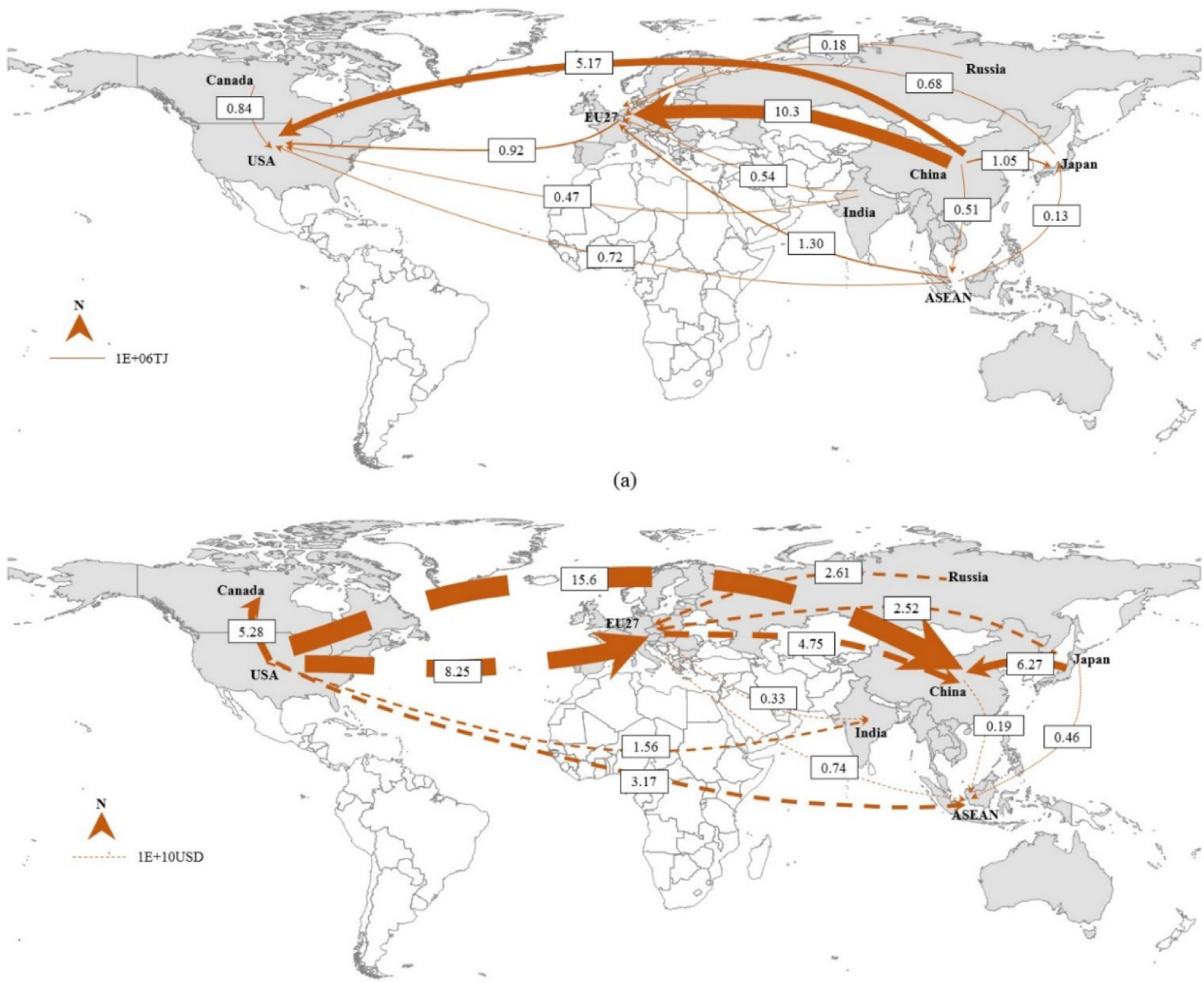

Fig. 10. Major interregional net trade flows in terms of (a) energy use and (b) currency.

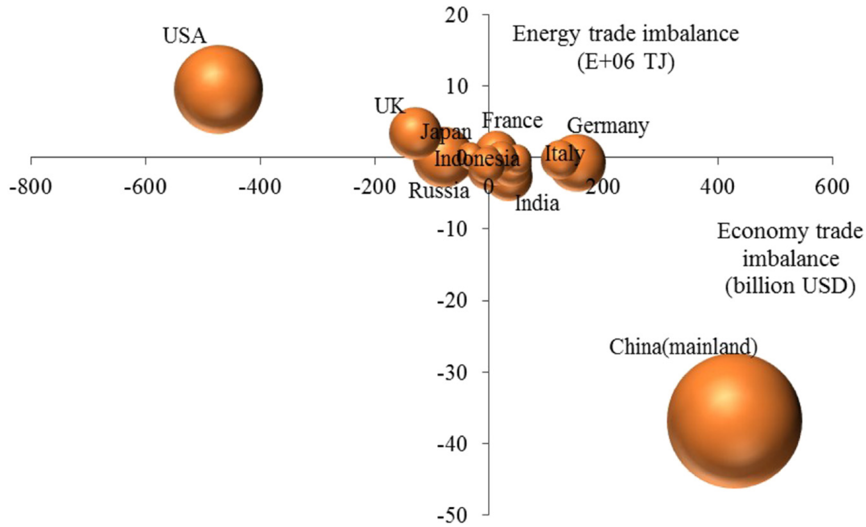

Fig. 11. Trade imbalance of major economies in terms of both energy use and currency.

of net outflow of energy use accompanies its high value-added goods (such as automobiles and electronic products) exported to EU27 and the United States. In addition, it is also worth noticing that Russia has a trade deficit with EU27 in terms of both currency and energy use.

3.5. Trade imbalances for major total-consumption-based energy users

To further illustrate the trade patterns of the economies from a total-consumption-based perspective, the consumer-product-related trade imbalances (trade imbalance brought by the exchange of consumer products) for the twenty major energy users are illustrated in Fig. 11. For an economy, it might be a net receiver of energy use and meanwhile net exporter of currency (corresponding to the second quadrant in Fig. 11), or a net exporter of both energy use and currency (corresponding to the third quadrant in Fig. 11), or a net exporter of energy use and net receiver of currency (corresponding to the fourth quadrant in Fig. 11), or a net receiver of both energy use and currency (corresponding to the first quadrant in Fig. 11). Besides, the gross trade volume of an economy is reflected by the size of the corresponding sphere in Fig. 11.

As witnessed, the United States, Japan, the United Kingdom, Australia, Iran and Saudi Arabia are located in the second quadrant, gaining a trade deficit in currency but a trade surplus in energy use. As previously stated, consumption-oriented economies such as the United States and the United Kingdom are highly reliant on imported products, especially the low-value consumer goods (such as furniture, bedding, sport equipment, etc.) from developing economies, thus resulting in an evident consumer-product-related trade deficit in monetary terms. Based on the 2012 MRIO table by Eora, the consumer-product-related trade deficit for the United States and the United Kingdom have respectively reached 473.16 billion US$ and 129.25 billion US$. Another underlying phenomenon generally being ignored is that the United States and the United Kingdom have at the same time acquired an energy benefit of 9.49E+06 TJ and 3.38E+06 TJ invisibly. Recently, in order to cut down its massive economic trade deficit, the United States has launched a series of regulations on imposing additional tariffs on products imported from abroad, such as the sanction tariffs on 200 billion worth of products coming from mainland China (WhiteHouse, 2018). Nevertheless, the invisible transfer of energy use has not been directed sufficient attention, which is to be further acknowledged in bilateral negotiations to reach a reciprocal trade agreement.

It could be witnessed that some other developed economies exhibit a different trend, which are observed to be in the fourth quadrant and near the horizontal axis. For instance, Germany and Italy respectively have a notable consumer-product-related trade surplus of 153.58 billion US$ and 123.81 billion US$ in monetary terms. This is because that though these economies depend heavily on low value-added products provided by the emerging markets, they export a large quantity of high-value consumer products to foreign economies due to their comparative advantages in industrial specialization. For instance, Germany as one of the largest exporter provides the world regions with massive 'Germany-made' consumer products including the automatic vehicles and assemblies, computers, and packaged medicaments, with the United States, the United Kingdom, France and China being its most important trading partners. According to OEC (observatory of economic complexity), cars and packaged medicaments have for years altogether held responsible for nearly one-fifth of Germany's total exports (OEC, 2018b). Though Germany and Italy absorb a considerable quantity of net inflows of currency, their energy accounts from a total-consumption-based perspective are relatively balanced. This is because that their exports of energy use are largely neutralized by the intake of energy use associated with the vast imports of resource-intensive and low value-added consumer products.

Meanwhile, it shall be noticed most of the emerging markets, mainly the developing countries such as mainland China, India and Brazil, situate in the fourth quadrant as well. Especially, China gains the largest consumer-product-related economic trade surplus, around three times as much as that of Germany as well as Japan. Statistics given by OEC suggest that low value-added clothing goods (knit sweaters, knit suits, coats, shirts, etc.), footwears (rubber, textile and leather footwear, etc.), furniture (light fixtures, seats, models and stuffed animals, mattress, etc.), and plastic products account for around one-fourth of mainland China's exports (OEC, 2018a). Whereas, a tradeoff towards vast energy usage is witnessed owing to the exported-oriented trade pattern of mainland China, whose trade deficit of energy use is in magnitude nearly the summed amount of the trade imbalances of all other major economies.

Situating in the first quadrant, France and Spain turn out to be net importers of both currency and energy use. The consumer-product-related trade surpluses of France and Spain in monetary terms are respectively 13.26 billion US$ and 20.22 billion US$ while their trade surpluses of energy use are respectively 6.73E+05 TJ and 5.24E+04 TJ. Though these two economies get an economic trade surplus, the energy use embedded in their imported consumer products has exceeded that embedded in the exports. Two primary reasons may account for this phenomenon. One reason could be that these economies mainly specialize in the high-value and energy-conservative products. The other may be that the average energy intensity of the export commodities in

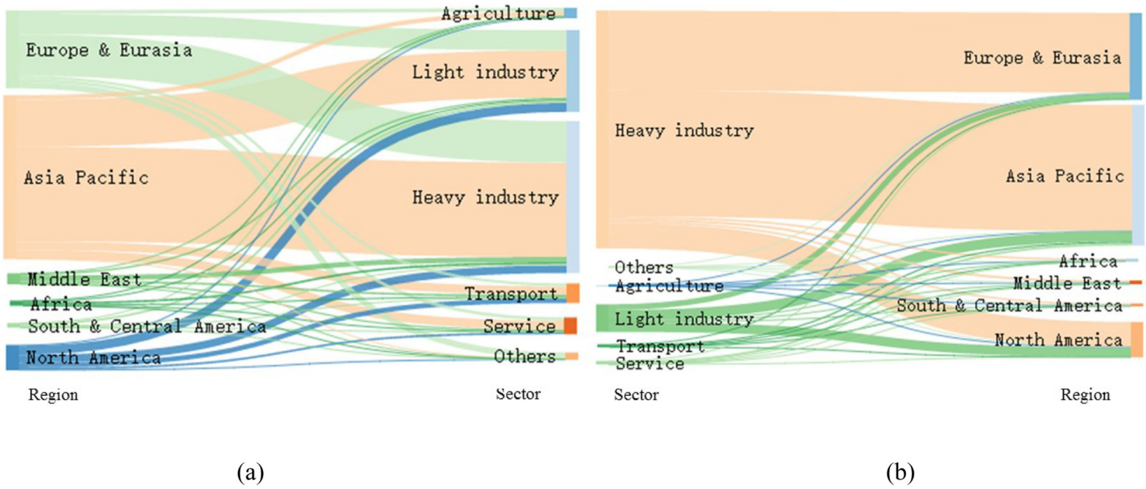

Fig. 12. Geographical and sectoral contributions to energy use embedded in the (a) imports and (b) exports of mainland China.

these economies are much lower than that in their trading partners, owing to their advantage in production and energy-utilization efficiencies. Inversely, Russia and Indonesia that locate in the third quadrant are revealed as net exporters of both currency and energy use.

3.6. Distinct trading economies

In this section, by illustrating the sources and destinations of the traded consumer products by geography and sector, the trade structures of mainland China and the United States (as two distinct trading economies) in terms of energy use are separately discussed, as respectively shown in Figs. 12 and 13. The world regions have been aggregated into six major regions, namely Asia Pacific, Europe & Eurasia, North America, South & Central America, Africa and Middle East, with the detailed classification attached in Appendix A. As demonstrated in Fig. 12, Asia Pacific is revealed as the largest market of mainland China's exports of energy use, occupying a share of 52%, followed by Europe & Eurasia (32%), and North America (13%). On the sectoral level, heavy industry and light industry come as the two leading sources of mainland China' exports of energy use, accounting for around 87% and 10% of the total. It is found that the North America is responsible for around one-tenth of heavy industry exports and one-third of light industry exports by mainland China, demonstrating the heavy dependence of North America on mainland China's light industry products. Meanwhile, with regard to the imports by mainland China, Asia & Pacific still maintains the first position, taking up a proportion of 57%.

For the United States, the largest supplier for its imports of energy use resides with Asia Pacific, responsible for 57% of the total. Meanwhile, the contributions by Europe & Eurasia and North America to the imports of the United States are generally approximate, the summed share of which is around 40%. On the sectoral level, 67% of the United States' imports of energy use originate from heavy industry abroad, 25% from light industry, and 5% from transport industry. Of the energy use embedded in the consumer products imported from heavy industry abroad, 60% is supplied by Asia & Pacific, 21% by Europe & Eurasia, and 17% by North America. Meanwhile, it is worth noticing that while the contributions by Middle East and South and Central America to the heavy product imports of the United States are marginal, these regions remain important sources to the United States' light industry imports. In recent years, the United States has gradually cut down its direct energy imports, imputed to the blossom in shale gas exploitation. Whereas, it remains a future work to explore from a holistic perspective whether the United States has lessened its dependence in foreign imports by giving full consideration to the changes in imports of energy use.

North America, and South and Central America serve the major destination markets for the United States' exports of energy use, altogether accounting for over 40% of the total. On the sectoral level, transport sector becomes the largest source of the United States' exports, sharing 41% of the total, followed by heavy industry (30%), light industry (21%), service industry (7%), etc. While North America serves the main destination of the exports by the light industry in the United States, Europe & Eurasia is the biggest market of those by the United States' heavy

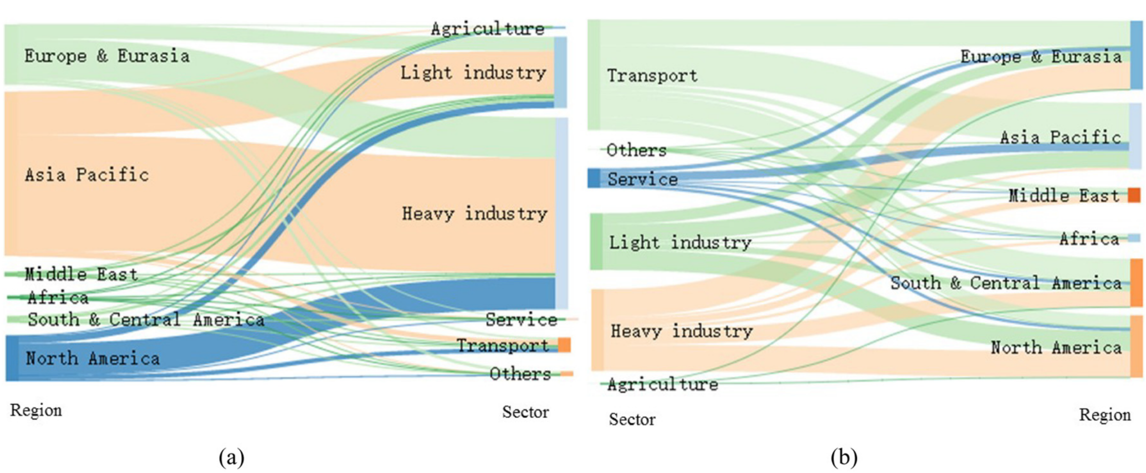

Fig. 13. Geographical and sectoral contributions to energy use embedded in the (a) imports and (b) exports of the United States.

industry. Meanwhile, of all the energy use exported by the transport industry in the United States, 36% of it goes to Asia & Pacific, 23% to Europe & Eurasia, 21% to South and Central America, and 11% to North America. As could be seen, due to the blossom of international trade and tourism, the services provided by the United States' transport industry have been warmly embraced all over the world, especially by nations in Asia & Pacific, to ship the products or tourists to the destination.

4. Conclusions

This study has drawn a new picture of nations' energy consumption from the side of the genuine final consumers and explored the transfer of energy use along with the interregional economic flows within the world economy. Parallel to the final-demand-based MRIO accounting model, a total-consumption-based MRIO accounting scheme is for the first time proposed by allocating the onsite energy use to the total genuine final consumption.

Our finding suggests that the energy use of a nation under the total-consumption-based MRIO scheme is different from that derived under existing accounting models. For the consumption-oriented developed economies such as the United States, the United Kingdom and France, their total-consumption-based energy use is obviously higher than final-demand- and territorial-based energy use. While for China as the largest developing economy, its total-consumption-based energy use is respectively 36% and 43% lower than its final-demand- and territorial-based energy use, due to the investment- and export-driven GDP structure and the comparatively lower level of consumption in contrast to the developed economies. From a total-consumption-based perspective, this study revealed that China acts as the largest importing market for EU27 as well as the United States, and is responsible for around half and 40% of their imports of energy use respectively. Though this phenomena of international transfer of energy use may to a certain degree help ease the domestic burden of massive energy requirement and environmental emissions for the consumption-oriented economies, it may to some extent lead to the challenge of energy shortage on the global scale, since much more energy consumption may be induced for producing per unit sectoral output in the emerging economies as compared to developed regions.

To ensure sustainability of global energy use, a technology transfer from import-oriented developed nations to the emerging export-oriented markets is necessary, which may help enhance the production efficiency in the emerging economies and offset the bilateral economic trade imbalance at the same time. Meanwhile, for some export-oriented developed economies (such as Japan, Germany, South Korea, etc.) exporting massive high value-added goods for final consumption, they may try to further enhance the production efficiencies, thus invisibly cutting down the energy usage in the upstream supply chain. For exported-oriented developing economies such as mainland China, apart from the improvement of production efficiencies, they needs to change their trade patterns to be more economically and ecologically competent in the global market. It is revealed in this study that heavy industry contributes to around 90% of mainland China's exports of energy use. While for the United States, tertiary industries such as transport and service sectors hold responsible for around half of its exports. As demonstrated, for mainland China, it is necessary alter its role from being the global factory of resource-intensive goods (mostly low value-added) to a provider of high value-added and knowledge-intensive products and services, such as advanced manufacturing, big data technologies, artificial intelligence and human capital service. It is also noticing that for mainland China, the per capita energy use induced by household consumption is only around three fifths of the world average level. With the increasingly demands of domestic rising middle class towards a more affluent lifestyle, China shall strengthen the delivery of high-quality, and high value-added goods or services to satisfy domestic consumptive needs, thus acquiring more embedded energy use to promote domestic living standards. By offers a new index from the side of the genuine final consumers, the total-consumption-based accounting scheme offers new information into the measurement of an economy's residential biophysical living standard.

Competing interests

The authors declare no competing financial interests.

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Appendix A. Supplementary data

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