Global overview for energy use of the world economy: Household-consumption-based accounting based on the world input-output database (WIOD)

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Abstract

Globalization has integrated nations into a world economy. Based on the world input-output database (WIOD), this paper explored the energy use of the world economy under a household-consumption-based MRIO (multi-region input-output) accounting scheme. Pertaining to normative economics, the household-consumption-based MRIO accounting scheme corresponds to the value judgement of household consumption being the ultimate driver of the economy, which complements existing accounting methods based on different viewpoints. The energy use associated with the internationally traded products is calculated to be around one-fifth of the global total energy consumption. For China as the largest exporter and also the biggest deficit economy in terms of energy use, its trade imbalance is nearly the summation of that of the United States, the United Kingdom, Japan and Germany. Energy self-sufficiency rates by supply and by demand are respectively proposed. While the United States economy as the largest importer maintains the majority of the energy welfare denoted by the onsite energy use at home, China exports large

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quantities of energy use abroad. For economies like Germany, South Korea and Taiwan, they could be regarded as hubs that export a considerable amount of energy use abroad and absorb massive energy use from outside simultaneously. For sustainable use of energy resources, economies are suggested to carefully identify their roles in the global trading network of energy use.

Keywords: World economy; Household-consumption-based MRIO accounting; Energy use; Trade imbalance; Hubs.

1. Introduction

1.1. Current energy accounting schemes for economies

The occurrences of energy crisis in the last several decades, such as the 1970s energy crisis and 1990 oil price shock (Adelman, 1990; Binder, 1973), give rise to renewed focus on energy accounting of national or supranational economies (Arto et al., 2016b; Song et al., 2017; Wu and Chen, 2017a). Generally speaking, energy accounting is of key essentiality to add our knowledge on different economies' contributions to the depletion of energy resources worldwide as well as to shed light on the cooperated efforts towards safeguarding energy security or mitigating energy-related emissions.

Direct energy expenditure is a widely-used metric by institutions or governmental authorities to measure the energy use physically taking place within an economy, as could be seen from the annual energy accounts for the world nations unveiled by international energy agency (IEA, 2016), and the energy statistical yearbooks by the National Bureau of Statistics of China (NBS, 2016a). This accounting method could be referred to as onsite-based accounting or production-based accounting (Kharrazi et al., 2015), sticking to the principle that an economy's energy use is directly driven by the onsite energy requirement of the domestic production activities. By pinpointing the energy-intensive industries, this method is fully supportive for policy makers to implementing energy-conservative measures on the production side (Wu et al., 2016b; Wu et al., 2016c).

While the production-based accounting places an eye on the onsite technical energy consumption within an economy, it is unable to reflect the energy use required to satisfy an economy's final requirement for goods and services given the lacking consideration of the energy embedded in the imported or exported goods (Su and Thomson, 2016; Tang et al., 2013; Yang et al., 2014; Zhang et al., 2017a). Currently, with the accelerated progress of globalization, the role played by international trade has been greatly enhanced. Different countries are connected by the globalized network and have a closely intertwined relationship with each other (Meng et al., 2016; Mi et al., 2018; Su and Ang, 2014; Zhang et al., 2017b). Therefore, it is highly probable that a product, which is manufactured in one country using energy that is either domestically exploited or imported from other nations, is exported to another country for reprocessing, and then re-exported for final use in a third country (Wu and Chen, 2017b). In this regard, following the demand-pull principle, a final-demand-based accounting method, which was firstly proposed by Leontief (1970), has been in recent years widely extended into a multi-region input-output (MRIO) model to deal with the shift of resources use along with the sliced-up global supply chain (Arto et al., 2016a; Behrens et al., 2007; Chen et al., 2018; Chen and Han, 2015; Su and Ang, 2017; Wiedmann et al., 2015; Wu et al., 2018). By including a set of nations and regions geographically located worldwide but conjoined by international trade, the final-demand-based MRIO accounting method apportions the energy use occurring along the supply chain to the final users (Owen et al., 2017; Zhang et al., 2016). For instance, supported by Eora database, Lan et al. (2016) explored the energy footprint of world nations by assigning the direct energy consumption to final demand. Su and Ang (2017) used the input-output framework to study the relations between energy use and GDP from two different viewpoints in terms of the final demand perspective and production perspective. Similarly, Wu and Chen (2017b) compared the energy use of the world nations as recorded by final-demand-based energy use and production-based energy use. Generally speaking, the final-demand-based MRIO accounting is fully implicative for global collaboration towards sustainability of energy use, such as energy-efficient technology transfer from developing countries to developed countries. In addition, it needs to be noted that in recent years the final-demand-based MRIO accounting finds extensive application in the field of carbon emission accounting and has been commonly termed as consumption-based accounting (Davis et al., 2011; Meng et al., 2018; Mi et al., 2017; Su and Ang, 2011; Zhang et al., 2018), which was firstly proposed by Peters and his colleagues (Peters, 2008; Peters and Hertwich, 2008; Peters et al., 2011) and then widely adopted.

Moreover, as noted in existing works, the driving force of the world economy could be interpreted in multiple ways, such as demand of final users (corresponding to the final-demand-based MRIO accounting method), primary inputs provided by the suppliers (corresponding to the income-based MRIO accounting method), and final production[1] (corresponding to final-production-based or sales-based MRIO accounting method)

[1] Under the MRIO model, while final demand of a nation refers to the region's requirements of goods or service for final users, the final production of a nation means the nation's output of final products. For the world economy, the total products generated by the final producers equal the amount of the world's final demand. Therefore, the final-production-based MRIO accounting method differs with final-demand-based MRIO method only in how much energy use a nation may get allocated.

(Kanemoto et al., 2012; Liang et al., 2017; Marques et al., 2013). Following the supply-driven principle that the primary input providers generate income by enabling the energy use in downstream processes (Wu et al., 2016a), the income-based MRIO accounting method assigns energy use to these primary suppliers situating at the initial stage of the supply chain. As a result, this method may facilitate some key economies as income beneficiaries to export their products to downstream economies with energy-efficient technologies. As for the final-production-based MRIO accounting method, final producers that situate at the final production stage (only a step before entering into final demand) are supposed to get allocated the energy use along the global supply chain (Kanemoto et al., 2012), which urges the nations and sectors with immense exports of final products to enhance their production efficiencies.

These several representative accounting methods shed light on the contributions of each nation to the global energy use based on different interpretation about the driving force of the world economy. For different accounting schemes, they are not facts of nature but subjective conventions for assignment founding on varied norms or ethical percepts, as having been addressed by Caldeira and Davis (2011) as well as by Steininger et al. (2016). Generally speaking, these accounting methods based on different norms are pertaining to normative economics, which deals with questions of "what ought to be " and involves value judgements about the economy (Samuelson and Nordhaus, 2009). Under different accounting schemes, while the global balance of energy use for the world economy in a specific year could be maintained, the energy use assigned to a nation as the constituent of the world economy bears slight or great difference. A judgment over which accounting scheme is better is logically meaningless (Peters, 2008), since the different systems of accounting just interpret the world economy from different subjective perspectives and serve different purposes. It is also noting that compared to normative economics, positive economics deals with questions of “what it is”, namely the facts of the economy or “the way things are”. Those studies that aim to trace the global energy use from source of exploitation to sink of final demand fall into the domain of positive economics, such as the series of embodied energy accounting for the world economy by Chen and his colleagues (Chen and Wu, 2017; Chen and Chen, 2011b; Kan et al., 2019; Wu and Chen, 2018, 2019). The origin of this thought resides with the physiocracy school led by Quesnay (1758), who regarded productive land as the sole source of the national wealth and created the economic table to trace how the agricultural products as the sole source of the wealth of nations finally sink into the society. By inheriting and extending the thought of physiocrats, Herendeen (1973) gave birth to the concept of embodied energy and established an energy balance model to explore how primary energy resources as the genuine energy support enters, circulates within, and sinks into the society in the form of embodied energy (Bullard and Herendeen, 1975a, b; Hannon, 2010; Herendeen, 1978; Herendeen, 2004). In recent years, by combing the embodiment theory of systems ecology by Odum (1983) into the biophysical balance model by Herendeen (1973), Chen and his colleagues extended the embodied energy accounting to global (Chen and Wu, 2017; Kan et al., 2019; Wu and Chen, 2018, 2019), national (Wu and Chen, 2017a) and regional scales (Li et al., 2016). In brief, regarding positive economics and normative economics, neither is correct nor incorrect. They remain as two ways in dealing with economic issues.

1.2. A household-consumption-based perspective

As an extension of normative economics, the household-consumption-based accounting as a new accounting scheme is proposed, holding to a commonly accepted belief that household consumption acts as the ultimate purpose of the production (Adam, 1827). Therefore, it appears to be natural that household consumption is to be allocated the energy use along the supply chain of the world economy.

According to the Columbia Encyclopedia, the original meaning of consumption represents the usage of goods or services (as objects of utility) by customers for the satisfaction of wants (O'Connor, 2001). This concept has been afterwards expanded by Carl Marx in the book "*Capital: A critique of political economy*" into a broad term (Marx, 1867) including productive consumption (namely the utilization of the means of production for commodity manufacturing) and residential consumption (namely the original meaning of consumption that corresponds to the household consumption in the MRIO model). The residential consumption has been referred to by Marx as the end in a round of production process, which creates the conceptual motive for producing actions and thus remains the precondition of production. Moreover, just as stated by Adam Smith in his monumental work "*An inquiry into the nature and causes of the wealth of nations*", residential consumption serves to be the destination and aim of all producing activities (Adam, 1827). This interpretation was later inherited by a number of classical and neo-classical economists, such as James Mill, Alfred Marshall, Jean Sismondi (Marshall, 1890; Sismondi, 1819). Then in 1936, John Keynes highlighted the role of household consumption by regarding inadequate household consumption as the fundamental reason accountable for insufficiency in effective demand (Keynes, 1936).

These apprehensions on the role of household consumption constitute the theoretical background for the allocation norm of this newly proposed household-consumption-based MRIO accounting scheme. Meanwhile, as witnessed from the global MRIO model, final demand is comprised of final consumption expenditure by households, that by government, that by non-profit organization, gross fixed capital formation and changes in inventories and valuables. Regarding final consumption by government, it guarantees that the government could thoroughly perform their duty of guarding the benefits of household consumers. A sentence coming from *Gettysburg Address* by Abraham Lincoln may best explain this: "government of the people, by the people, for the people shall not perish from the earth" (Lincoln, 1994). Parallelly, similar explanation applies to final consumption by non-profit organization. As for fixed capital and changes in inventories and valuables, though presented to the society as part of the final demand, they are bound to come into the economic circle and function as inputs for the production activities (Bullard and Herendeen, 1975b; Wu et al., 2018).

In this paper, a tentative effort is undertaken to probe into the energy use of the world economy using a household consumption-based accounting scheme. First, the energy use of different national and supra-national economies within the world is quantified by combing the global MRIO table and energy statistics. After that, the trade interrelations between nations in terms of both currency and energy use are penetrated and visualized. Policy implications are proposed based on the results.

2. Method and data sources

2.1. Household consumption-based MRIO model

Multi-region input-output analysis has been applied to analyzing the connection between economy and ecological flows in terms of energy use (Chen and Chen, 2013; Chen and Chen, 2011b; Wu and Chen, 2018), land use (Chen and Han, 2015; Wu et al., 2018), carbon emissions (Chen and Chen, 2011a; Deng and Xu, 2017) and mercury emissions (Chen et al., 2016) for the global economy. The demand-based accounting manner, generally referred to as environmental-extended input-output analysis, is widely applied to allocating onsite energy use to final demand following the demand-pull principle as previously mentioned, with the derived virtual energy intensity applicable only to the products as final demand. Under the household consumption-based MRIO accounting model, the onsite energy use has been totally allocated to products used as household consumption. The virtual energy intensities derived are defined only for products used as household consumption. Specific algorithms are shown in the next section.

2.2. Algorithm

The energy MRIO table is presented in Table 1. Under the final-demand-based MRIO model, the energy use embedded in final demand is formulated as:

$$E_{\mathrm{f}} = E\hat{X}^{-1}\left(I - Z\hat{X}^{-1}\right)^{-1}\hat{F}, \tag{1}$$

where E is the vector of sectoral onsite energy use; X is the vector of sectoral total output; Z is the square matrix of intermediate inputs; $\left(I - Z\hat{X}^{-1}\right)^{-1}$ is the Leontief inverse matrix; F is the vector of final demand ($\hat{F}$ is the corresponding diagonal matrix). Therefore, the vector for virtual energy intensity of final products (products that are used as final demand) is obtained as:

$$\varepsilon_{\mathrm{f}} = E\hat{X}^{-1}\left(I - Z\hat{X}^{-1}\right)^{-1} . \quad (2)$$

Household consumption is covered within the categories of final demand in the MRIO model. The linear relations between final demand and household consumption can be expressed as:

$$H = \hat{\delta}F , \quad (3)$$

where F is the column vector of final demand; H is the column vector of household consumption, representing the sectoral products that go to household consumption; $\hat{\delta}$ is the diagonal matrix that depicts the corresponding linear relationship between the sectoral products used as final demand and the sectoral products used as household consumption. In a given input-output table, the column vector of household consumption could be directly obtained. With regard to the column vector of final demand, it could be obtained by summing up the subcategories of final demand (such as household consumption, government consumption, consumption of non-profit organizations serving household, gross fixed capital formation, and changes in inventories and valuables). The diagonal matrix could then be calculated.

By introducing Eq. (3) into Eq. (1), the onsite energy use is totally assigned to household consumption. Therefore, the energy use initiated by household consumption can be expressed as:

$$E_h = E\hat{X}^{-1}\left(I - Z\hat{X}^{-1}\right)^{-1}\hat{\delta}^{-1}\hat{H} . \quad (4)$$

The energy embedded in per unit of products that are used for household consumption is thus obtained as:

$$\varepsilon_h = E\hat{X}^{-1}\left(I - Z\hat{X}^{-1}\right)^{-1}\hat{\delta}^{-1} , \quad (5)$$

where ε_h is the vector of virtual energy intensity which is applicable only to the products used as household consumption. By multiplying the virtual energy intensity with an economy's household consumption, the economy's household-consumption-based energy use is determined. The household-consumption-based energy use of Economy *r* can be formulated as:

$$HCE^{\mathrm{r}} = \sum_{s=1}^{n}\sum_{j=1}^{m}\left(\varepsilon_{hj}^{s} h_j^{sr}\right). \tag{6}$$

Besides, under the production-based accounting scheme, the direct energy use of Economy *r* is expressed as:

$$DEU^{\mathrm{r}} = \sum_{j=1}^{m} e_j^r . \tag{7}$$

Meanwhile, for Economy *r*, energy embedded in its imports (*EEI*) and energy embedded in its exports (*EEX*), as two basic indicators depicting the energy trade patterns, can be respectively generated by:

$$EEI^{\mathrm{r}} = \sum_{s=1(s\neq r)}^{n}\sum_{j=1}^{m}\left(\varepsilon_{hj}^{s} h_j^{sr}\right), \tag{8}$$

and

$$EEX^{\mathrm{r}} = \sum_{i=1}^{m}\sum_{s=1(s\neq r)}^{n}\left(\varepsilon_{hi}^{r} h_i^{rs}\right). \tag{9}$$

Therefore, the trade balance of Economy *r* is thus obtained as

$$EEB^{\mathrm{r}} = EEI^{\mathrm{r}} - EEX^{\mathrm{r}}. \tag{10}$$

EEB reflects one economy's net trade patterns in terms of energy use. A positive (negative) *EEB* manifests the role of an economy as a net importer (exporter) of energy use.

[Insert Table 1]

2.3. Data sources

Data for MRIO table and sectoral onsite energy use are from the World Input-Output Database (WIOD, 2016). The global MRIO input-output tables have been released for the period from 1995 to 2011 (released in 2013), while the latest data for sectoral direct energy use has been only updated to the year 2009 (Timmer, 2015). To match the energy data, the 2009 world input-output table is adopted, which covers 27 European Union (EU) countries (excluding Croatia), 13 other major economies and a region standing for the rest of the world (Timmer, 2015). Each economy is comprised of 35 sectors. The currency flow in the MRIO table is expressed in millions of dollars while the sectoral energy use is in units of TJ. Besides, the populations for the nations or regions (excluding Taiwan) are gathered from the World Bank (WB, 2017). Data for Taiwan's population come from the National Bureau of Statistics of the People's Republic of China (NBS, 2016b).

It is worth noticing that there are several other existing databases contributed by different organizations, such as Eora (Lenzen et al., 2013), GTAP (Andrew and Peters, 2013), and EXIOPOL (Tukker et al., 2013). Differences in data quality have been previously observed among these databases (Arto et al., 2014; Geschke et al., 2014; Moran and Wood, 2014; Owen et al., 2014). In the future, harmonizing these global MRIO databases will be helpful for energy accounting for the world economy.

3. Results

3.1. Household-consumption-based energy use of world nations

Under the household-consumption-based MRIO accounting scheme, the amount of energy use initiated by the global household consumption is 6.58E+08 TJ in total, which maintains a balance with the total onsite energy use of the world economy.

The household-consumption-based energy use for the 40 economies are obtained based on the WIOD data, which are visualized in Fig. 1. Appendix A lists the detailed numerical results. As the top ten household-consumption-based energy users, the United States, China, Japan, Russia, India, Germany, the United Kingdom, France, Canada and Brazil are respectively revealed to induce 1.33E+08 TJ, 8.35E+07 TJ, 4.04E+07 TJ, 3.10E+07 TJ, 3.01E+07 TJ, 2.73E+07 TJ, 2.54E+07 TJ, 1.92E+07 TJ, 1.57E+07 TJ and 1.48E+07 TJ of energy use. Serving the largest energy user among these economies, the United States holds accountable about one-fifth of the total energy use of the world economy. As a consumption-oriented economy whose household consumption is equivalent to around 30% of global total (Timmer, 2015), the United States relies on both local and imported consumer products to fulfill the consumption demands of local residents, which inevitably induces great quantities of energy use. As the second biggest household-consumption-based energy user, China lags behind the United States by around 60% in terms of energy use, suggesting the big gap of consumption level between China and the United States. The sectoral contributions to household-consumption-based energy use of the five major economies are depicted in Fig. 2. More information for the sectors could be found in Appendix B. For the United States, agriculture industry, mining & electricity industry, light industry, heavy industry, transport industry, and service industry respectively contribute 0.93%, 16.38%, 12.52%, 25.07%, 5.00% and 40.09% of its household-consumption-based energy use. Similar to the United States, Japan is revealed to be highly dependent on service industry that accounts for around two fifths of its household-consumption-based energy use. Whereas, for China economy, its energy profile is quite different. Heavy industry accounts for over half (56.16% exactly) of China's household-consumption-based energy use, while service industry only shares one fifth (20.07% exactly). This trend is also observed for another developing nation, India, whose tertiary industry is accountable for less than one-tenth (8.21% exactly) of its household-consumption-based energy use.

[Insert Fig. 1]

[Insert Fig. 2]

For comparison, energy use allocated to an economy as denoted by final-demand-based energy use (FDE) and direct energy use (DEU) are also calculated respectively, as depicted in Fig. 1. As demonstrated, the United States still maintains the first place among the 40 nations in terms of direct energy use. Its direct energy expenditure reaches an amount of 1.23E+08 TJ, which is slightly higher than China whose direct energy use amounts to 1.15E+08 TJ. Russia, India, Japan, Germany, South Korea, Canada, Brazil and France come as the successors, whose direct energy use respectively shares 6.35%, 4.83%, 4.71%, 2.71%, 2.58%, 2.32%, 2.13% and 2.04% of the global total. Under the final-demand-based accounting scheme, the top ten energy users are the United States, China, Japan, India, Russia, Germany, France, Canada, Brazil and the United Kingdom, which in total account for over 60% of the energy use of the world economy.

The results imply that, one economy would get allocated different quantities of energy use under different energy accounting frameworks. For the United States, its household-consumption-based energy use is approximate to its final-demand-based energy use, but 8.46% larger than its direct energy use. As an economy highly dependent on household consumption to boost the economic growth, the United States is unable to rely only on domestic production capacity to satisfy its consumptive demands, especially under the context of flourishing loan consumption. Therefore, the United States brings in massive consumer products from overseas to satisfy the residential wants. In this way the United States invisibly gains certain quantities of energy use from foreign regions. For Japan, its household-consumption-based energy use is 11.60% larger than its final-demand-based energy use and 30.32% larger than its direct energy use. Similar tendency is also observed for Germany, the United Kingdom and France etc. In particular, for the United Kingdom, its household-consumption-based energy use is 1.78 and 2.35 times larger than its final-demand-based energy use and direct energy use respectively. Generally, for these developed nations (also serving as large importers), household consumption expenditure is accountable for a high share of the national final demand. Therefore, they tend to get allocated more energy use under the household-consumption-based energy accounting scheme.

However, for developing or less developed economies, the situation is rather different. For China, its household-consumption-based energy use is 16.50% smaller than its final-demand-based energy use and 27.39% smaller than its direct energy use. China has achieved unprecedented economic progress in the last four decades, which is largely imputed to the manufacturing-oriented and export-led growth model. With the advantage of low labor cost, China is largely involved in the global supply chain and provides the world economy with cheap commodities “made in China”, playing the role of the “world factory”. Since the large amounts of commodities exported are largely low value-added goods, intensive energy consumption has been initiated in the production processes occurring within China's national borders to satisfy the foreign consumptive demands. Besides, in contrast to the developed nations, China has for several years been characterized by a much lower share of household consumption. According to the World Bank (WB, 2017), household consumption holds accountable for around 70% of the GDP of the United States, while for China this proportion remains around 40%. Therefore, by means of the household-consumption-based energy accounting, China is allocated less energy use compared to that under final-demand-based energy accounting or production-based energy accounting. Similarly, India's household-consumption-based energy use is respectively 5.35% and 5.23% smaller than its direct energy use and final-demand-based energy use.

Fig. 3 presents the per-capita household-consumption-based energy use of the 40 economies. Generally, developed economies have smaller populations with better life quality than the less developed or developing economies. As illustrated, the per capita household-consumption-based energy use of developed economies is generally larger than that of developing economies. Among these 40 economies, Canada (0.468 TJ/cap), Australia (0.443 TJ/cap), Luxembourg (0.44 TJ/cap), the United States (0.433 TJ/cap) and Finland (0.43 TJ/cap) are the five leading economies in terms of per capita household-consumption-based energy use, while Brazil (0.076 TJ/cap), Turkey (0.074 TJ/cap), China (0.063 TJ/cap), Indonesia (0.025 TJ/cap), India (0.024 TJ/cap) are coupled with the lowest per-capita household-consumption-based energy use. As witnessed, though China serves the second largest energy user among all these economies, its per capita household-consumption-based energy use is just about one sixth of that for the United States as well as that for the United Kingdom. While for India, its per-capita household-consumption-based energy use is only one-twentieth of that of the United States. This is a reflection of the comparatively inferior life quality as measured by per capita household-consumption-based energy use in developing nations, mainly due to the lower level of household consumption as well as the large population. Therefore, there is vast potential for these developing nations to improve domestic living standards.

[Insert Fig. 3]

3.2. Energy embedded in the traded consumer products

The ongoing globalization emphasizes the increasingly critical role played by international trade within the world economy. As all energy use has been apportioned to household consumption under the household-consumption-based MRIO accounting scheme, international exchange of consumer products may result in cross-national transfer of energy use among the regions.

For the world economy, it remains as the biggest economic entity, which receives no economic inputs from the cosmic background. Therefore, the import of a nation within the world economy is just the export of another nation. In this regard, the summation of the energy use imports of all nations within the world economy equals that of the total exports, which is here referred to as the global total trade volume in terms of energy use. The global total trade volume of energy use is calculated to be 1.12E+08 TJ, in magnitude around one-fifth of total onsite energy use of the world economy. The energy use embedded in the imports (*EEI*) and that embedded in the exports (*EEX*) of the 40 nations are respectively obtained, as illustrated in Fig. 4 and Fig. 5.

[Insert Fig. 4]

[Insert Fig. 5]

As demonstrated in Fig. 4, the United States, the United Kingdom, Germany, Japan, France, Canada, Netherlands, Italy, Spain and Russia turn out to be the top ten importers in terms of energy use. For the United States as the largest importer of energy use, its import is calculated to amount to 1.84E+07 TJ, in magnitude around 1.6 times that of Germany (1.11E+07 TJ), twice that of Japan (8.38E+06 TJ), and around four times that of France (4.77E+06 TJ), respectively. At witnessed, the leading importers of energy use are mainly the developed nations. Relying on foreign imports to meet domestic needs, these developed nations are able to make full use of international trade to grab the utility of energy resources from other nations, thus alleviating the pressure on domestic energy supply. The top ten exporters of energy use are revealed to be China, the United States, South Korea, Germany, India, Netherlands, France, the United Kingdom, Italy and Belgium, respectively responsible for 28.42%, 14.18%, 4.52%, 3.84%, 3.53%, 2.70%, 2.16%, 1.96%, 1.79% and 1.64% of the global total trade volume. As witnessed, the export of China is almost equivalent to the aggregated amount of that by the United States, South Korea, Germany, India and Netherlands. By supplying the rest of the world economy with large quantities of commodities "made in China", China also transfers the utility of energy resources to the foreign nations, thus intensifying the concern of depleting domestic energy resources. Besides, as could be seen, some developed nations, such as the United States, Germany and Netherlands, turn out to serve dual roles of important importers and exporters. For instance, on one hand, the United States is highly dependent on low value-added goods (such as furniture, toys and clothing) from developing nations represented by China. On another hand, the United States remains a vital importing market of the North America and

South America regions.

Moreover, the net trade of the 40 economies in terms of energy use are illustrated in Fig. 6. The total net trade of energy use amounts to 4.23E+07 TJ, in magnitude around one-fifteenth of the global total energy use. As demonstrated, among the 40 economies, thirty four regions are revealed to be net importers while other six regions turn out to be net exporters. The five major net exporters turn out to be the United Kingdom, Germany, Japan, the United States and France, while the top five largest net exporters are China, India, South Korea, Bulgaria and Czech Republic. For China as the largest deficit economy in terms of energy use, its export is around sixteen times as much as the import. The sectoral contributions to the imports and exports of five major trading economies, i.e., China, the United States, the United Kingdom, Germany and Japan, are illustrated in Fig. 7. As witnessed, for China, heavy industry and light industry are the two main sources of its exports of energy use, which account for 81.76% of China's total exports. Meanwhile, in terms of energy use, heavy industry appears to be a dominant contributor to the imports of the developed nations, which respectively account for 55.98%, 66.58% and 31.74% of the total imports of the United States, Germany and Japan, respectively.

[Insert Fig. 6]

[Insert Fig. 7]

3.3. Trade connections between the major regions

To figure out the trade connections among the major regions in terms of energy use, the whole world is divided into 15 regions, i.e., the European Union (EU, including 27 member states except Croatia, mainly because Croatia has not been an official member of the

European Union until 2013), other 13 major economies listed in the WIOD and the one representing the rest of the world (ROW). The inter-regional trade flows in terms of energy use are presented in Fig. 8 (a), within which there are 210 flows of energy use in total. The arc length of each nation expresses its exports of energy use. The chords reflect the relations of trade between every two regions, whose color conforms to the region that exports more energy use to the other region connected. As witnessed, China acts as the largest exporter among the 15 regions, accounting for one-third of the global total trade volume, followed by ROW, the United States, EU, South Korea and India, etc.

Among the energy use outflows of China, the largest trade flow is the export from China to EU, which reaches an amount of 1.04E+07 TJ and shares 32.60% of China's total exports of energy use. Meanwhile, the United States, Japan, ROW, South Korea, and Canada are also important receivers of China's exports of energy use and hold accountable for 19.96%, 16.56%, 13.42%, 4.19% and 3.11% of the total, respectively. EU is revealed to be the largest importer of energy use among all nations, receiving 3.74E+07 TJ (equivalent to around 30% of global trade volume) of energy use from the rest 14 regions. As a crucial economic entity in the world, EU receives large quantities of consumer products from abroad to support domestic residential consumption. At the same time, massive energy welfare (3.74E+07 TJ) flows into EU in an invisible way, thus greatly enhancing EU's domestic living standards. Apart from China as a prominent contributor to EU's imports of energy use, South Korea and India are also revealed to be important source markets, respectively occupying 8.33% and 3.17% of the energy use inflows of EU. For decades, consumer products manufactured by South Korea, such as electronic and automobile products, enjoy a reputation in the world. In this study, the exports of South Korea are revealed to be 5.05E+06 TJ, sharing around one-twentieth of the global total trade volume. Of the 5.05E+06 TJ of energy use exported from South Korea, 61.68% of it flows into EU, 8.49% entering the United States, 3.11% into Japan, 2.79% into China, 1.97% into Russia, etc. Meanwhile, for India as a newly emerging economy, it exports 5.05E+06 TJ of energy use to foreign nations, 36.02% of which flows into the United States, 30.05% into EU, 3.04% into Canada, 2.43% into Australia, etc. Besides, as previously mentioned, EU also remains as an important exporter of energy use, occupying around one-tenth of the global total trade volume. The United States and Russia turn out to be EU's largest two exporting markets, respectively accountable for 21.45% and 8.10% of EU's exports of energy use.

[Insert Fig. 8]

Besides, the net trade connections between the 15 regions in terms of energy use are shown in Fig. 8 (b). The thickness at both ends of the chord represents the net trade volume of energy use between the two regions and the color corresponds to the net exporter of the two regions linked. The major net trade flows in terms of energy use and currency are respectively described in Fig. 9 (a) and Fig. 9 (b). Generally, the net exporter of energy use in bilateral trade would receive a trade surplus of currency. The largest net trade flow runs from China to EU, amounting to 9.98E+06 TJ. At witnessed, the trade imbalance in terms of energy use between China and EU is huge. Though EU maintains an economic trade deficit with China (78.4 billion USD), EU grabs massive energy benefits by importing China's consumer products, which helps safeguard its energy security. Apart from EU, the United States also gains a considerable amount of energy use from China, which is calculated to be 6.23E+06 TJ. Moreover, the United States turns out to benefit a lot from the trade with other Asia Pacific regions. The United States has an energy trade surplus of

1.38E+06 TJ with India, a surplus of 6.28E+04TJ with Japan, a surplus of 2.15E+05 TJ with Taiwan, and a surplus of 8.15E+04 TJ with Indonesia. Meanwhile, Japan as a net exporter of energy use, is coupled with a trade surplus of 6.63E+06 TJ. The trade imbalance between Japan and China amounts to 5.13E+06 TJ, which in magnitude almost equals the summation of that between Japan and its other trade partners.

4. **Discussions**

4.1. Trade imbalances

Trade imbalance, such as that between China and the United States, as well as that between Germany and the United States, has become a widely-discussed issue and caused severe trade friction between nations (Lin and Wang, 2018; USTR, 2018). While the economic trade imbalance has been intensively debated, the imbalance of energy use (as an analogy to price in the economic market) caused by the international exchange of products has received less attention. In this study, the consumer-product-related trade imbalance in terms of currency and that of energy use are investigated.

As illustrated in Fig. 10, the four quadrants in the rectangular coordinate reflect four kinds of trade schemes, with the spherical size implying the total trade volume of a nation. At witnessed, the United States, the United Kingdom, Japan, France and Canada are mainly located in the second quadrant, which serve as net importers of energy use but net exporters of currency. These developed countries, including the United States, the United Kingdom, Japan, Australia and France, tend to bring in lots of consumer products from foreign nations, and are respectively coupled with a consumer-product-related currency trade deficit reaching up to 245.19 billion USD, 75.84 billion USD, 52.28 billion USD, 27.67 billion

USD and 13.06 billion USD respectively. In the meantime, they receive certain amounts of energy use from foreign regions. While for China and India located in the fourth quadrant, they serve as the suppliers of consumer products required by the developed nations, and are associated with a consumer-product-related currency trade surplus amounting to 325.06 billion USD and 65.46 billion USD respectively. As calculated in this study, the consumer-product-related trade imbalance for China in terms of currency is around 1.3 times that for the United States, four times that for the United Kingdom, six times that for Japan, and twenty-five times that for France. Correspondingly, the consumer-product-related trade imbalance for China in terms of energy use is the summation of that for the United States, the United Kingdom, Australia, France and Japan. Recently, China has been blamed by the United States government for gaining massive economic surplus in bilateral trade, which is referred to by the United States' president as not reciprocal (Trump, 2018b). Given this, the United States government has taken a series of actions to cut down the bilateral trade imbalance, such as increasing tariffs on 200 billion worth of imported products from China, and demanding China to buy in more products from the United States (Trump, 2018a; WhiteHouse, 2018). The results in this study, however, suggest that China's economic trade surplus comes hand in hand with the stunning trade deficit in terms of energy use. In this regard, by taking into consideration of the trade imbalances in terms of both currency and energy use, the bilateral trade between the United States and China could be in some degree regarded as reciprocal. Similar to China, South Korea is also revealed to be receiving a trade surplus of currency and trade deficit of energy use. South Korea bears a resemblance to China as a prominent exporter of consumer goods, while the difference is that South Korea tends to export the technology-intensive or service-intensive products (electronic products, transportation, etc.).

[Insert Fig. 10]

Generally, a region with a trade surplus of currency is associated with a trade deficit of energy use. Whereas, there are some exceptions. For example, Germany, Italy, Netherlands and Spain situating in the first quadrant receive a trade surplus in terms of both currency and energy use. Generally, though importing massive low value-added consumer goods from developing nations to fulfill domestic demands, these nations export considerable quantities of high value-added goods to other nations. Meanwhile, due to the different economic structure and higher level of production technology, consumer products produced in the developed nations are less energy-intensive. For instance, the average virtual energy intensities of the consumer products manufactured in Germany, Italy, Netherlands, and Spain are respectively calculated to be 12.12 TJ/million USD, 11.13 TJ/million USD, 15.74 TJ/million USD and 11.49 TJ/million USD, whereas that in China, Russia and India are calculated to be 55.41 TJ/million USD, 57.02 TJ/million USD and 40.45 TJ/million USD.

4.2. Energy self-sufficiency rate of economies

Under the household-consumption-based MRIO energy accounting scheme, the household-consumption-based energy use of each economy is respectively quantified. Whereas, the original sources of the household-consumption-based energy use of an economy are still unknown. Though the onsite energy use of all economic sectors of the world economy has been totally assigned to the consumer products, it remains unknown to us how much welfare denoted by the use of the onsite energy consumption within an economy is maintained at home (Chen and Wu, 2017). In other words, a question might be raised: What is the amount of a national economy's onsite energy use that is assigned to the goods or service used for domestic household consumption? To answer this question, two indicators are proposed in this paper, namely energy self-sufficiency rate by supply (defined as the ratio of a national economy's onsite energy use that is allocated to its own household consumption to the total domestic onsite energy use), and energy self-sufficiency rate by demand (defined as the ratio of a national economy's onsite energy use that is allocated to its own household consumption to the economy's total household-consumption-based energy use), to penetrate the original sources of an economy's household-consumption-based energy use from both the supply side and demand side.

The energy self-sufficiency rates by supply and that by demand are respectively presented in Fig. 11 and Fig. 12. At witnessed, for the United States economy, the energy self-sufficiency rate by supply is calculated to be 0.81, while that for China is only 0.62. As previously noted, large quantities of onsite energy consumption occur both in the United States and China, the amount of which generally approaches each other. Whereas, the energy self-sufficiency rate by supply implies that the United States maintains the majority of the energy welfare at home, while China exports large quantities of energy use abroad to enhance the living standards in foreign nations. Similar to the United States, Japan is found to be with an energy self-sufficiency rate of 0.81. Where for other economies including Germany, South Korea and Taiwan, their energy self-sufficiency rates by supply are respectively 0.60, 0.44 and 0.41. Though characterized with high living standards, these economies could be regarded as export-oriented nations, which requires massive onsite energy use to produce the high value-added goods exported to other economies. In the meantime, the energy self-sufficiency rate by demand for Germany, South Korea and Taiwan are respectively 0.39, 0.61 and 0.55. As witnessed, while these economies export massive energy use abroad, they also receive considerable amount of energy use from foreign economies to fulfill the demands of domestic consumers. Besides, the energy self-sufficiency rate for the United States is 0.75. As reflected, though the United States economy receives massive imports of energy use from abroad as previously mentioned, the majority of its household-consumption-based energy use stems from its domestic onsite energy consumption. With regard to developing economies, the energy self-sufficiency rates by demand for China, India and Brazil are respectively 0.86, 0.86 and 0.78, which is approximate to each other. The implication is that the household-consumption energy use allocated to these developing economies mainly originates from the domestic onsite energy use, rather than energy use imported from other foreign economies via interregional trade.

[Insert Fig. 11]

[Insert Fig. 12]

5. Conclusions and policy implications

By integrating nations into a world economy, globalization has resulted in the regional specialization of industries as well as the re-deployment of production and consumption of goods or services. By making full use of international trade, one region is capable of acquiring energy use from foreign economies in an invisible way. In view of household consumption as the ultimate purpose and driving force of all producing activities, this paper investigated the energy use of the world economy under the household-consumption-based MRIO energy accounting scheme. The trade relations between different economies in terms of energy use are explored.

Under the household-consumption-based accounting scheme, the top two energy users are revealed to be the United States and China, followed by Japan, Russia, India, Germany, etc. While the direct energy expenditure of the United States is approximate to that of China, the household-consumption-based energy use of the United States surpasses that of China by around 60%. The cross-national transfer of energy use induced by international trade of consumer products is quantified, which sums up to around 20% of the global total energy use. China serves the biggest exporter of energy use, accountable for around 30% of the global total trade volume, while the United States, Germany, the United Kingdom, Netherlands, France and Italy are revealed as big importers. With regard to the net trade, the United Kingdom, Germany, Japan, the United States and France remain the major net importers while China, India, South Korea, Bulgaria and Czech Republic turn out to be the major net exporters.

The results obtained in this work have essential implications for comprehending trade connections of nations in terms of energy use. China has for decades served as the supplier of low-cost manufactured commodities. As revealed in this study, China is the largest exporter and also the largest deficit region of energy use. Around one-third of its energy use outflows go to EU, one-fifth going to the United States, one-sixth going to Japan, etc. Regarding the sectoral components of China's exports of energy use, heavy and light industries are responsible for over 80% of the total. Therefore, an alternation of domestic industrial structure is essential for China to keep more energy welfare inside the economy. It is of urgent significance to promote the expansion of knowledge-based, technology-intensive industries in China. At calculated in this work, service industry dedicates only one-fifth of the household-consumption-based energy use of China economy in 2009, while this ratio is over half for the United States and Japan. Machine learning, big data processing and new types of materials might be the new frontier areas that might revolutionize the global economy. In fact, artificial intelligence, cloud computing, automatic driving and nanometer materials have witnessed rapid development in China in recent years. In the reports of the 19th National Congress of the Communist Party of China (Xi, 2017), it has been emphasized that China is striving to establish a technology-, quality-, aerospace-, web-, transportation-, digital- and intelligence-oriented robust economy. Besides, China shall outsource the excess production capacity, especially the manufacturing industries, to those underdeveloped economies. The Belt and Road initiative offers unprecedented opportunities for China to transfer the heavy industries to the underdeveloped economies, which is beneficial for the economic development of both sides. Besides, as revealed in this study, while the energy self-sufficiency rate by supply is 0.62 for China, that by demand is 0.86, suggesting that China exports massive energy use abroad while absorbing little inside. This is mainly due to the low level of consumption in China economy. Whereas, things are changing now. With the rising middle class, consumers in China have an inclination for high-quality and high value products. The results in this study imply that the living standard in China as denoted by per capital household-consumption-based energy use is only one-sixth of that in the United States. Therefore, it could be foreseen that the share of household consumption in the national GDP is supposed to largely increase in the next few years. In this context, it is important to cultivate an energy-saving and green consumption culture, which also conforms to the claim of constructing an ecologically civilized society.

For the United States, it is revealed as gaining much energy use from developing economies, accompanied by the massive trade deficit of currency. Its economic structure has altered not much in these two or three decades. In the near future, drastic changes are unlikely to take place in the United States. Therefore, to lessen its trade deficit with the developing economies (especially with China), the United States are recommended to transfer those high value-added technology to China. The benefits are bilateral. Though offset by the exports to an extent, the energy use received by the United States will still remain considerable. Meanwhile, this may help propel the transition of industrial structure in China and lessen the large trade deficit of energy use for China. In addition, for energy conservation, the United States may impose energy tax on the imported products and carefully choose the energy-efficient products, which may help propel the producers to adopt energy-saving technologies. For economies like Germany, South Korea and Taiwan, they have made full use of the global supply chain to achieve the configuration of resources. While importing large amounts of consumer products, they also export massive highly-reputed commodities to foreign nations. As a result, their budget of energy use maintains a balance with that of currency. These economies are recommended to continue their current development modes and make further improvement on their specialized products. In general, in the future there will be no products entitled as "made in China" nor "made in Germany", but made in the globalized world. Therefore, each economy shall carefully pinpoint their position in the global supply chain and adjust their industrial structure accordingly to promote economic development and sustained energy use at the same time.

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