# The unequal contribution to global energy consumption along the supply chain

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HIGHLIGHTS

- Different frameworks of energy consumption are proposed and discussed.
- National energy consumptions at different production stages are identified.
- Sectoral contributions to energy consumption are identified
- China accounts for the majority of global energy consumption.
- Energy consumptions of emerging countries increased faster than the developed.

ABSTRACT

Reducing fossil fuel consumption is a top priority option for climate change mitigation, which requires collaborations of partner along the supply chain, such as energy suppliers, energy consumer and consumers of goods and services. A comprehensive analysis of the fossil fuel consumption is useful for policy makers to reduce demand but still absent. This study explores the national contribution to global energy consumption from different perspectives in global supply chain and is designed to complement current energy reduction policies. For the developed countries, energy consumptions are stable from 2000-2014, while that of emerging countries almost doubled (e.g., China and India). Most of the developing countries are producers whose production-based and final production-based energy consumptions are higher than their consumption-based ones, except India after global financial crisis. In contrast, the developed countries are consumers, whose consumption-based energy consumptions are higher. At sectoral level, service sector is the biggest contributor of consumption- and income-based energy consumption. The analysis in this

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study can create opportunities for all the parties alongside the supply chain in reducing fossil fuel consumption.

Keywords: inequality; energy consumption; production-based; consumption-based; income-based

1 **Introduction**

Climate change is one of the biggest and urgent threat to the planet and human societies (Thomas et al., 2004). Fossil fuel combustion is the primary source of global greenhouse gas (GHG) emissions (Davis and Socolow, 2014), which contributes to the climate change. However, the need for energy to satisfy social and economic development is increasing (Arto et al., 2016). Climate change mitigation and energy security are two critical challenges toward a sustainable future. In current trajectory, the world's total energy consumption is projected to rise by 28% from 575 quadrillion British thermal units (Btu) in 2015 to 736 quadrillion Btu in 2040 (U.S. Energy Information Administration), which challenges the current climate change mitigation actions. Meanwhile, it is reported (Quadrelli and Peterson, 2007) that energy consumption has contributed to over four fifths of global anthropogenic carbon emissions. Therefore, more efforts are supposed to be in place in informing and implanting policies on curbing energy consumptions and the related carbon emissions.

Different methods are used for accounting regional energy consumptions. A traditional method is production-based energy consumption accounting, which measures all energy consumption generated by the production activities of a country (Peters, 2008). However, in a globalized world, final consumptions in one country often cause production and energy consumption elsewhere (Davis and Caldeira, 2010). Considering the interaction of energy consumption and international trade, consumption-based accounting has been proposed to adjust the production-based accounting by adding the energy consumption associated with the production of imports and removing that the associated with the production of exports (Malik et al., 2018; Wiedmann and Lenzen, 2018; Wu and Chen, 2017). In this framework, Leontief demand-driven Input-Output (IO) models have been used to help integrate the energy consumption and economic activities (Lan et al., 2016). However, challenges still remain in adequately charactering the temporal change of national energy consumption from different perspectives. Furthermore, the link of final consumption of products and services to the producers represent part of the global supply chain so that it is also important to look at the potential for supply-side policies (Marques et al., 2012).

Downstream responsibility is little addressed in academic literature and corporate sustainability reports (Lenzen and Murray, 2010). In contrast to the Leontief demand-driven IO models, the Ghosh supply-driven model links production to the primary inputs in the supply chain (Ghosh, 1958; Miller and Blair, 2009). It is characterized with energy consumption enabled by primary suppliers which are required to generate income of a country through wages, profits and rents (payment to primary factors of production). The supply-side model has been applied to GHG emissions to analyse the forward linkage effects. Marques et al. (2012) quantified income-based environmental responsibility for GHG emissions by 112 regions in the world and compared the results with those obtained from production-based and consumption-based frameworks. Liang et al. (2017) assessed the income-based emissions and new profiles for nations and sectors. Mathematically, income-based accounting adjusts the production-based accounting by removing the domestic energy consumption generated downstream of imported products and adding the foreign emissions generated downstream of exported products. However, downstream responsibility has never received the same attention as its consumption-based cognate.

Meanwhile, energy consumptions are induced both domestically and abroad when a country produces final goods and services. Since only final goods enter the domain of consumption, in recent years a final production-based accounting has been raised to associate the energy consumption with the final producing activities. Difference between this and the consumption-based accounting is the agents (final producers or final consumers) that are adopted to allocate the factor uses. Therefore, for a region that mainly serves as producer of intermediate products, the energy consumption allocated to it is supposed to be much less than that allocated to a producer of final goods. To identify differences between these methods, Kanemoto et al. (2011) compared emission inventories established under consumption-based, final production-based and production-based accounting frameworks.

Drawing the recent literature on allocating responsibility in different frameworks, this study focuses on energy consumption from different perspectives and is designed to complement current energy mitigation policies. This study complements previous works by identifying national energy consumption at different production stages and sectors to provide insights into energy policies. Specifically, we construct a time-series energy consumption inventory of nations during 2000-2014 from the perspectives of income, production and consumption. We also reveal the temporal changes and sectoral contributions in regional income-based, production-based and consumption-based energy consumption.

2 **Methods and data**

2.1 Environmentally Extended Input-output Analysis

This study uses a globally Environmentally Extended Input-output Analysis (EEIOA) to assess the production-based, final production-based, consumption-based and income-based energy consumption of nations from 2000 to 2014. EEIOA is originally developed by Leontief (Leontief, 1970), which is also referred to Leontief demand-driven model and links environmental pressure data to the final consumer of the related products or services. Here, we adopt the framework of Multi-regional Input-Output (MRIO) model which is based on monetary flows to analyse the economic interdependence between different national economies/regions, each composed by a number of industrial sectors (Davis et al., 2010; Mi et al., 2018a; Rocco et al., 2018). The MRIO model has been widely used in environmental analysis, e.g., greenhouse gases emissions (Meng et al., 2018b; Mi et al., 2017; Vogt-Schilb et al., 2019), air pollutant emissions (Meng et al., 2016b; Meng et al., 2018a; Wang et al., 2019), energy consumption (Chen et al., 2018b), water-energy nexus (Chen et al., 2018a; Zhang et al., 2019), biodiversity (Lenzen et al., 2012), etc., over the past decades.

The typical single region Leontief demand-driven modelling (Meng et al., 2016a; Meng et al., 2015) is based on a sector-by-sector matrix (**z**) in which the total output (**x**) required by a certain final demand vector (**y**) in the region or country under consideration can be described as equation (1):

$$\mathbf{x} = \mathbf{z} + \mathbf{y} \tag{1}$$

The standard MRIO model can be expressed as:

$$\begin{pmatrix} \mathbf{x}^1 \\ \mathbf{x}^2 \\ \vdots \\ \mathbf{x}^r \end{pmatrix} = \begin{pmatrix} \mathbf{A}^{11} & \mathbf{A}^{12} & \cdots & \mathbf{A}^{1s} \\ \mathbf{A}^{21} & \mathbf{A}^{22} & \cdots & \mathbf{A}^{2s} \\ \vdots & \vdots & \ddots & \vdots \\ \mathbf{A}^{r1} & \mathbf{A}^{r2} & \cdots & \mathbf{A}^{rs} \end{pmatrix} \begin{pmatrix} \mathbf{x}^1 \\ \mathbf{x}^2 \\ \vdots \\ \mathbf{x}^r \end{pmatrix} + \begin{pmatrix} \sum_s \mathbf{y}^{1s} \\ \sum_s \mathbf{y}^{2s} \\ \vdots \\ \sum_s \mathbf{y}^{rs} \end{pmatrix} \tag{2}$$

where $\mathbf{X}^{\mathrm{r}}$ is a vector for sectoral total outputs in region *r*; $\boldsymbol{A}^{rs}$ represents the coefficient of industry requirements from region *r* to *s* to produce per unit of output *j*. $\boldsymbol{y}^{rs}$ is the final demand supply from region *r* to *s*; and *s* indicates the total number of regions, which is 43 in this study.

In this framework, production-based accounting assesses a nation’s role as a direct consumer, which refers to the energy consumption within the territorial boundary. The production-based energy consumption in region *r* is:

$$\mathbf{P}^r = \mathbf{E}^r(\mathbf{I}-\mathbf{A})^{-1}\mathbf{y} = \mathbf{E}^r\mathbf{L}\mathbf{y} \tag{3}$$

Final production-based accounting assesses a nation’s role as the final producer, which refers to both direct and indirect energy consumption embodied in the final products of the nation along the whole production chain. The final production-based energy consumption in region *r* is:

$$\mathbf{F}^s = \mathbf{E}(\mathbf{I}-\mathbf{A})^{-1}\mathbf{y}^{s\bullet} = \mathbf{E}\mathbf{L}\mathbf{y}^{s\bullet} \tag{4}$$

Consumption-based accounting assesses a nation’s role as a final consumer (Meng et al., 2017; Yi et al., 2019), which refers to both direct and indirect energy consumption embodied in the products consumed by the nation. The consumption-based energy consumption in region *s* can be expressed as:

$$\mathbf{C}^s = \mathbf{E}(\mathbf{I}-\mathbf{A})^{-1}\mathbf{y}^{\bullet s} = \mathbf{E}\mathbf{L}\mathbf{y}^{\bullet s} \tag{5}$$

where $\mathbf{E}^{\mathbf{s}}$ and $\mathbf{E}^{\mathbf{r}}$ are the direct energy intensity vector for region *s* and *r* but zeros for all other regions. $\mathbf{E}$ is calculated by each sector’s energy consumption divided by the sector’s total output x (Lin et al., 2014; Meng et al., 2019). **L**= (**I**-**A**)$^{-1}$ is the Leontief inverse matrix, which captures both direct and indirect inputs to satisfy one unit of final demand in monetary value, Leontief MRIO model is regarded as demand-driven. Changes in the final demand initials the upstream outputs. $\mathbf{y}^{\bullet s}$ is the final consumption of products in region *s* from each sector from all regions, and $\mathbf{y}^{s\bullet}$ is the final consumption of all regions from region *s*.

2.2 Supply-side Input-output Analysis

In contrast to the Leontief demand-driven model, Ghosh MRIO model is regarded as supply-driven. Changes in primary inputs (e.g., labour and capital) drive downstream production activities (Ghosh, 1958; Liang et al., 2017). Income-based accounting investigates a nation’s role as a primary supplier at the beginning of the supply chain, which refers to both direct and indirect downstream energy consumption enabled by its primary inputs of labour, capital, etc. Income-based energy consumption in region *s* is calculated as:

$$\mathbf{D}^s = \mathbf{V}^s(\mathbf{I}-\mathbf{B})^{-1}\mathbf{E} \tag{6}$$

where $\mathbf{V}^s$ is the row vector which indicates the primary input of each sector in region *s*. The element $\boldsymbol{b}_{ij}$ of matrix **B** is direct sales from sector *i* to sector *j*, in terms of unitary output in sector *i*. The matrix (**I**-**B**)$^{-1}$ reflects both direct and indirect outputs from various sectors enabled by primary inputs of particular sectors, defined as Ghosh Inverse matrix.

2.3 Data sources

This study uses MRIO tables and sectoral energy consumption data to connect the energy consumption to the economic activities. The MRIO tables used are from World Input-Output Database (WIOD) released in 2016 (Timmer et al., 2016), which provide detailed interregional transaction information on 44 regions (covering more than 85% of global GDP), including 28 EU countries and 15 other major economies, and an aggregated “rest of world” region. However, in this study, the number of regions is 43 because People's Republic of China and Taiwan are aggregated into one region because of data availability. Each economy in the MRIO table is further divided into 56 sectors. The energy data used in this study is derived from International Energy Agency (2019), which is also divided into 56 sectors.

The sectoral value-added amounts for 43 regions were derived directly from the MRIO table, consisting of employee compensation, net taxes on production, depreciation of fixed assets and operating surplus. In this paper, the effects of sub-items will not be distinguished, and we merely utilize total value added (i.e. GDP measured by the income approach) to calculate vector ***D****,* as shown in equation (6). The economic data from the WIOD are in current prices. To remove the impact of inflation on the monetary output, the producer price index (PPI, National Account Main Aggregates Database) is used to adjust all the monetary data based on prices in year 2000 to provide a consistent analysis from 2000 to 2014.

3 Results and discussions

3.1 Regional contribution to global energy consumption

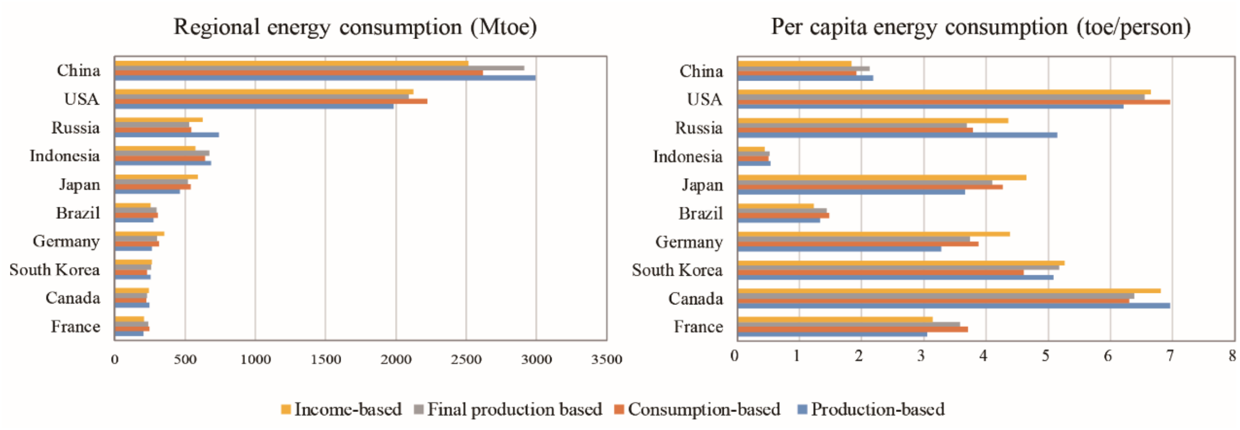

Figure 1. Total and per capita income-, production-, final production- and consumption-based energy consumption of selected 10 regions in 2014.

Figure 1 presents the regional breakdown of fossil fuel energy consumptions in 2014 from all responsibility principles for 10 selected regions, which collectively account for about 70% of the global energy consumption from production perspective. Clearly, China is the largest energy user by any measure. Its production-, final production-, consumption-, and income-based energy consumption in 2014 were 2994, 2914, 2619, and 2517 Mtoe (million tonnes of oil equivalent), contributing 24.7%, 24.0%, 21.6% and 20.7% of total energy consumption, respectively. Compared with the US, the world's second largest consumer, China's share rose by 50.9%, 39.3%, 17.8% and 18.5%, respectively.

In general, production-based energy consumption is higher than the consumption-based ones for developing regions, such as China, Russia, and Indonesia. The results of energy consumption from final production-based accounting, which depend not only on all related countries' energy intensities upstream, but also the inter-regional production network, reveal different profiles across countries. China and Indonesia shared the same pattern, with final production-based energy consumption slightly lower than production-based ones, and 10.1% and 4.4% less than the consumption-based ones. In Russia, the final production-based energy consumption was 26.4% less while 2.8% more than the production- and consumption-based ones, respectively, while income-based one was 18.2% and 15.0% higher, which indicates that Russia acts more as a primary supplier than as a final seller or final consumer of energy consumption. This is because Russia is a major exporter of resources, such as fossil fuels, which are essential and could induce substantial energy consumptions in downstream processes (e.g., electricity generation). Therefore, with the supply-based model, by considering the foreign energy consumption generated downstream of exported products, Russia's energy use is revealed as more than those obtained using the final production- and consumption-based ones.

High income-based energy consumptions are observed in another two resource-exporting countries: Japan and Germany. Thus, the important role of resource-exporting (direct or indirect) regions as primary suppliers for global energy consumption is highlighted by the income-based accounting. If global energy consumption reduction considers results from the income-based accounting, in addition to those from the production- and consumption-based models, resource-exporting regions should share more responsibilities. This finding informs that supply-side measure can identify the resource-exporting regions which was overlooked before.

Per capita energy consumptions in developed countries (e.g., the United States, Canada, Japan, France, Germany) are much higher than that in developing regions (e.g., China, Brazil, Indonesia). For instance, the per capita production-, consumption-, final production-, and income-based energy consumptions in the US were respectively 6.21, 6.55, 6.96 and 6.65 toe/person in 2014, which were 2.84, 3.08, 3.64 and 3.62 times of the ones for China. Furthermore, within the developing regions, per capita energy consumption in China is much higher than that of in Brazil and Indonesia from all perspectives.

3.2 Temporal trends in regional energy consumption

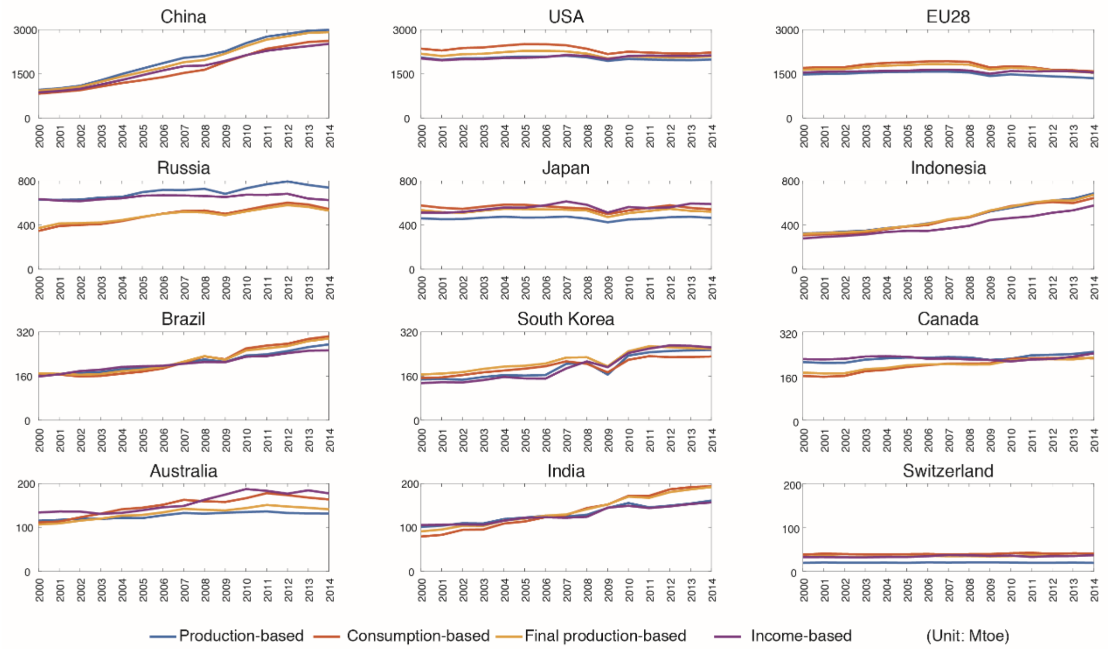

Figure 2. Energy consumptions of selected regions over the period 2000-2014.

Global total fossil-fuel energy consumption witnessed a rapid growth, from 8.4×10^6 Mtoe in 2000 to 1.2×10^7 Mtoe in 2014. Energy consumptions of developing regions kept growing during 2000-2014 (Figure 2), mainly due to their increasing primary inputs (e.g., capital and labour forces) to promote economic development. Since 2012, the growth rate of China's energy consumption has been stable due to the changes in energy mix and industrial structure (Guan et al., 2018; Mi et al., 2018b).

Income-based energy consumptions of China, Indonesia, India, and Brazil in 2014 increased by 190%, 108%, 49%, and 60%, respectively, compared with 2000. This shows these developing regions gain increasing benefits from both energy consumption income and by serving the providers of primary inputs. Since the 1990s, China has implemented a series of policy incentives (e.g., tax exemption) to attract foreign investment. Besides, the constant migration of rural peasants into urban areas in China has satisfied the increasing labour needs of domestic industries for producing the exported commodities. The robust investment and low-cost labour have led to the booming economic growth of Chinese economy, whose income in the form of payment to primary factors of production has increased by around nine times from 2000 to 2014 according to the World Bank. Therefore, income-based energy consumptions of China nearly tripled during this time-span. Even around 2007 or 2008, the effect of global financial crisis on the income-based energy consumption in China is very limited.

The energy consumptions of developed regions remained relatively stable during 2000–2014, except for Australia and South Korea, whose income-based energy consumption in 2014 increased by 33% and 96% than 2000 levels, respectively (Figure 2). This demonstrates the economies of developed regions have been in a comparatively steady state during the last decade except that there is a short-term drop during global financial crisis. However, the energy consumption rebounded in 2010 because of the rapid easing of energy price and substantial investment in many countries (Peters et al., 2012).

3.3 Indicator change

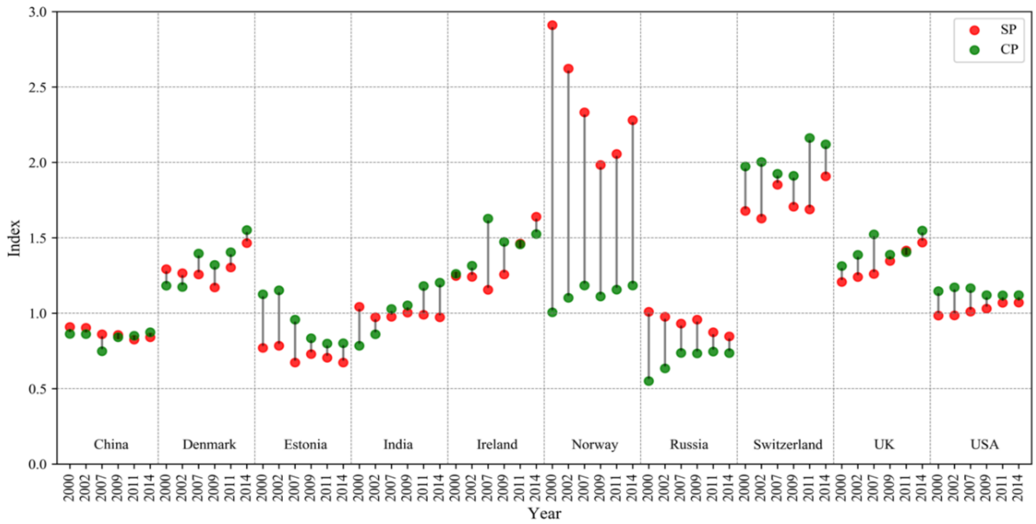

Figure 3. The evolution of role in driving energy consumption of selected countries (SP = income-based / production-based energy, CP = consumption-based / production-based energy).

Figure 3 shows the temporal change of indictors in turning points for selected countries. As consumption-based accounting sheds light on how energy is required to generate final demand, income-based accounting sheds light on how energy is enabled to generate income. We define two indicators here, one is SP, the ratio of income-based energy to production-based energy, is used to compare the role of a country as a supplier or producer. The other one is CP, the ratio of consumption-based energy to production-based energy, is used to compare the role of a country as a consumer or producer. These indicators can help us clearly understand the role of each country in driving energy consumption and how they evolve.

We find that, for some countries, responsibility values vary substantially when applying different allocation methods, while for some other countries they are comparable. Notably, the contributions of Norway as a producer and consumer are comparable ($\mathrm{CP} \approx 1$), but the energy consumption from the income-based accounting is 2-3 times of that from the production-based one. However, the big gap has shrunk from 2000 to 2014. This indicates that income-based responsibility can complement production- and consumption-based responsibility in some cases by highlighting countries which was overlooked before as resource-exporting countries.

For developed countries in Europe the income-based and consumption-based energy consumption are all larger than the production-based energy ($\mathrm{SP}, \mathrm{CP} > 1$), while the difference is much larger for Switzerland ($\mathrm{SP}, \mathrm{CP} \approx 2$). For developing countries such as China and Russia, their consumption-based energy consumptions are less than the production-based ones ($\mathrm{CP} < 1$), while the gaps are shrinking. However, their gaps between income-based and production-based energy consumption (SP) are widening during 2000-2014. Though India is a developing country, its consumption-based energy consumption has outpaced the production-based one ($\mathrm{CP} > 1$) after global financial crisis, because of the escalating final consumption. In contrast, India's incomed-based energy consumption is comparable to the production-based energy consumption during the last two decades.

3.4 Sectoral contributions in different perspectives

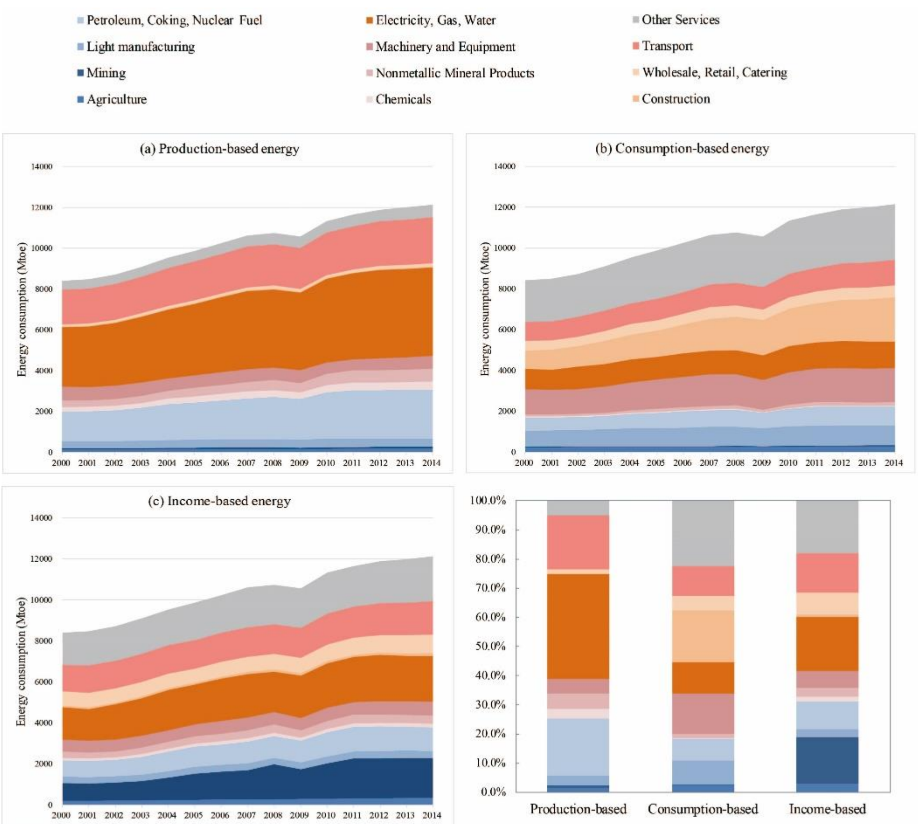

Figure 4. Temporal change in sectoral energy consumption from (a) production-, (b) consumption-, (c) income-based accounting and (d) comparison of sectoral contribution in 2014.

Sectoral breakdown for energy consumption from different perspectives (Figure 3) shows different profiles. The top 20 sectors in income-based energy consumption are mainly related to basic materials (i.e., agriculture, mining, metal, and electricity) and manufacture-related services. These sectors located upstream of the supply chain are critical to industrial production and result in significant downstream energy consumption. Besides, these sectors mainly locate in regions with high GDP, i.e., in US, China, India, Russia, and Brazil. In summary, under the income-based accounting, the major contributors are electricity (18.4%), other services (18.1%), mining (16.1%) and transport sector (13.4%).The biggest sectoral contributor to global production-based accounting is electricity (35.7%), followed by petroleum, coking and nuclear fuel (18.7%) and transport sector (18.7%). Under the consumption-based accounting, the main contributors are other services (22.4%), construction (17.7%), machinery and equipment (13.7%), electricity (10.89%) and transport sector (10.4%). Under the consumption-based and income-based accounting, service sector (including transport, wholesale and other services) respectively shares 37.5% and 38.9% of global total energy consumption, compared to a ratio of 24.8% under the production-based one. Therefore, the tertiary industries as major beneficiary of income and the supplier of high value-added consumer products should take more responsibility in curbing energy consumption.

4 Conclusion and policy implications

The aim of this study is to clarify the role of each region as a supplier, producer, final producer and final consumer in energy consumption. The analysis of national development characteristics and contribution along the global supply chain from different points of view provides a more comprehensive understanding on how energy consumption can be curbed.

The new finding in this study can be summarized as 1) Global energy consumption increased rapidly, and China is the largest energy user from all perspectives. For the developed countries, energy consumptions are stable from 2000-2014, while that of emerging countries almost doubled. 2) Most of the developing countries are producers, whose production- and final production-based energy consumptions are higher than their consumption-based ones. In contrast, the developed countries are consumers, whose consumption-based energy consumptions are higher. 3) At sectoral level, service sector is the biggest contributor of consumption- and income-based energy consumption.

The policy implications are also different because of the diverse trajectory across countries. China and Russia serve as the producers and they use energy in the production of goods or services. Therefore, more efforts should be emphasized on improving energy efficiency. This applies especially for China since it is the largest energy consumer in the world. Norway is an important supplier of resources, which enables the energy consumption of downstream countries.

From a consumption-based perspective, importing countries can improve their environmental preference by selecting producers from abroad with higher energy efficiency. Recent studies have suggested that changes in lifestyles and consumer choice are necessary to reduce environmental pressures (Hubacek et al., 2007; Wiedenhofer et al., 2017). For example, He et al. (2018) has shown that increasing consumption of meat, cooking oil and other-starchy foods drive the environmental burdens, which can be addressed by changing our daily diet habits.

Based on this study, we can identify some possible future researches. In supply-side, we can further explore the upstream and downstream links of the supply chain and international trade, and then consider adopting better policies to complement or replace production-side and demand-side approaches. Besides, the feasibility and effectiveness of policy implementation should be conducted based on these different frameworks of energy consumption.

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