How can net petroleum importers achieve risk aversion in in a globalized world: A multi-regional input-output perspective

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Abstract

Paying attention to the national flows and drivers of embodied petroleum consumption in net petroleum importers are important for petroleum safety risk aversion and environmental protection policy formulation. This study utilized the multi-regional input-output model to determine the top five embodied petroleum net importers (i.e. the United States, Japan, Germany, the United Kingdom and France) under the economic globalization, and traced the flows of embodied petroleum consumption through international trade. Combined with the Logarithmic Mean Divisia Index method, this study also deeply investigated the drivers of changes embodied petroleum in net imports. From the perspective of international trade, the United States was not only the largest importer but also the largest exporter of embodied petroleum. Among the trade flows of embodied petroleum, the largest trade flow was from China to the United States, which indicated that China was the world factory and the United States was the consumer power. The embodied petroleum trade markets of Germany, the United Kingdom and France was mainly distributed in Europe & Eurasia resulted from European economic integration. The largest contributor to the decrease of embodied petroleum imports in top 4 net importers was the petroleum intensity effect. Meanwhile, the import dependence effect was the largest contributor to the increase of France's embodied petroleum net imports. In order to further avoid the risk of petroleum security, constructing the diversified petroleum product import strategy is an extremely effective path. Moreover, improving energy efficiency is another way to solve the contradiction between petroleum supply and demand.

1. Introduction

Petroleum is a non-renewable strategic resource for safeguarding the country's economic and political security(Xu et al., 2011). However, the petroleum self-sufficiency rate varies greatly from country to country, which results from uneven petroleum distribution in the world. Due to the strategic and non-renewable nature of petroleum resources, access to and control of sufficient petroleum resources has become one of the significant goals of a major national security strategy. As a result, many petroleum-related social and political issues have arisen and even wars have been launched (Cilliers and Dietrich, 2000; Conca, 2015; Stoff, 1980). There is spatial heterogeneity between global petroleum consumption and resource endowment, making petroleum transnational and cross-regional mobility inevitable. International trade plays an important role in the way that countries meet domestic petroleum demand, which can redistribute petroleum distribution in the world.

When petroleum consumption countries formulate and implement national petroleum security strategies, they only consider petroleum consumption directly used in any specific production and final demand sectors, but do not take into account the indirect petroleum trade which embodied in the use of products and services that require petroleum inputs in the production process. Petroleum embodied in traded products and services is called embodied petroleum, which can substitute for direct petroleum trade and consumption. In the context of global trade, countries are increasingly participating in international trade, and the phenomenon of importing of embodied petroleum products or services from foreign countries to meet domestic petroleum demand has become widespread. In order to properly investigate the petroleum consumption and the impartiality of petroleum resources distribution in various countries, it is imperative to comprehensively review inter-regional petroleum flows and linkages in global supply chains. The petroleum footprint has been introduced to further identify the flows of petroleum under international trade. The petroleum footprint is based on embodied petroleum measures, it can also be used to quantify the total petroleum demand that embodied in products and services consumed by individuals, towns, cities or countries. Under international trade, petroleum footprint across global supply chains can be used to explore petroleum flows and the impartiality of petroleum resources distribution in various countries.

For countries with net imports of embodied petroleum, petroleum resources have far more restrictive effects on the development of their national economic strength and national status than the net exporters of embodied petroleum. Because the petroleum products produced by net importers cannot satisfy domestic demand, their dependence on foreign countries is greater than that of net embodied petroleum exporters. Once the trading partners providing embodied petroleum products and services cannot guarantee supply, this will cause risks to the petroleum security of net importers. Therefore, the embodied petroleum consumption and petroleum footprint in the international trade of net embodied petroleum importers are more worth investigating.

Taking into account the above issues, this paper takes the net embodied petroleum importers as the research object, and the research objectives are to: (1) holistically examine global petroleum footprint and embodied petroleum trade in globalized world economy and further identified the top 5 net importers of embodied petroleum; (2) deeply determine the petroleum footprint of the top 5 net importers and their foremost embodied petroleum trading partners; (3) decompose the change of net embodied petroleum imports of top 5 net importers to explore the key factors that influencing the change of net embodied petroleum imports.

The rest of the paper is organized as follows: Section 2 presents the related literature review. Section 3 describes the MRIO model and decomposition Methodology. Section 4 describes the global trade volume of embodied petroleum, the regional and sectoral trading patterns and the decomposition results of top 5 net importers. Section 5 concludes.

2. Literature Review

2.1 Review of embodied petroleum and petroleum footprint

Embodied petroleum was the extension of embodied energy which was a considerable indicator used to estimate total energy demand and was conceptualized by Chapman in the 1970s (Chapman, 2007). In 1980, embodied energy was defined as the total energy input embedded in the products or services which included direct energy input and indirect energy input (Costanza, 1980). So far, the embodied energy method has been widely used in order to study the consumption and transfer of energy more systematically and accurately(Chen and Chen, 2015; Limmeechokchai and Suksuntornsiri, 2007; Lixiao et al., 2014; Su and Zhang, 2016; Wu, X.D. et al., 2016). Xu et al. examined the embodied energy in imports of the United Kingdom, and pointed out that if the embodied energy in net imports are considered, the gap between energy consumption and production in UK is far greater than the gap that is generally believed, which will have an impact on UK's energy security(Tang et al., 2013). Yang et al. established an EIO-LCA (Environmental Input–Output Life Cycle Assessment) model to evaluate the impact of Sino-USA trade on embodied energy consumption, and found that the United States was the net importer of embodied energy in the trade between the two countries(Yang et al., 2014). Li et al. evaluated the energy embodied in Macao's foreign trade during 2000–2011, and the results showed that the embodied energy of Macao was more than twice that of direct energy use(Li et al., 2014). The indirect effects emphasized by embodied energy have been recognized by various fields, such as carbon emissions(Arce et al., 2016; Davis and Ken, 2010; Limmeechokchai and Suksuntornsiri, 2007; Minx et al., 2009; Wiebe et al., 2012), coal use(Wu and Chen, 2018; Wu, X.D. et al., 2016), land use (Weinzettel et al., 2013; Yu et al., 2013)and water footprint(Ali et al., 2017; Chang et al., 2016; Chen, Z.M. and Chen, G.Q., 2013). Here, the concept of embodied energy was expanded for total petroleum consumption hidden in commercial products and services, which can be denoted as embodied petroleum.

Petroleum is called as the blood of industry and it provides energy and material support to a wide range of industries, and there are a large number of indirect petroleum hidden in these commercial products and services. For example, as a big manufacturing country, China produces shoes, sports equipment, tires and other items that are exported to foreign countries. Synthetic rubber can be found in these products, and petroleum is the main raw material for making synthetic rubber. Petroleum is therefore indirectly used by these products made in China and flows between countries through international trade. In fact, many high-income countries are always importing from low- and middle-income areas to meet the domestic demand for petroleum-intensive products and services in order to reduce domestic energy consumption and protect the domestic environment. Therefore, in a highly globalized world, some high-income countries have shifted resources and environmental pressures to low- and middle-income countries through international trade (Arto et al., 2016b; Chen, B. et al., 2017; Kanemoto et al., 2011; Peters and Hertwich, 2006; Robert Alan et al., 2015). Tang et al. applied the Input-Output approach to quantify the net petroleum exports embodied in international trade, and found that China's dependence on foreign petroleum was underestimated(Tang et al., 2012).

Petroleum footprint was the extension of water footprint and carbon footprint which were the considerable indicators used to measure human pressure on the natural environment, quantifying the total water demand and the anthropogenic carbon emissions that embodied in products and services consumed by individuals, towns, cities or countries(Ali et al., 2018; Arto et al., 2016a; Chen, Z.M. and Chen, G.Q., 2013). Based on embodied petroleum accounting, the petroleum footprint can be used to better measure human use of petroleum resources and further quantify total petroleum demand that embodied in products and services consumed in international trade. Previous studies have made significant research on water footprint and carbon footprint, while the research on petroleum footprint is minimal(Gerbens-Leenes et al., 2018; Serrano et al., 2016). Based on water footprint and carbon footprint, this paper extends petroleum footprint to study petroleum flows embodied in import and export products and services.

However, at present, there is relatively little research on embodied petroleum, and most of the research is focused on embodied energy and embodied carbon emissions. Previous studies on embodied energy and embodied carbon emissions were usually in one country (Cellura et al., 2014; Limmeechokchai and Suksuntornsiri, 2007; Tang et al., 2013), two countries (Dong et al., 2010; Wang and Li, 2016; Wu, R. et al., 2016; Yang et al., 2014), an industry (Hong et al., 2016; Thormark, 2002; Zhu et al., 2012) or a global perspective (Chen et al., 2018; Chen, Z.-M. and Chen, G., 2013; Zhang et al., 2017), but not enough for net importers. However, for countries with net imports of embodied petroleum, their actual petroleum requirement and petroleum import dependence are always underestimated. In order to accurately measure the total petroleum demand and regional and sectoral trading patterns of net importers, it is important to explore a comprehensive review for embodied petroleum and petroleum footprint between regions of net importers.

2.2 Review of decomposition technique

The increase in net imports of embodied petroleum is related to energy security and economic development throughout the country. Therefore, it is imperative to explore the driving factors behind the changes in net imports of embodied petroleum. When performing factor decomposition analysis, there are frequently two main decomposition techniques: structural decomposition analysis (SDA) and exponential decomposition analysis (IDA) (Jiang and Li, 2017; Jiang et al., 2018; Li and Rui, 2017; Sun et al., 2018). Since SDA is dependent on the input-output model that is also adapted to the accounting of embodied energy and carbon emissions in international trade, many previous studies have utilized the SDA method to quantify the driving forces behind the embodied energy and embodied emissions in trade(Das and Paul, 2014; Lin et al.; Su and Ang, 2017; Su and Ang, 2012; Supasa et al., 2016). Ji et al. employed SDA method to explore the drivers for the increase of the embodied carbon emission in China-US trade, and the results show that carbon intensity was the largest contributor while trade volume was the largest inhibitor (Ji et al., 2017). Su et al. investigated the key factors of Singapore's emission changes by applying SDA method and found that fuel switching and energy efficiency can contribute to curbing emissions growth (Su et al., 2017). Zhong used SDA method to decompose the change of embodied energy into six factors and found that the total final demand is the key driving force for the increase of embodied energy consumption (Zhong, 2018).

Since the SDA method relies on the input-output table, the factor of decomposition is subject to the input-output table. Wang et al compared the advantages and disadvantages of SDA method and IDA method in energy consumption and carbon emission research from two aspects of methodology and application (Wang et al., 2017). Furthermore, many scholars believe that the application of IDA method is more widely used in the field of energy economy through empirical analysis (Jiang et al., 2019; Qiang et al., 2017; Xu and Ang, 2013; Zhao and Li, 2018). The IDA method consists of the Laspeyres index method and the Divisia index method: the former application is hindered by the residual problem; the latter can be further developed into the Arithmetic Mean Divisia Index (AMDI) and Logarithmic Mean Divisia Index

(LMDI) methods (Jianbo et al., 2016; Li and Wang, 2016; Li and Jiang, 2018; Lin and Long, 2016; Wang et al., 2018a; Wang et al., 2018b). LMDI is more popular than AMDI because of its simple calculation, easy to understand and accurate decomposition results, in addition, LMDI has become the most popular method of factor decomposition research (Ang, 2005; Ang and Choi, 1997; Ang and Liu, 2001; Ang et al., 2003; Ang et al., 2014; Cansino et al., 2015; Wang and Li, 2016; Wang et al., 2016; Zhang and Da, 2015).When investigating the driving factors behind the embodied energy and emissions in international trade, the LMDI method was also utilized by many scholars (Dong et al., 2010; Liu et al., 2015; Su et al., 2013). Chen et al. employed the LMDI method to explore the drivers of embodied emissions during 2000–2001, and the results showed that trade structure and embodied emission intensity were the significant contributors to Macao as a net embodied emissions importer (Chen, B et al., 2017). Tang et al. employed the Environmental Input-Output method and LMDI method to investigate the main factors that influencing the embodied energy use changes in trade of Guangdong’s each sector (Tang et al., 2018).

By comparing the SDA method with the LMDI method, in order to make the factors of decomposition not limited by the input-output tables, this paper used LMDI method to factorize the change of net embodied petroleum imports.

3. Methodology

3.1 Multi-Regional Input-Output Model

The input-output analysis includes the single-region input-output (SRIO) analysis and the multi-region input-output (MRIO) analysis(Gavrilova and Vilu, 2004; Wiedmann et al., 2010; Zhang et al., 2017). Compared with the “technical identity hypothesis” of the SRIO analysis, the MRIO analysis considers that the energy consumption intensity of different regions is different due to the technical level of production, which makes the measurement results more accurate (Wiedmann, 2009; Wiedmann and Barrett, 2013). Then, the MRIO analysis can trace the consumption products of a country to its producing country and then derive the amount of energy transfer, which is beneficial to analyze the industrial linkages and trade links between countries and departments(Chen et al., 2016; Qi et al., 2014). Therefore, in this paper, the MRIO model was utilized to investigate the net importers of embodied petroleum in global world economy.

The multi-regional input-output tables based on the world economy of m-region, n-sector provide a unified framework for MRIO analysis to explore the flow of environmental resources on a global scale, whose fundamental structure is shown in Table A1 (see Appendix A). The row balance of tabular scheme which represents that each country's outputs are used to satisfy intermediate use and final use can be used as the starting point for MRIO analysis, which could be expressed as follows:

$$\begin{bmatrix} x_1 \\ x_2 \\ \vdots \\ x_m \end{bmatrix} = \begin{bmatrix} A_{11} & A_{12} & \cdots & A_{1m} \\ A_{21} & A_{22} & \cdots & A_{2m} \\ \vdots & \vdots & \ddots & \vdots \\ A_{m1} & A_{m2} & \cdots & A_{mm} \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \\ \vdots \\ x_m \end{bmatrix} + \begin{bmatrix} y_{11} + \sum_{s \neq 1} y_{1s} \\ y_{22} + \sum_{s \neq 2} y_{2s} \\ \vdots \\ y_{mm} + \sum_{s \neq m} y_{ms} \end{bmatrix} (1)$$

where x_r is the total economic output of the r country; A_{rr} denotes the demand of each country's domestic production departments, that is, the direct consumption coefficient matrix; A_{rs} denotes the demand of different country's production departments, and the element of the input coefficient matrix is $a_{ij}^{rs} = z_{ij}^{rs} / x_j^r$, where z_{ij}^{rs} denotes the intermediate use by the sector i of country r from the sector j of country s. y_{rr} is the final demand of r country that from domestic production, and y_{rs} is the final demand of country s that produced from country r. Eq. (1) can be rearranged as follows:

$$\begin{bmatrix} x_1 \\ x_2 \\ \vdots \\ x_m \end{bmatrix} = \begin{bmatrix} I - A_{11} & I - A_{12} & \cdots & I - A_{1m} \\ I - A_{21} & I - A_{22} & \cdots & I - A_{2m} \\ \vdots & \vdots & \ddots & \vdots \\ I - A_{m1} & I - A_{m2} & \cdots & I - A_{mm} \end{bmatrix} \begin{bmatrix} \sum_s^m y_{1s} \\ \sum_s^m y_{2s} \\ \vdots \\ \sum_s^m y_{ms} \end{bmatrix}$$

$$= \begin{bmatrix} L_{11} & L_{12} & \cdots & L_{1m} \\ L_{21} & L_{22} & \cdots & L_{2m} \\ \vdots & \vdots & \ddots & \vdots \\ L_{m1} & L_{m2} & \cdots & L_{mm} \end{bmatrix} \begin{bmatrix} \sum_s^m y_{1s} \\ \sum_s^m y_{2s} \\ \vdots \\ \sum_s^m y_{ms} \end{bmatrix} (2)$$

In simply notation, the Eq. (2) can be rewritten as follows:

$$X = AX + Y = (I - A)^{-1} * Y = L * Y (3)$$

where $L_{rs} = I - A_{rs}$ is the inverse Leontief matrix, represents that the quantity of total output of country r resulting from an increase in the final demand of country s by one unit. Given the final demand, the total output that meets these final demand can be obtained by multiplying the inverse Leontief matrix and the final demand. Therefore, with properly given the inverse Leontief matrix and final demand, the total economic output of country r can be obtained as follows:

$$X_r = \sum_s^m L_{rs} \sum_u^m Y_{su} (4)$$

The embodied petroleum intensity of sector i in country r satisfy $f_i^r = p_i^r / x_i^r$, where p_i^r denotes the total embodied petroleum use of sector i in country r. In the context of a globalized world economy, energy resources flow internationally through international trade. By expanding the inverse Leontief matrix, the petroleum inverse Leontief matrix can be obtained by multiplying the inverse Leontief matrix and a diagonal matrix F which contains the embodied petroleum intensity. Therefore, the embodied petroleum (EP) can be calculated by multiplying the petroleum inverse Leontief matrix and the final demand, which is shown as follows:

$$\mathrm{EP} = \mathrm{F}^*\mathrm{L}^*\mathrm{Y} (5)$$

In detailed matrix notation, the Eq. (5) can be rewritten as follows:

$$\begin{bmatrix} \mathrm{EP}_{1s} \\ \mathrm{EP}_{2s} \\ \vdots \\ \mathrm{EP}_{ms} \end{bmatrix} = \begin{bmatrix} \mathrm{f}_1 & 0 & \cdots & 0 \\ 0 & \mathrm{f}_2 & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \cdots & \mathrm{f}_\mathrm{m} \end{bmatrix} \begin{bmatrix} L_{11} & L_{12} & \cdots & L_{1m} \\ L_{21} & L_{22} & \cdots & L_{2m} \\ \vdots & \vdots & \ddots & \vdots \\ L_{m1} & L_{m2} & \cdots & L_{mm} \end{bmatrix} \begin{bmatrix} \sum_s^m y_{1s} \\ \sum_s^m y_{2s} \\ \vdots \\ \sum_s^m y_{ms} \end{bmatrix}$$

$$= \begin{bmatrix} \mathrm{f}_1 L_{11} & \mathrm{f}_1 L_{12} & \cdots & \mathrm{f}_1 L_{1m} \\ \mathrm{f}_2 L_{21} & \mathrm{f}_2 L_{22} & \cdots & \mathrm{f}_2 L_{2m} \\ \vdots & \vdots & \ddots & \vdots \\ \mathrm{f}_\mathrm{m} L_{m1} & \mathrm{f}_\mathrm{m} L_{m2} & \cdots & \mathrm{f}_\mathrm{m} L_{mm} \end{bmatrix} \begin{bmatrix} \sum_s^m y_{1s} \\ \sum_s^m y_{2s} \\ \vdots \\ \sum_s^m y_{ms} \end{bmatrix} (6)$$

where $\mathrm{EP}_{\mathrm{rs}}$ represents the embodied petroleum consumption of country r for the final demand of country s, and can describe the embodied petroleum flows from country r to country s.

The total embodied petroleum in imports of country r, EPM_r, can be expressed as follows:

$$\mathrm{EPM}_\mathrm{r} = \sum_{r \neq s}^m EP_{sr} = \sum_{s \neq r}^m f_s x_{sr} (7)$$

The total embodied petroleum in exports of country r, EPE_r, can be expressed as follows:

$$\mathrm{EPE}_\mathrm{r} = \sum_{s \neq r}^m EP_{rs} = \sum_{s \neq r}^m f_s x_{sr} (8)$$

The total embodied petroleum in net imports of country r, EPN_r, can be expressed as follows:

$$\mathrm{EPN}_\mathrm{r} = \mathrm{EPM}_\mathrm{r} - \mathrm{EPE}_\mathrm{r} (9)$$

3.2 Decomposition Methodology: the LMDI method

In order to more comprehensively analyze the net importers of embodied petroleum in global world economy, in this paper, the total embodied petroleum in net imports is decomposed into many elements to analyze the driving factors affecting the changes of total embodied petroleum in net imports.

Based on the Kaya Identity(Kaya, 1989), the total embodied petroleum in net imports can be expressed as the following identity:

$$EPN_{\mathrm{r}} = \frac{EPN_r}{EPC_r} \times \frac{EPC_r}{GDP_r} \times \frac{GDP_r}{P_r} \times P_r (10)$$

$$= D_r \times I_r \times G_r \times P_r (11)$$

where $EPC_r = \sum_r^m EP_{sr}$ represents the total embodied petroleum consumption of country r; GDP_r and P_r represent the gross domestic product and total population of country r, respectively. $D_r = \frac{EPN_r}{EPC_r}$ represents the share of the total embodied petroleum in the net imports to the total embodied petroleum consumption of country r, which is defined as embodied energy import dependence; $I_r = \frac{EPC_r}{GDP_r}$ represents the embodied petroleum consumption per unit of gross domestic product of country r, which is defined as petroleum intensity; $G_r = \frac{GDP_r}{P_r}$ represents gross domestic product per person of country r, which is defined as per capital GDP.

The LMDI method includes two forms: additive decomposition form and multiplicative decomposition form (Ang, 2004; Ang, 2015; Jiang et al., 2018). In this paper, the additive decomposition form is used to decompose the change of the embodied petroleum in net imports into four driving factors, which is shown as follows:

$$\Delta EPN_{\mathrm{r}} = EPN_r^t - EPN_r^0 = \Delta N_{Dt}^r + \Delta N_{It}^r + \Delta N_{Gt}^r + \Delta N_{Pt}^r (12)$$

where t represents the target year and 0 represents the based year; ΔN_{Dt}^r represents the import dependence effect, ΔN_{It}^r represents the petroleum intensity effect; ΔN_{Gt}^r represents the economic effect; ΔN_{Pt}^r represents the population effect. These four driving factors can be calculated by the following formula:

$$\Delta N_{Dt}^r = \frac{EPN_r^t - EPN_r^0}{lnEPN_r^t - lnEPN_r^0} \times ln\frac{D_r^t}{D_r^0} (12a)$$

$$\Delta N_{It}^{r} = \frac{EPN_r^t - EPN_r^0}{lnEPN_r^t - lnEPN_r^0} \times ln\frac{I_r^t}{I_r^0} (12b)$$

$$\Delta N_{Gt}^{r} = \frac{EPN_r^t - EPN_r^0}{lnEPN_r^t - lnEPN_r^0} \times ln\frac{G_r^t}{G_r^0} (12c)$$

$$\Delta N_{Pt}^{r} = \frac{EPN_r^t - EPN_r^0}{lnEPN_r^t - lnEPN_r^0} \times ln\frac{P_r^t}{P_r^0} (12d)$$

3.3 Data Source

The calculations in this study were executed using the World Input-Output Database (WIOD), which is a multi-region input-output (MRIO) database developed by the European Union. The World Input-Output Table (WIOT) compiled by WIOD contains 41 countries which include the 27 member states of the European Union, 13 major economies outside the EU and a ROW (Rest of the World) area composed of the rest of the country (see Appendix B), each country has 35 sectors (see Appendix C), and temporal coverage (1995–2014). The data of gross energy use (in TJ) comes from Environmental Accounts of WIOD, which runs from 1995 to 2009. Therefore, this study period started from 2001 and end in 2009. WIOD was chosen over the other available MRIO databases because of its homogeneous sector classification, which allows industries in different countries to be directly compared. And in 2009, the total GDP of 40 countries accounted for 86.14% of global GDP, so WIOD can better reflect the current production patterns and trade patterns. In this paper, WIOD is used to obtain the input-output table for the world economy of 2009, and the petroleum use includes Crude oil, NGL and feedstock, Diesel oil for road transport, Motor gasoline, Jet fuel (kerosene and gasoline), Light Fuel oil, Heavy fuel oil, Naphtha and Other petroleum products according to the list of Energy commodities in the WIOD system of satellite accounts. The data about GDP (constant 2010 US$) and population are from Word Bank.

4. Results And Discussion

4.1 Global petroleum footprint and embodied petroleum trade in the global supply chain

From the global perspective, the total consumption volume of embodied petroleum associated with international trade was increased from 8.29E + 07 TJ in 2001 to 1.03E + 08 TJ in 2009, which indicated an average annual growth rate of 2.81%. The petroleum consumption embodied in international trade should not be underestimated in the global petroleum consumption accounting due to the huge trade volume of embodied petroleum.

In order to further explore the trade volume of embodied petroleum in detail, this paper has calculated global petroleum footprint and embodied petroleum trade in the global supply chain, which was shown in Fig. 1 and Table 1. The United States is the largest embodied petroleum importer, leading the other 39 regions with absolute advantage, which indicated the United States imports massive petroleum-intensive products and services. However, embodied petroleum volume in imports of the United States was not always growing during 2001–2009, it reached peak in 2005 with 2.20E + 07 TJ and dropped to its lowest point in 2009 with 1.60E + 07 TJ. From the perspective of average value of EPM during 2001–2009, Japan was the second largest importer with an EPM of 7.17E + 06 TJ, followed by Germany (5.51E + 06 TJ) and China (5.88E + 06 TJ). The embodied petroleum in imports of Japan and Germany revealed a little volatile during 2001–2009. However, as for China, the embodied petroleum in imports has grown by a large margin during the study period, from 3.72E + 06 TJ in 2001 to 7.81E + 06 TJ in 2009, with an average annual growth rate of 9.70%. China continued to import petroleum-intensive products and services from foreign countries, making its embodied petroleum in imports increased rapidly, which resulted in that EPM of China has surpassed Germany since 2007 and surpassed Japan in 2009. In addition, during 2001–2009, countries with the EPM exceeding 5E + 06TJ were also in the Unites Kingdom and France. It can be seen that countries with considerable EPM are basically developed countries, except China, which reflects that developed countries tend to transfer high-pollution and high-energy industries to developing countries, and then obtain energy-intensive products and services through international trade to reduce domestic energy consumption and environmental pollution.

Regarding the embodied petroleum in exports, the Unite States was also the leading exporter with 8.59E + 06 TJ of average value of embodied petroleum, but no longer had the absolute advantage over other countries during 2001–2009. It can be seen that the Unite States was not only the largest embodied petroleum importer but also the largest embodied petroleum exporter, which indicated that the United States was committed to promoting global trade liberalization and was the largest participating country in international trade between 2001 and 2009. China, as the second largest exporter of embodied petroleum, its growth trend of EPE was similar to that of the Unite States, with growth from 2001(3.91E + 06 TJ) to peak in 2008 (8.88E + 06 TJ) and a downward trend in 2009 (7.71E + 06 TJ). Russia and South Korea were the third and fourth embodied petroleum exporters followed by Germany and the Netherlands, with 5.44E + 06 TJ and 4.80E + 06 TJ of average values of embodied petroleum in exports, respectively. However, the embodied petroleum in exports of top 6 exporters all showed a down tendency during 2008–2009.

Regarding the embodied petroleum in net imports, the increase or decrease in EPN of many countries was not large, which showing a gathering point in Table 1. During the whole study period (2001–2009), 24 regions always have positive EPN with embodied petroleum deficit, which means they are always embodied petroleum net importers; and 8 regions always have negative EPN with embodied petroleum surplus, which means they are always embodied petroleum net exporters; while the other 8 regions have positive and negative alternating EPN values. The United States, as the dominant embodied petroleum net importer, EPN of it has increased or decreased greatly during 2001–2009, which peaked in 2005 with 1.37E + 07 TJ and fell to a minimum in 2009 with 6.58E + 06 TJ. Russia is the world's leading net exporter of embodied petroleum with an average value of EPN of -4.39E + 06 TJ, whose EPN was always positive during 2001–2009. From the perspective of average value of EPN during 2001–2009, Japan, Germany, the United Kingdom and France were the top 5 largest net importers of embodied petroleum.

International trade causes trade flows of embodied petroleum between regions, the major trade flows of average values of embodied petroleum during 2001–2009 are shown in Fig. 2. The whole world economy is divided into 20 major economies, i.e. China includes China and Taiwan; EU21 represents the remaining 21 EU countries in addition to the six EU countries listed separately; ROW represents Rest of the World classified by WIOD. Since the ROW under the WIOD division contains more complex countries, the trade flow associated with ROW is relatively larger than other countries. Among the trade flows of embodied petroleum (regardless of the trade flows of ROW), the largest trade flow was from China to the United States with 2.18E + 06 TJ of embodied petroleum exported from China to the United States, which indicated that China was the world factory and the United States was the consumer power. China, as the world factory, not only meets domestic demand, but also provides petroleum-intensive products and services to foreign countries. ROW is the largest recipient of Chinese exports of embodied petroleum, followed by the United States and Japan. The second trade flow was related to the export from Canada to the United States. On average, 1.90E + 07 TJ of embodied petroleum was imported into the United States each year during 2001–2009, of which 22.80% was from China and Canada. The third and fourth trade flows of embodied petroleum were exports from EU21, 1.89E + 06 TJ of embodied petroleum was exported to Germany and 1.06 E + 06 TJ of embodied petroleum was exported to the United States. The trade flow which also exceeded 1.00E + 06 TJ was from Russia to EU21 with 1.02E + 06 TJ of embodied petroleum. It can be seen that the embodied petroleum trade flows in the United States are the most significant with the exception of ROW, therefore the United States was regarded as one of the world's major trading centers during 2001–2009.

4.2 Regional and sectoral trading patterns of embodied petroleum net importers

Based on the average value of EPN during 2001–2009, the top 5 net importers of embodied petroleum were the United States, Japan, Germany, the United Kingdom and France. In order to explore more deeply the regional and sectoral trading patterns of embodied petroleum net importers, the import and export transactions of the five leading net importers have been analyzed in more detail, which were shown in Fig. 4. The 41 regions divided by WIOD were aggregated into five major regions, and 35 sectors divided by WIOD were aggregated into seven major sectors, which are shown in Appendix B and C.

The United States, as the largest embodied petroleum importer, 41.70% of its average import volume was from ROW during 2001–2009, 20.93% from Asia Pacific, 20.65% from Europe & Eurasia, 14.90% from North America and 1.82% from South America. Most imports from other regions were all required by their heavy manufacturing sector. The average value of embodied petroleum in imports of the United States during 2001–2009 was 1.90E + 07 TJ, and 1.54E + 07 TJ of embodied petroleum imports came from the heavy manufacturing sector. Therefore, from the perspective of sectoral trading patterns, the heavy manufacturing sector was the largest supplier of imported embodied petroleum products for the United States. The second largest supplier for the United States was the transport sector, and imports of embodied petroleum products related to the transport sector accounted for 8.22% of total embodied petroleum imports, followed by light manufacturing sector (3.25%) and electricity sector (2.97%). Similarly, the United States was also the largest exporter of embodied petroleum products. Of the exports of the United States, ROW was the significant receiver followed by Europe & Eurasia and North America. 76.85% of the exported embodied petroleum products was from the heavy manufacturing sector in the United States, and 14.50% was from the transport sector.

Japan's import markets of embodied petroleum products were mainly distributed in ROW (49.62%), which mainly provided by their heavy manufacturing sectors. In addition, the imports from Asia pacific and Europe & Eurasia constituted 29.90% and 10.15% of Japan’s total embodied petroleum imports, respectively. On the sectoral level, the embodied petroleum imports from the heavy manufacturing sector make up 80.17% of the total embodied petroleum imports in Japan, which was much higher than other sectors. Similar to the United States, the second supplier for Japan was the transport sector, and imports of embodied petroleum products related to the transport sector accounted for 10.75% of total embodied petroleum imports, followed by electricity sector (2.57%). For the embodied petroleum exports from Japan, the largest trade flow was exported to ROW, accounting for 35.08% of total exports, followed by Asia pacific (23.56%). It is worth noting that Japan’s embodied petroleum imports from North America account for a small share of total imports, but 22.23% of its petroleum products were exported to North America. From the perspective of sectoral trading patterns, similar to imports, the heavy manufacturing sector was the Japan’s largest export recipient, but the proportion decreased to 66.49%. Among Japan’s total embodied petroleum products exports, 25.47% of that was exported to foreign transport sector, and 3.67% was to service sector.

The average value of embodied petroleum in imports of the Germany during 2001–2009 was 6.34E + 06 TJ, and Europe & Eurasia were the largest markets for Germany which provided 3.43E + 06 TJ of embodied petroleum. Among the Germany’s imports from Europe & Eurasia, 85.28% were associated with the heavy manufacturing sector. In addition, of the total embodied petroleum imports in Germany, 24.60% was from ROW and 12.20% was from Asia pacific. On the sectoral level, the heavy manufacturing sector made the biggest contribution to Germany’s imports which accounted for 81.82% of total embodied petroleum imports. Meanwhile, the mining sector played a weak role on total imports, accounting for only 0.92%. For the embodied petroleum exports from Germany, the embodied petroleum products provided by the heavy manufacturing sector constitute 84.37% of Germany’s total exports, which were mainly exported to three markets of Europe & Eurasia, ROW and North America. It is worth noting that in the embodied petroleum trade between Germany and North America, Germany's imports from North America accounted for 7.93% of total imports, and North America is the second smallest import market that is only higher than South America. However, Germany's exports to North America accounted for 14.43% of total exports, and North America is the third largest export market higher than Asia pacific.

The United Kingdom was the fourth largest net importer of embodied petroleum according to the average value in net imports during 2001–2009. The embodied petroleum import markets in the United Kingdom was mainly distributed in ROW, while the export markets were mainly distributed in Europe & Eurasia. Among the United Kingdom's total imports, 43.38% was from ROW, 35.90% was from Europe & Eurasia, 10.57% was from Asia pacific and 9.53% was from North America. Of the United Kingdom's exports of embodied petroleum product, 52.59% are exported to Europe and 20.41% are exported to North America. However, as the largest import market, ROW was only the third largest export market. The embodied petroleum from the United Kingdom exported to ROW accounted for 20.34% of total exports. From the perspective of sectoral trading patterns, both import and export trades are mainly driven by the heavy manufacturing and the transport sector.

For France's embodied petroleum international trade, whether it is import or export, the largest trade markets were mainly distributed in Europe & Eurasia. 42.63% of total embodied petroleum imports was imported from Europe & Eurasia, and 51.24% of total embodied petroleum exports was exported to Europe & Eurasia in France. ROW was the second largest importing market, and 39.06% of embodied petroleum products were imported from there. Similarly, ROW was the second largest exporting market, and 25.49% of embodied petroleum products were exported to there. For France, the embodied petroleum products imported from abroad are basically provided by their heavy manufacturing sector. Similarly, the embodied petroleum products exported to foreign countries were also required by their heavy manufacturing sector of France. The transport sector also played an important role in the process of embodied petroleum international trade. The embodied petroleum imports associated with the transport sector made up 8.01% of total imports in France, and the exports associated with the transport sector accounted for 13.42% of total exports.

4.3 Decomposition of embodied petroleum in net imports

In order to further explore the factors affecting the net import of embodied petroleum, a factor decomposition analysis was carried out on the embodied petroleum in net imports, and the decomposition results of top 5 net importers are shown in Fig. 5 and Fig. 6. As shown in Fig. 5, the embodied petroleum in net imports of the United States have shown a very regular growth trend, increasing from 2001 to 2005 and decreasing from 2005 to 2009. From the cumulative effect, the EPN of the United States has decreased by 2.97E + 08 TJ, which was mainly driven by the petroleum intensity effect, accounting for about 92.94% of total imports decrease. From the cumulative effect, the decrease of United States' EPN from the import dependence effect was decreased by 1.72E + 08 TJ, accounting for about 57.89% of total net imports decrease. Moreover, the economic effect and the population effect played the negative effect on the decrease of United States' EPN, accounting for about − 24.25% and − 26.58% of total imports decrease, respectively. As shown in Fig. 5, from the impact of the annual effect, the petroleum intensity effect always played an active role on the decrease of United States' EPN and the population effect always played a negative role on the decrease of United States' EPN during 2001–2009. For the import dependence effect, its direction of action was consistent with the direction of change in total net imports of embodied petroleum. For the economic effect, its direction of action also has changed, which played a promoting role during 2001–2007 and played an inhibiting role during 2007–2009.

As shown in Fig. 5, the volume of embodied petroleum in net imports of Japan showed a trend of increase or decrease in volatility. However, from the cumulative effect, Japan’s total net imports volume decreased by 1.54E + 08 TJ during 2001–2009, which was mainly driven by the import dependence effect and the petroleum intensity effect. As shown in Fig. 6, the petroleum intensity effect always played the inhibitory effect during 2001–2009, which constituted 54.25% of Japan’s total EPN and was the largest contributor to the reduction in embodied petroleum imports of Japan. Comparing the direction of the import dependence effect and the total effect, it can be seen that the direction of the annual embodied petroleum in net imports volume depended on the direction of the import dependence effect. However, results in the change of direction of action, the import dependence effect was the second largest contributor to the reduction in EPN of Japan. In addition, the economic effect and the population effect was relatively small, and has always promoted the increase of Japan’s EPN.

Figure 5 shows that Germany’s EPN fell by a total of 45.24E + 06 TJ during the study period. From the cumulative effect, the impact of the import dependence effect, the petroleum intensity effect and the population effect played the promoting role for the increase of Germany’s embodied petroleum imports. As shown in Fig. 6, although the population effect contributed only 2.57% to total embodied petroleum imports changes, it always played positive role on the decline in total net imports except for 2001–2003. As for the economic effect, although its direction of action has been changing, it contributed to the growth of the EPN from the cumulative perspective. Unlike the United States and Japan, the petroleum intensity effect of Germany did not always inhibit the EPN during 2001–2009, which was the second most influential factor effect after the import dependence effect. For the import dependence effect, it can be seen that it was the largest contributor for the annual changes of total EPN export for 2006–2007. During 2006–2007, the inhibiting effect of the petroleum intensity effect exceeded that of the import dependence effect.

As shown in Fig. 5, from the cumulative effect, the largest contributors to the changes of embodied petroleum net imports in the United States, Japan and Germany were the petroleum intensity effect. Similar to the top 3 net importers, in the United Kingdom, the petroleum intensity effect also played the significant role on the changes of EPN, which accounted for about 149.26% of total imports decrease. The second largest contributor to the changes of EPN was the economic effect from the absolute value perspective, which accounted for about − 41.86% of total net imports decrease. Followed by the economic effect, the population effect also played the inhibiting effect on the decrease of EPN, which accounted for about − 27.43% of total imports decrease. Figure 6 shows that although the import dependence effect has the greatest impact on annual net imports changes except for 2002–2003 and 2005–2006, the cumulative effect was indeed the lowest, accounting for only 20.04% of the total imports decrease.

It can be seen that the embodied petroleum net imports of the top 4 net importers showed the downward trend during the period 2001–2009, while France, as the fifth largest net importer of embodied petroleum, accumulated a cumulative increase of 1.68E + 08 TJ during the study period (Fig. 5). The embodied petroleum net imports in France has always shown a growing trend during the study period except for 2005–2006. As shown in Fig. 6, during 2001–2005 and 2006–2008, the increase of embodied petroleum net imports was mainly driven by the import dependence effect; while during 2005–2006, the decrease of embodied petroleum net imports was mainly driven by the petroleum intensity effect. The population effect always played an active role on the increase of the embodied petroleum net imports during 2001–2009, which constitute 7.71% of France's total imports from the cumulative perspective. The economic effect's direction of action has changed, which played a promoting role in 2001–2007, and played an inhibiting role in the remaining years.

5. Conclusions And Policy Implications

5.1 Conclusions

This paper explores the petroleum footprint and embodied petroleum trade evolution in global world economy based on MRIO and LMDI method. A major contribution beyond previous research is the provision of time series analysis of the world's petroleum footprint in the global supply chain through MRIO method. This analysis reveals the top 5 net importers of embodied petroleum and analyzes the regional and sectoral trading patterns in international trade. Another contribution is to explore the drivers of the embodied petroleum trade volume of the top 5 net importers through the LMDI approach. This analysis reveals the extent to which the import dependence effect, the petroleum intensity effect, the economic effect and the population effect affect different countries.

With this paper, the main conclusions can be shown as following:

For the world as a whole, the total embodied petroleum trade volume increased from 8.29E + 07 TJ in 2001 to 1.03E + 08 TJ in 2009 with the average annual growth rate of 2.81%. The United States was found to be the largest embodied petroleum importer, and was also the largest embodied petroleum exporter during the whole study period. From the perspective of average value, the United States, Japan, Germany, China and the United Kingdom were the five largest importers of embodied petroleum, in contrast to the United States, China, Russia, South Korea and Germany as the top five exporters, the United States, Japan, Germany, the United Kingdom and France as the top five net importers. International trade causes trade flows of visual petroleum between regions, the trade flow associated with ROW is relatively larger than other countries resulted from ROW under the WIRD division contains more complex countries. If regardless of the trade flows of ROW, both of the largest and second largest trade flows were exported to the United States, the former came from China and the latter came from Japan. Moreover, the third and fourth trade flows of embodied petroleum were exports from EU21, 1.89E + 06 TJ of embodied petroleum was exported to Germany and 1.06 E + 06 TJ of embodied petroleum was exported to the United States.

As for the sectoral trading patterns of embodied petroleum top five net importers, the commonality was that both imports and exports are driven primarily by the heavy manufacturing sector and the transport sector, which indicated that petroleum is the blood of industry. As for the regional trading patterns of embodied petroleum top five net importers, the main distribution markets for imports and exports in each country are basically different. For the United States and Japan, ROW was both their largest import market and the largest export market. Whether it is import or export, Asia pacific was the second largest embodied petroleum trade market of Japan. However, the embodied petroleum trade markets of Germany, the United Kingdom and France was mainly distributed in Europe & Eurasia resulted from they are all European countries.

Among the top five net importers of embodied petroleum, the volume of net embodied petroleum imports of top four net importers showed a down tendency during the whole study period. From the cumulative effect, the largest contributor to the changes of embodied petroleum imports in United States, Japan, Germany and the United Kingdom was the petroleum intensity effect, which played an inhibiting role on the increase of their embodied petroleum net imports. However, embodied petroleum net imports in France has always shown a growing trend during the study period except for 2005–2006, which was manly driven by the import dependence effect. The import dependence effect was the largest contributor to the increase of its embodied petroleum net imports.

5.2 Policy Implications

Because of the importance of petroleum in the country's economic politics, and as one of the main sources of air pollution. The results of this study also have important implications for petroleum security risk aversion and environmental protection policy formulation. Under international trade, if a country's petroleum is mainly dependent on imports, once the importing country stops supplying it, it will endanger national security. Moreover, under international trade, the petroleum use in a country is transferred internationally, resulting in its actual petroleum demand and petroleum import dependence are always underestimated or overestimated. Therefore, considering only direct petroleum consumption analysis is not conducive to the formulation and implementation of national petroleum security strategy.

The substantial increase in embodied petroleum imports and the continuous expansion of import dependence make economic and social development and national security face new challenges. Therefore, in order to ensure petroleum supply and national security, these countries must actively take measures to avoid petroleum security risk aversion. According to the research results of this paper, for the major importers of embodied petroleum, while increasing domestic petroleum and gas exploration and development and ensuring stable and increased domestic petroleum production, efforts should be made to do the following three aspects:

(1) In order to ensure stable petroleum supply and diversify petroleum import risks, it is necessary to implement a diversified import strategy and build a new pattern of diversified petroleum imports. Specifically, these countries should actively develop strategic petroleum partnerships with other countries,

strive to open up new petroleum supply areas, and reduce excessive dependence on their original petroleum cooperative partners.

(2) In view of the insufficiency and shortage of domestic petroleum resources, the embodied petroleum net importers should actively participate in the development and utilization of global oil resources and implement the transnational operation strategy. The government should encourage and support domestic petroleum enterprises to participate in foreign petroleum exploration and development, make full use of foreign petroleum resources, and establish long-term and stable overseas petroleum supply channels.

(3) Since energy efficiency is an important factor aggravating the contradiction between domestic petroleum supply and demand, energy efficiency can be improved from two aspects: energy saving and energy structure adjustment. Regarding energy-saving measures, the focus is to reduce the proportion of industries with high fuel consumption, promote the application of new technologies and processes, and develop fuel-saving products. The focus of energy restructuring is to increase the proportion of natural gas and renewable energy consumption. Specifically, the government should vigorously develop the natural gas industry and encourage the application of renewable energy such as wind and solar energy to reduce the intensity of dependence on petroleum.

Declarations

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Consent to Participate Not applicable

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Tables

Table 1 is not available with this version

Figures

Figure 1

Global petroleum footprint and embodied petroleum trade in the global supply chain. ((a) embodied petroleum in imports (EPM) and (b) embodied petroleum in exports (EPE) of 40 regions during 2001-2009. See Appendix B for details of the regions)

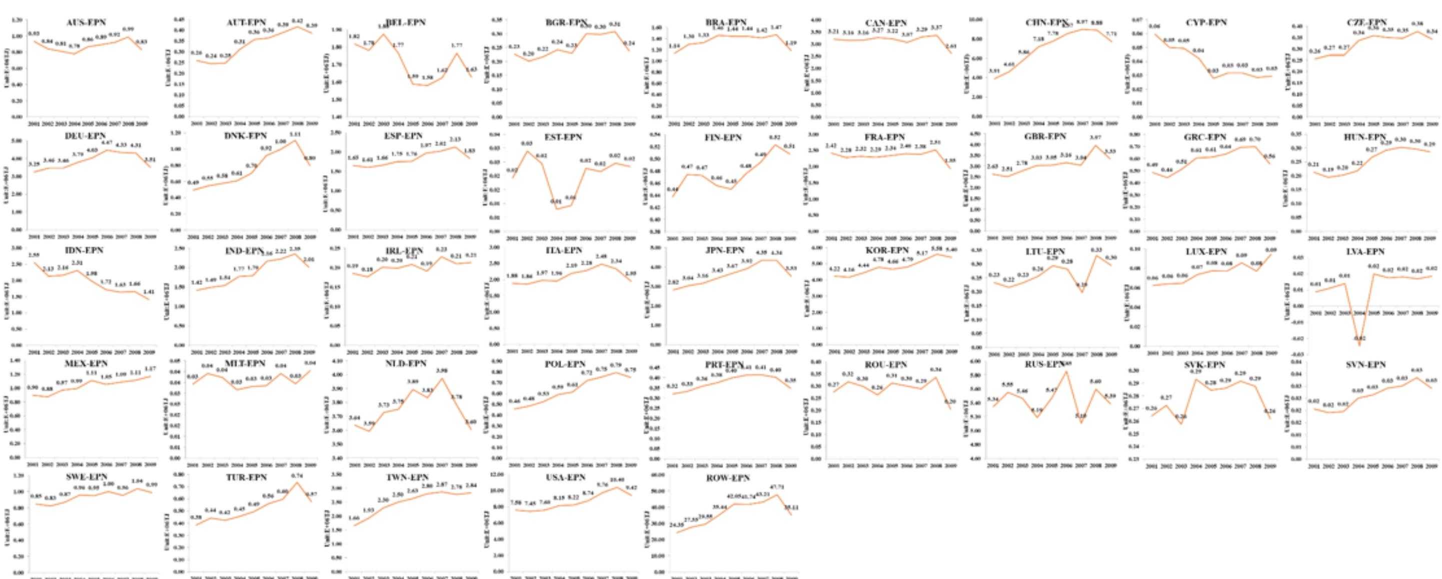

Figure 2

Embodied petroleum in the net imports (EPN) of 40 regions during 2001-2009 (Unite: E+06TJ)

Figure 3

Average values of embodied petroleum connections between the 20 major economies over 2001-2009. (The chord's color corresponds to the larger exporter of the two economies. See Appendix B for details of the 20 major economies)

Figure 4

Regional and sectoral trading patterns to embodied petroleum in imports and exports of top 5 net importers. (The trade flows in Sankey diagrams are the average value of embodied petroleum between 2001 and 2009; See Appendix B and Appendix C for details of the regions and the sectors, respectively.)

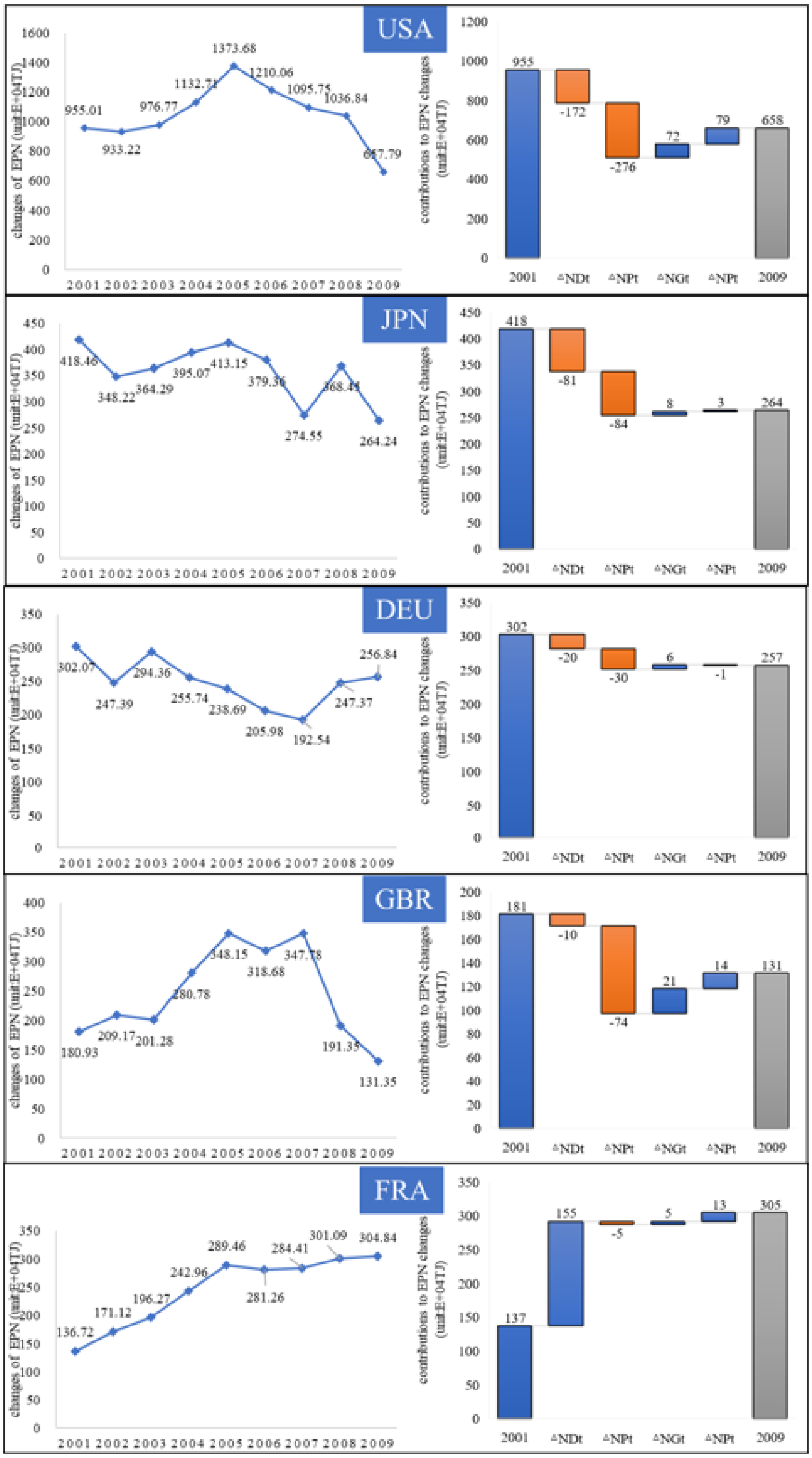

Figure 5

The changes of EPN and cumulative effect of decomposition for top 5 largest net importers during 2001-2009

Figure 6

Decomposition of net imports of embodied petroleum for top 5 net importers during 2001-2009

Supplementary Files

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