The oil-slick trade: An analysis on embodied crude oil in China's trade and consumption during 1995-2011

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Abstract: China has become the world's second largest crude oil importer and consumer. Meanwhile, China has also become the world workshop and the world's largest exporter of commodities. The globalization of production and consumption has important impact on China's oil consumption, which can't be adequately assessed only through checking China's direct imports and exports of crude oil. Based on a global multi-regional input-output model, this article examining both China's direct trade of crude oil and embodied crude oil in China' exports and imports of goods and services during 1995-2011. The results showed that about one fifth to one third of imported oil is used to producing exports in China. Therefore, China is playing the role as a transit hub of crude oil from extraction places to global final consumers, particularly those in advanced countries. Foreign consumers actually benefit from China's global hunt for natural resources, a fact usually overlooked by critics of China's oil thirst. China was net exporter of embodied oil. Net exports of embodied oil increased after China's entry into the World Trade of Organization in 2001, but decreased quickly after the financial crisis starting in 2008 due to weak foreign demand and aggressive economic stimulus in China. In addition, China's oil demand from production was greater than that from consumption, whereas the gap has shrunk quickly in recent years. We also found that China's oil import dependence assessed from consumption end was higher than import dependence assessed from production end, a traditional indicator often discussed in the context of energy security. We discussed various policy implications of these results in context of China's recent reforms in economic and environmental governance.

Keywords: Embodied crude oil; Multi-regional input-output analysis; Oil demand from consumption; Oil import dependence

1. Introduction

According to the statistics from BP energy review, China overtaking Japan became the world's second largest oil consumer in 2002, and also became the second largest oil importer in 2009 (BP, 2016). The tremendous amount of oil consumption and imports and their rapid growth in China has aroused concern over China's energy security (e.g., Ge and Fan, 2013; Leung, 2011; Wu et al., 2007; Zhang, 2011). Meanwhile, China's efforts to securing foreign oil through supporting its state-owned oil companies in oil seeking and exploitation globally, particularly in Africa and South America, have drawn criticism and concern from some western countries (Chen, 2006; Deepak, 2014; Marton and Matura, 2011; Daojiong, 2006; Zweig and Jianhai, 2005). Therefore, the massive and increasing consumption of oil in China has become not only a domestic challenge but also an international issue.

In the context of energy security, researchers have paid special attention to the trade in crude oil of China. However, in order to get more detailed picture of China's oil consumption, we need not only to consider the direct trade flows of oil, but also analyze indirect oil flows *embodied* in China's trade of final goods and services. On the one hand, as a major world's workshop, China needs not only labor and capital but also tremendous natural resources including oil to produce its exports. During 1995-2015, the commodity export value of China increased by over 14 times, which makes China the world biggest commodity exporter.[1] China joined the World Trade of Organization (WTO) in 2001, which gave Chinese firms great opportunity to expand their exports. The ratio of export value to Gross Domestic Product (GDP) rose up from 20% in 2001 to 35% in 2007,[2] due to the upsurge of exports in this period. Previous studies have shown that huge amounts of energy were used to producing exports of China (Cui et al., 2015; Liu et al., 2010; Yang et al., 2014). Therefore, a great deal of crude oil, as one key source of energy, may be exported indirectly when they are used in export production in China; although China's direct exports of crude oil are very limited nowadays. Quantifying the crude oil embodied in China's exports would help reveal the contribution of export production to the mammoth oil consumption in China. Moreover, since China imports a great deal of oil, it's interesting and significant to explore how many oil imports are '*re-exported*' by producing non-oil goods and services consumed by the other countries. On the other hand, China's direct import of crude oil cannot reveal the indirect demand for foreign oil by consuming imported goods and services, which can be assessed by calculating the crude oil embodied in China's imports of finished products.

While direct trade of crude oil of China was widely discussed in previous studies, studies on embodied crude oil in China's trade of goods are rare. As one exception, Tang et al.(2012) estimated oil embodied in China's exports and imports using a single region input-output (SRIO) model based on Chinese input-output tables of 1997, 2002, and 2007. Compared with the SRIO model, one major advantage of the multi-regional input-output MRIO model is the estimation bias of emissions or materials embodied in imports can be reduced significantly as differences in production technology between China and its trade partners are modeled directly (Andrew et al., 2009; Lenzen et al., 2004). Thanks to new development of MRIO databases (Tukker and Dietzenbacher, 2013), MRIO models have been widely used to analyze various emissions embodied in international trade and final consumption (e.g., Arto et al., 2014; Davis et al., 2011; Kanemoto et al., 2014; Moran et al., 2013; Peng et al., 2016; Peters et al., 2011; Tukker et al., 2014; Wiebe et al., 2012a). Meanwhile, MRIO models are often used to quantify nature resources embodied in international trade and final consumption, such as water (e.g., Chen and Chen, 2013; Lutter et al., 2016; Moran et al., 2013; Tukker et al., 2014), and raw materials including fossil fuel (e.g., Bruckner et al., 2012; Giljum et al., 2014; Tukker et al., 2014; Wiebe et al., 2012b; Wiedmann et al., 2015).

In the present article, we assess crude oil embodied in trade and final demand of China using a global MRIO model, which relates most closely to the strand of literature on embodied material flows reviewed above. First, we analyze the (direct) oil exports and imports of China in the period of 1995-2015. We show the changes of sources of China's oil imports in this period. Second, we analyze the embodied crude oil in China's exports and

[1] Calculation based on data from UN Comtrade Database, https://comtrade.un.org/data/

[2] Calculation based on data from online database of China's National Bureau of Statistics (CNBS), http://data.stats.gov.cn/easyquery.htm?cn=C01

imports in the period of 1995-2011. We estimate how much oil imported is re-exported by producing exports in China. Third, we estimate China's oil demand from the *consumption* perspective, that is, crude oil embodied in China's final consumption. The oil 'consumption' of China analyzed in previous studies generally refers to *domestic* oil use by *production*, which reflects China's oil dependence from the production. On the contrary, the analysis on crude oil embodied in China's final consumption help reveal the China's oil dependence from the consumption. Finally, we compare oil import dependence of China from consumption perspective and that from production perspective. Oil import dependence from production, reflected by the share of imports in domestic oil consumption, is widely discussed in the context of energy security (e.g., Alhajji and Williams, 2003), whereas import dependence from consumption is rarely analyzed.

The article is structured as follows. Section 2 describes the MRIO methodology, indicators, and dataset used in the empirical section. Section 3 reports and discusses main results from our calculation. Section 4 concludes the article.

2. Methodology and Data

2.1 Estimating the crude oil embodied in trade in MRIO framework

An MRIO model covering the global economy is used in the present study. Suppose there are *m* countries/regions in the world, the general identity in the MRIO model can be written as follows.

$$\begin{pmatrix} \mathbf{x}_1 \\ \mathbf{x}_2 \\ \vdots \\ \mathbf{x}_m \end{pmatrix} = \begin{pmatrix} \mathbf{A}_{11} & \mathbf{A}_{12} & \cdots & \mathbf{A}_{1m} \\ \mathbf{A}_{21} & \mathbf{A}_{22} & \cdots & \mathbf{A}_{2m} \\ \vdots & \vdots & \ddots & \vdots \\ \mathbf{A}_{m1} & \mathbf{A}_{m2} & \cdots & \mathbf{A}_{mm} \end{pmatrix} \begin{pmatrix} \mathbf{x}_1 \\ \mathbf{x}_2 \\ \vdots \\ \mathbf{x}_m \end{pmatrix} + \begin{pmatrix} \sum_i \mathbf{y}_{1i} \\ \sum_i \mathbf{y}_{2i} \\ \vdots \\ \sum_i \mathbf{y}_{mi} \end{pmatrix} \tag{1}$$

where $\mathbf{x}_i \ (i = 1, 2, \cdots, m)$ is the vector of total output in country *i*. $\mathbf{y}_{ii}$ is the vector of final products (or final output) supplied by country *i* and also consumed in country *i*. $\mathbf{y}_{ji} (i \neq j)$ is the vector of final products supplied by country *j* but consumed in country *i*, which reflects the import of final products from country *j* to country *i*. $(\mathbf{y}'_{1i}, \mathbf{y}'_{2i}, \cdots, \mathbf{y}'_{mi})$ is the final demand of country *i*. The block matrix on the right hand side reflects the inter-industry requirements for intermediate inputs. The diagonal matrix, $\mathbf{A}_{ii}$, is the requirement from sectors in country *i* for domestic intermediate inputs to produce one unit of output. The off-diagonal matrix, $\mathbf{A}_{ij}$ $(i \neq j)$, is the requirement from sectors in country *i* for imported intermediates from sectors in country *j*. Therefore, the off-diagonal matrices represent bilateral trade in intermediates between any two countries on the sectoral level.

In the MRIO model, the coefficient matrices of inter-industry requirements are fixed for a given period. Therefore, given arbitrary final demand, the total output can be solved readily

from equation (1) when the block matrix on the right hand side is nonsingular.

By using equation (1), we can decompose the total output in each country into components corresponding to the final demand they support as follows.

$$\begin{pmatrix} \mathbf{x}_{11} & \mathbf{x}_{12} & \cdots & \mathbf{x}_{1m} \\ \mathbf{x}_{21} & \mathbf{x}_{22} & \cdots & \mathbf{x}_{2m} \\ \vdots & \vdots & \ddots & \vdots \\ \mathbf{x}_{m1} & \mathbf{x}_{m1} & \cdots & \mathbf{x}_{mm} \end{pmatrix} = \begin{pmatrix} \mathbf{I}-\mathbf{A}_{11} & -\mathbf{A}_{12} & \cdots & -\mathbf{A}_{1m} \\ -\mathbf{A}_{21} & \mathbf{I}-\mathbf{A}_{22} & \cdots & -\mathbf{A}_{2m} \\ \vdots & \vdots & \ddots & \vdots \\ -\mathbf{A}_{m1} & -\mathbf{A}_{m2} & \cdots & \mathbf{I}-\mathbf{A}_{mm} \end{pmatrix}^{-1} \begin{pmatrix} \mathbf{y}_{11} & \mathbf{y}_{12} & \cdots & \mathbf{y}_{1m} \\ \mathbf{y}_{21} & \mathbf{y}_{22} & \cdots & \mathbf{y}_{2m} \\ \vdots & \vdots & \ddots & \vdots \\ \mathbf{y}_{m1} & \mathbf{y}_{m1} & \cdots & \mathbf{y}_{mm} \end{pmatrix} \quad (2)$$

where $\mathbf{x}_{ij}$ is the output *induced* by the final demand, $\mathbf{y}_{ij}$. The inversed matrix is called Leontief inversed matrix. The total output equal the sum of induced output, that is, $\mathbf{x}_i = \mathbf{x}_{ii} + \sum_{j \neq i} \mathbf{x}_{ij}$. We call the block matrix on the left hand side *induced* output matrix.

The crude oil embodied in exports of country *i*, OEE_i, is defined as the crude oil used by sectors *within* country *i* to produce final demand of the other countries, that is,

$$OEE_i = \mathbf{f}_i' \sum_{j \neq i} \mathbf{x}_{ij} \quad (3)$$

where the vector $\mathbf{f}_i$ is the *physical* quantity of crude oil (from domestic extraction and import) used to produce one unit of output in each sector in country *i*.

On the contrary, the crude oil embodied in imports of country *i*, OEI_i, is defined as the crude oil used by sectors *outside* country *i* to produce the final demand of country *i*, or,

$$OEI_i = \sum_{j \neq i} \mathbf{f}_j' \mathbf{x}_{ji} \quad (4)$$

Definitions above have been widely used in MRIO literature analyzing emissions or raw material embodied in trade (e.g., Arto et al., 2014; Bruckner et al., 2012; Davis and Caldeira, 2010; Peters et al., 2011; Muñoz and Steininger, 2010; Wiebe et al., 2012a).

2.2 Construction of crude oil use intensity vector

In their study, Bruckner et al.(2012) used material domestic extraction data to construct the vector $\mathbf{f}_i$, which is appropriate to explore the impact of consumption on raw material extraction. Based on equations (3) and (4), we see that there will be little crude oil embodied in imports of country *i* from those countries with scarce crude oil reserve or low extraction activities, when only domestic extraction data is used in the vector $\mathbf{f}_i$. For example, even though there are large imports of China from Japan and South Korea, the crude oil embodied in imports of China from these two countries could be very little since most crude oil they used are from importing rather than domestic extraction. Then it would be difficult to see how the active trade relation between China and Japan affect the crude oil consumption in China. To deal with this disadvantage in analysis, we first adjust the domestic exaction quantity using physical trade data of crude oil to obtain domestic crude oil use by production of country *i*, u_i. That is, u_i equals domestic extraction of crude oil, d_i, subtracting crude oil export, e_i, then adding up the import, m_i, that is,

$$u_i = d_i - e_i + m_i \quad (5)$$

Therefore, the meaning of vector $\mathbf{f}_i$, in the present study is different from that in Bruckner

et al.(2012). $\mathbf{f}_i$ in the present study should be interpreted as crude oil *use* intensity, whereas it's *extraction* intensity in Bruckner et al.(2012). However, this trade adjustment does *not* affect the global total, because global export of crude oil equals global import. In other words, the summation over u_i in every country still equals the global extraction of crude oil.

We use the data of domestic extraction in the environmental accounts of the WIOD (Genty et al., 2012). The domestic extraction of crude oil is allocated to the single aggregated extraction sector, i.e. *Mining and Quarrying*, in the environmental accounts. To carry out trade-adjustment, we firstly allocate the imported crude oil to the oil processing sector in the importing country, i.e. *Coke, Refined Petroleum and Nuclear Fuel* using the sector classification of WIOD. In addition, Genty et al.(2012) recommend to re-allocate the crude oil extraction from sector *Mining and Quarrying* to processing sector *Coke, Refined Petroleum and Nuclear Fuel* to alleviate the calculation bias resulting from the high aggregation of mining sector in the WIOD. With similar consideration, Bruckner et al.(2012) also re-allocated construction minerals from miming sector to the construction sector. Following their recommendation, we further re-allocate the domestic extraction after subtracting export, d_i-e_i, to the sector, *Coke, Refined Petroleum and Nuclear Fuel*. In other words, all u_i are allocated to the sector, *Coke, Refined Petroleum and Nuclear Fuel* in constructing vector $\mathbf{f}_i$ in the present study. The re-allocation above can also avoid overestimation of embodied crude oil. In the MRIO model as discussed in last subsection, the direct crude oil trade flows between countries are reflected in value terms in the cross-country input coefficients from *Mining and Quarrying* sector of the extracting country sector to processing sectors (mainly *Coke, Refined Petroleum and Nuclear Fuel*) of the other countries in the off-diagonal matrix, $\mathbf{A}_{ij}$, in equation (1). Therefore, crude oil embodied in trade will be overestimated if d_i-e_i remains in the mining sector. However, the *international* input coefficients from mining sectors to processing sectors will not affect the calculation of embodied in trade when d_i-e_i is re-allocated from mining sector the processing sector in all countries.

2.3 Production-based and consumption-based crude oil demand

We define the *production-based* crude oil demand of country *i*, PBD_i, as crude oil used *within* country *i* to produce final demand of *all* countries, which can also be calculated as

$$PBD_i = \mathbf{f}_i' \sum_j \mathbf{x}_{ij} = \mathbf{f}_i' \mathbf{x}_{ii} + \mathbf{f}_i' \sum_{j \neq i} \mathbf{x}_{ij} = SD_i + OEE_i \qquad (6)$$

where $SD_i \equiv \mathbf{f}_i' \mathbf{x}_{ii}$, which is the crude oil used for producing domestic final demand in country *i* (self-demand for crude oil). Equation (6) shows that PBD_i equals SD_i plus crude oil embodied in its exports, OEE_i. Since $\mathbf{x}_i = \sum_j \mathbf{x}_{ij}$, PBD_{i} equals the u_i by definition in the subsection 2.2.

And we define *consumption-based* crude oil demand of country *i*, CBD_i, as the crude oil used in *all* country to produce the final demand of country *i*. In equation, CBD_i can be calculated by

$$CBD_i = \sum_j \mathbf{f}_j' \mathbf{x}_{ji} = \mathbf{f}_i' \mathbf{x}_{ii} + \sum_{j \neq i} \mathbf{f}_j' \mathbf{x}_{ji} = SD_i + OEI_i \qquad (7)$$

Equation (7) shows that CBD_i equals SD_i plus crude oil embodied in its imports.

Therefore, the difference in quantity between PBD_i and CBD_i equals the net exports of crude oil embodied in trade. Definitions in equation (6) and (7) are also similar to previous studies on emissions or material (e.g., Bruckner et al., 2012; Davis and Caldeira, 2010; Peters et al., 2011; Muñoz and Steininger, 2010; Wiebe et al., 2012).

As discuss in subsection 2.2, the trade adjustment for crude oil use before calculation indicates that all the three components SD_i, OEE_i, and OEI_i include crude oil supplied by domestic extraction of country i and by foreign countries. In order to analyze the extent to which China's crude oil demand from production or consumption depend on import, we want to split these PBD_i and CBD_i into Chinese oil (crude oil from domestic extraction) and imported oil (crude oil from foreign extraction). Suppose we know exactly how much imported crude oil is used to produce goods and services for domestic final demand and how much for foreign final demand in each country, and then we have

$$PBD_c = SD_c + OEE_c = \underbrace{(SD_{c,chn} + OEE_{c,chn})}_{p1:\ Chinese\ oil} + \underbrace{(SD_{c,imp} + OEE_{c,imp})}_{p2:\ imported\ oil} \tag{8}$$

$$CBD_c = SD_c + OEI_c = \underbrace{(SD_{c,chn} + OEI_{c,chn})}_{c1:\ Chinese\ oil} + \underbrace{(SD_{c,imp} + OEI_{c,imp})}_{c2:\ imported\ oil} \tag{9}$$

where subscript c is the index for China. Note that OEI of China also include some Chinese oil because foreign countries may have used crude oil imported from China to produce their exports. $OEE_{c,imp}$ is the part of imported oil which is '*re-exported*' by embodying in exports of China. For instance, some crude oil imported from the Middle East will be re-exported to USA when firms in China use this oil to produce goods exported to USA, which can be interpreted as *indirect* crude oil exports from the Middle East to the USA. In the present study, we define the import dependence from *production* end as the share of imported oil in PBD, that is, p_1/PBD_c. Similarly, we define the import dependence from *consumption* end as the share of imported oil in CBD, that is, c_1/CBD_c.

Since detailed data of crude oil use is not available, it's impossible to carry out exactly the decomposition as in equations (8) and (9). Therefore, we have to make some proportion assumptions in the present study. Specifically, we assume that all sectors in the economy use the same the share of crude oil from import which further equals the share of total crude oil import in total crude oil use by production, that is, m_i divided by u_i. According to these assumptions, we have

$$s_{wc} = \frac{SD_{c,imp}}{SD_c} = \frac{OEE_{c,imp}}{OEE_c} = \frac{m_c}{u_c} \tag{10}$$

$$OEI_{c,imp} = \sum\nolimits_{i \neq c} s_{ic} OEE_{ic} = \sum\nolimits_{i \neq c} \frac{m_{ic}}{u_i} OEE_{ic} \tag{11}$$

where s_{wc} is the crude oil import share of China, s_{ic} is crude oil import share from China in country i. m_c is total import of crude oil in China, m_{ic} is crude oil import of country i from China, and u_c and u_i are total use of crude oil by production in China and country i, respectively. OEE_{ic} is crude oil embodied in exports from country i to China. Using equations (10) and (11), we can estimate those four components in equation (8) and (9) and calculate

China's crude oil import dependence from production end and consumption end.

2.4 Data preparation

Global Input-output data. The global input-output data we use for calculation are from the World Input-Output Database (WIOD) (Timmer et al., 2015). The latest version of WIOD provides annual time-series of World Input–Output Tables (WIOTs) from 1995 through 2011 and environmental satellites from 1995 through 2009. The WIOT has 40 economies including most major trade partners of China and one aggregated region, *ROW* (Rest of the World). There are 35 sectors per country/region.

Crude oil extraction data. The domestic extraction data of crude oil for 41 countries and regions for years from 1995 to 2009 are from the environmental satellites of WIOTs (Genty et al., 2012). Domestic extraction data for 41 countries and regions for the years 2010 and 2011 are estimated based on the oil production data from the *BP Statistical Review of World Energy* (June 2016) (BP review hereafter)(BP, 2016). The global totals of oil extraction in WIOD are about 7%~9% lower than the production data from the BP review in the period 2001-2009 which may be due to different product range in the data. The extraction data from WIOD only include only crude oil whereas the BP review includes crude oil, tight oil, oil sands and NGLs. In order to make these two data sources more comparable, we choose to adjust the global totals in 2010 and 2011 from BP review. We assume the discrepancy in oil extraction data between the two data sources does not change during 2009~2011. Then the global oil production data from BP review for the years 2010 and 2011 are lowed by the same percentage as in 2009 (the gap is 8.8% in this year). Next, we need to estimate the domestic extraction for 41 economies. BP review also provides oil production data of major oil production countries and regions, 13 of which also appear in the country list of WIOD. The production shares of these 13 countries from BP review and global totals after adjustment are used to estimate their domestic extraction for the years 2010 and 2011. The total extraction quantity of all the other 28 countries and regions (includes ROW) is obtained as remainder. The domestic extraction of each country and region is estimated using the regional shares in 2009 based on WIOD extraction data and the remainder from the last step.

Crude oil bilateral trade data. To obtain the data for u_i in equation (5), we need the bilateral crude oil trade data of the 41 economies in physical unit. Crude oil trade data in kilograms (HS commodity code: 2709) except Taiwan is taken from the UN Comtrade Database (http://comtrade.un.org/data/). We use import data to construct export as import data generally more accurate. In other words, the crude oil export of country *i* is estimated by the totaling up the crude oil import of the other countries from country *i*. Note that aggregated region, ROW, should be seen as one region when carrying out the trade adjustment. For example, the crude oil export of ROW is the total crude oil import of 40 economies in the WIOD from all countries included in the ROW. The crude oil trades between countries in the ROW should be considered as intra-regional trades which won't affect the adjustment in equation (5). Crude oil trade data for Belgium and Luxembourg are combined together as Belgium-Luxembourg until 1999. We simply split these data during 1995~1998 using the import shares of Belgium and Luxembourg in 1999. The crude oil trade data of Taiwan is taken from its annual energy balance sheet. The unit of these raw data is kilo liter. We converse it to kilograms using the coefficients provided in the instruction file for the energy

balance sheets.

3. Results

3.1 Crude oil trade of China

Based on trade data from the UN comtrade database, we report some major fact about crude oil trade of China in this subsection. As shown in Figure 1, imports of crude oil increased significantly in China in the past 20 years. China's imports of crude oil reached 335.5 Mt (million tonnes) in 2015, 18 times greater than the imports in 1995 (17.1 Mt). Although China itself is one of the biggest oil producers, it has become the world's second largest oil importer (after the USA). The share of crude oil imports in China's total oil use by domestic production rose from 11.5% in 1995 to 61% in 2015. China's oil exports are much lower than imports after 1997 and had decreased to below 1 Mt since 2012. Therefore, crude oil net imports of China have been only slightly lower than imports since 1999 and have very similar growth trend to imports.

Note that significant increase of oil imports (or net imports) began in 2001, the year when China joined the World Trade of Organization (WTO). This is not coincidence. The accession to the WTO had brought export boom in China. The average growth rate per annum of commodity exports reached 24.4% in the period of 2000-2008, which was more than two times than the growth rate (10.9%) during 1995-2000.[3] The boom of exports in China after 2000 might have raised the demand for imported oil because crude oil is major energy and material input in the production of exports. However, we can see this only in the next subsection where the crude oil embodied in exports is analyzed.

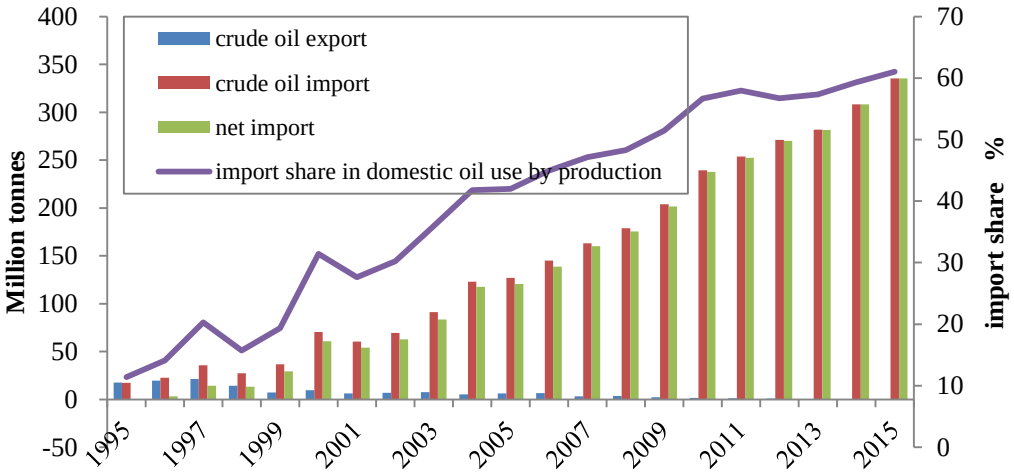

Figure 1. Crude oil trade of China during 1995-2015.

Note: Domestic oil use by production, that is, u_i, is calculated through the equation (5). Domestic extraction data after 2009 is from BP statistical review.

Table 1 reports structure of sources of China's crude oil imports. In 2015, more than half

[3] Calculation based on commodity export data from the UN comtrade database.

(50.3%) of imported crude oil in China was supplied by the seven countries (Saudi Arabia, Iraq, Oman, Iran, Kuwait, The United Arab Emirates, and Qatar) in the Middle East. Oil exporters in the western and northern Africa (Angola, Sudan, and Congo in particular) supplied 17.7% of China's total oil imports. Russia is the second biggest oil exporter to China (after Saudi Arabia) which supplied 12.6% of China's total oil imports. In addition, 12% of China's total oil imports came from four major oil exporters (Venezuela, Brazil, Columbia, and Ecuador) in South America. In 2015, 58.4% of China's oil imports was supplied by Organization of Petroleum Exporting Countries (OPEC).

There were several prominent changes in origin structure of China's oil imports during 1995-2015. First, oil exporters in the Middle East and Africa have always been the major sources of China's oil imports since 1995. And their significance further rises greatly in the past 20 years. The import share from the Middle East increased from 31% to 50.3% while the import share from Africa increased from 10.8% to 17.7%. Second, Russia and South America has become two new major suppliers of China oil import. The import shares from Russia and South America increased by 12.4 and 12 percentage points, respectively. In fact, the China's import share of crude oil from Russia and South America was below one percent in 1995. Third, the relative importance of South Asia as China's oil supplier has declined significantly. Import share of crude oil from the three major oil exporters in South Asia (Vietnam, Indonesia, and Malaysia) was 38.8% in 1995, higher than the import share from the Middle East in the same year. However, the import share from this region declined to 1.2% in 2015. Finally, there were remarkable changes in oil import shares from some individual country in each region. The import shares from Saudi Arabia, Iraq, Kuwait, Angola, Russia, Venezuela, and Brazil have risen up greatly, whereas the import shares from Oman, Indonesia, Vietnam, and Malaysia have dropped significantly. In consideration of energy security, the Chinese government has endeavored to diversify the sources of crude oil in the past twenty years. In general, the changes in the sources of China's oil imports as shown in Table 1 indicate that China has achieved such strategic goal to some extent.

Table 1. Sources of crude oil import of China during 1995-2015 (%)

	1995	1997	2000	2002	2005	2007	2010	2012	2015
The Middle East									
Saudi Arabia	2.0	1.4	8.2	16.4	17.5	16.1	18.7	19.9	15.1
Iraq	0.0	0.7	4.5	0.8	0.9	0.9	4.7	5.8	9.6
Oman	21.4	25.5	22.3	11.6	8.5	8.4	6.6	7.2	9.6
Iran	5.4	7.8	10.0	15.3	11.3	12.6	8.9	8.1	7.9
Kuwait	0.0	0.2	0.6	1.5	1.3	2.2	4.1	3.9	4.3
The United Arab Emirates	2.2	0.1	0.6	0.0	2.0	2.2	2.2	3.2	3.7
Qatar	0.0	0.2	2.3	0.7	0.3	0.2	0.2	0.4	0.1
subtotal	**31.0**	**35.9**	**48.4**	**46.3**	**41.8**	**42.6**	**45.4**	**48.5**	**50.3**
Western and northern Africa									
Angola	5.8	10.8	12.3	8.2	13.8	15.3	16.5	14.8	11.5
Sudan	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.7	2.4
Congo	0.1	2.8	2.1	1.5	4.4	2.9	2.1	2.0	1.7
Libya	1.2	0.2	0.2	0.0	1.8	1.8	3.1	2.7	0.6

Equatorial Guinea	0.0	0.6	1.7	2.6	2.9	2.0	0.3	0.7	0.6
Gabon	0.5	1.1	0.7	0.0	0.0	0.5	0.2	0.1	0.5
Nigeria	2.3	0.0	1.8	0.7	1.0	0.5	0.5	0.3	0.2
Algeria	0.8	0.0	0.0	0.0	0.6	1.0	0.7	0.9	0.1
subtotal	**10.8**	**15.4**	**18.7**	**13.0**	**24.5**	**24.1**	**23.4**	**22.3**	**17.7**
Central Asia & Eastern Europe									
Russia	0.2	1.3	2.1	4.4	10.1	8.9	6.4	9.0	12.6
Kazakhstan	0.0	0.1	1.0	1.4	1.0	3.7	4.2	3.9	1.5
subtotal	**0.2**	**1.5**	**3.1**	**5.8**	**11.1**	**12.6**	**10.6**	**12.9**	**14.1**
South America									
Venezuela	0.0	0.0	0.0	0.0	1.5	2.5	3.2	5.6	4.8
Brazil	0.0	0.0	0.3	0.0	1.1	1.4	3.4	2.2	4.1
Columbia	0.0	0.0	0.0	0.0	0.0	0.5	0.8	1.1	2.6
Ecuador	0.0	0.0	0.0	0.0	0.1	0.1	0.3	0.3	0.4
subtotal	**0.0**	**0.0**	**0.3**	**0.0**	**2.7**	**4.6**	**7.7**	**9.3**	**12.0**
South Asia									
Vietnam	4.5	4.2	4.5	5.1	2.5	0.3	0.3	0.3	0.6
Indonesia	30.9	18.6	6.5	4.7	3.2	1.4	0.6	0.2	0.5
Malaysia	3.4	0.6	1.1	2.4	0.3	0.3	0.9	0.4	0.1
subtotal	**38.8**	**23.4**	**12.1**	**12.2**	**6.0**	**2.0**	**1.7**	**0.9**	**1.2**
Others	**19.3**	**23.8**	**17.3**	**22.7**	**13.9**	**14.1**	**11.1**	**6.1**	**4.8**
OPEC12	**19.7**	**21.4**	**40.4**	**43.6**	**52.1**	**55.5**	**63.1**	**66.0**	**58.4**

3.2 Crude oil embodied in trade of China

Although China's crude oil exports are small compared to imports (Figure 1), substantial crude oil can be exported indirectly by producing exports of goods and services in China which has become the workshop of the world. Meanwhile, crude oil imported by China might contribute importantly to export production in China. These questions can be analyzed by calculating crude oil embodied in exports (OEE) of China.

As shown in Table 2, OEE of China increased by 274%, from 33.8 Mt in 1995 to 126.5 Mt in 2011, which were near to the total domestic oil use by production in Korea (126.6 Mt) and more than domestic oil use in Germany (90.4 Mt). About 78% of the increment occurred after 2001 in which China joined the WTO. The average growth rate by annum of OEE reached 13.5% in the period of 2001-2008. The OEE of China in 2009 decreased by 16% due to the financial crisis beginning in 2008. It rose up again in 2010 and maintained its level in 2011 which was still lower than the peak in 2008. The share of OEE in China's domestic use of oil increased from 23% in 1995 to 37% in 2007 but decreased to 28.9% in 2011.

Table 2 also reports the major destinations of OEE of China. About 62% of OEE flowed into developed economies in 2011. More than half China's OEE flowed to the USA, the EU, Japan, South Korea and Taiwan. However, export share to developed economies has decreased during 1995-2011 as Chinese exporters expand their market in the emerging economies. Export share of OEE from China to 6 emerging economies, that is, BRIITM (Brazil, Russia, India, Indonesia, Turkey, and Mexico) increased from 4.5% in 1995 to 13.9%

in 2011.

One piece of important information not revealed in the crude oil trade data is the influence of foreign demand on China's oil importing, which can be explored by analyzing the crude oil embodied in exports of China. Using the equation (10), we can estimate how many crude oil imports were re-exported by producing exports. As we can see in Figure 3, the quantity of re-exported crude oil increased significantly in the period of 1995-2011, from 3.9 Mt to 73.4 Mt, or by near 18 times. The share of re-export in total import of crude oil of China increased from 22.6% in 1995 to 36.7% in 2007, which means more than one third of crude oil imported by China was re-exported by producing exports. However, this share decreased to 28.9% in 2011 due to the deceleration of exports in China after the financial crisis arising in 2008. In general, Figure 3 indicates that foreign final consumption has played a significant role in determining the import demand of crude oil in China. As one of the largest production and processing base in the global production network, China is indeed acting as an important *transit hub* of various raw materials including crude oil from the extracting countries to the consumers of finished goods mainly from developed countries.

Table 2. Crude oil embodied in exports of China during 1995-2011.

	Total (Mt)	Region share (%)						
		USA	EU	JKT	CA	BRIITM	ROW	Developed economies
1995	33.8	23.9	21.7	20.4	5.0	4.5	24.6	71.0
1996	33.2	23.8	21.0	20.4	5.0	4.8	25.1	70.1
1997	39.8	24.7	22.1	21.3	4.9	7.9	19.0	73.0
1998	38.1	27.2	24.7	17.1	4.9	7.5	18.6	73.9
1999	40.7	27.1	24.1	21.1	5.3	6.5	15.9	77.7
2000	55.2	26.8	21.1	19.7	4.4	8.3	19.6	72.1
2001	53.8	25.4	21.4	19.2	4.2	8.3	21.5	70.2
2002	62.6	25.1	19.6	17.2	4.4	7.5	26.2	66.3
2003	80.3	23.4	20.5	16.4	4.7	7.3	27.7	65.1
2004	100.4	24.3	21.5	15.9	4.9	7.4	26.0	66.6
2005	108.0	24.7	20.3	15.5	5.1	7.6	26.8	65.6
2006	119.2	24.1	20.7	14.3	5.0	8.5	27.4	64.1
2007	127.1	22.2	21.8	12.9	5.2	9.7	28.2	62.1
2008	130.5	21.2	20.9	12.4	5.5	10.7	29.3	60.0
2009	109.4	21.6	20.7	13.3	6.8	10.6	26.9	62.5
2010	125.4	20.9	20.7	13.3	6.8	12.3	25.9	61.8
2011	126.5	19.9	20.4	14.5	7.3	13.9	24.0	62.2

Note: EU includes 27 member countries; 'JKT' includes three eastern Asia economies, Japan, South Korea, and Taiwan; 'CA' includes Canada and Australia; BRIITM include 6 emerging countries, Brazil, Russia, India, Indonesia, Turkey, and Mexico. Developed economies include the USA, the EU, JKT, and CA.

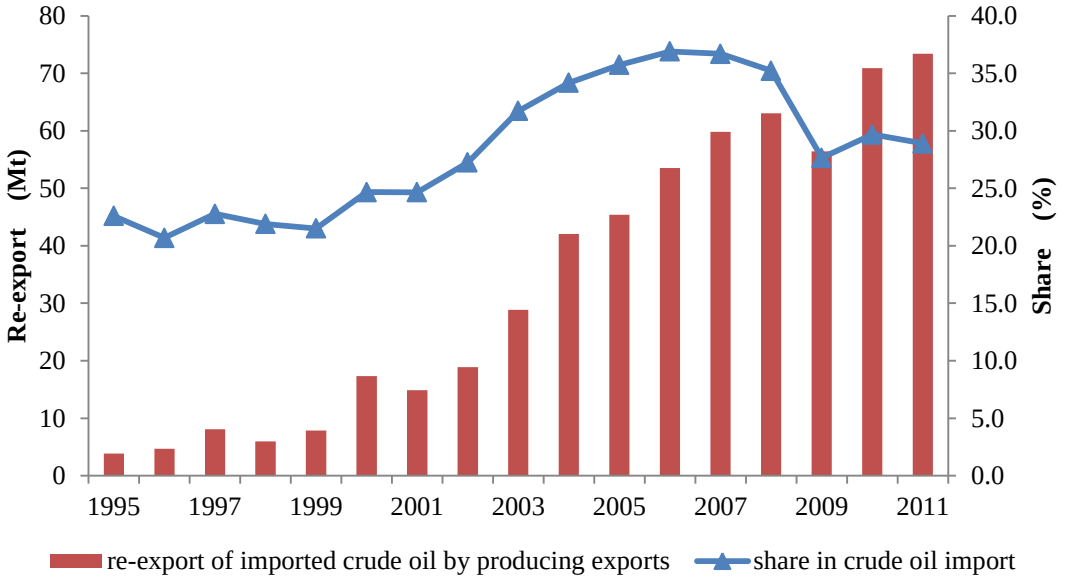

Figure 2. Re-export of imported crude oil by producing exports in China during 1995-2011

Another piece of important information not revealed in the crude oil trade data is that China also indirectly 'imports' crude oil by consuming goods and services imported, which can be revealed by analyzing the crude oil embodied in imports(OEI) of China. Table 3 shows the results of calculation of China's OEI in the study period. Like the OEE, OEI of China increased remarkably during 1995-2011, from 22.8 Mt to 117.2 Mt, or by 415% which is greater than the growth of OEE. Unlike the OEE which decreased sharply after financial crisis in 2008, OEI of China in 2009 maintained the level of 2008 and continued to increase after 2009. This difference can be explained by the economic policy launched by the Chinese government after the financial crisis in 2008. To stabilize the economy, the Chinese government announced a 4 trillion Chinese Yuan stimulus package in November 2008, which mainly aimed to expand the domestic demand. The stimulus package was carried out during 2009-2010, which had supported the imports of goods and services. Commodity exports of China decreased 16% during 2008-2009 due to due to the weak foreign demand, while commodity imports decreased only 11% in this period. China's exports increased by 58%, while its imports increased more greatly, by 73.4%, during 2009-2011. Meanwhile, the stimulus package promoted the imports of energy intensive intermediate products because the stimulus package was predominantly investment-focused and mainly used to build the infrastructure in China. Therefore, there appeared a surge of OEI during 2009-2011 as shown in Table 3.

The regional structure of the OEI is also different from the OEE. In 2011, 45.2% of OEI of China came from developed economies, which is near to the proportion in 1995. Import shares from the US and the EU are 8.4% and 7.9% in 2011. And more than one quarter (26.3 %) of OEI came from the three East Asian economies, that is, the JKT (Japan, South Korea, and Taiwan). Japan, South Korea, and Taiwan are major exporters of goods and services to China. They are also economies that rely heavily on imported crude oil because of low domestic reserve. Therefore, China's OEI from Japan, South Korea, and Taiwan can be seen as indirect import of crude oil from the Middle East which is the major exporter of crude

oil to these three economies. If we had used the domestic extraction data to construct intensity vector $\mathbf{f}_i$ without trade adjustment as mentioned in subsection 2.2, we would find very small OEI from the JKT, and then we cannot reveal the effect of large trade between China and the JKT on the international flows of crude oil. In regard of the trend, the share of OEI from developed economies to China increased before 1998 mainly due to the increasing share from the JKT, but decreased in the period of 2001-2009, and rose again after 2009.

Table 3. Crude oil embodied in imports of China during 1995-2011.

	Total (Mt)	Region share (%)						
		USA	EU	JKT	CA	BRIITM	ROW	Developed economies
1995	22.8	9.5	7.9	26.3	2.0	9.9	44.4	45.7
1996	26.9	8.1	7.2	26.5	2.9	8.5	46.7	44.8
1997	31.5	7.5	6.7	37.6	3.0	8.3	36.9	54.8
1998	32.9	6.2	6.3	40.1	2.6	13.1	31.6	55.3
1999	38.6	6.2	6.3	31.6	2.1	12.7	41.1	46.2
2000	43.0	5.5	6.9	36.8	1.5	15.0	34.3	50.7
2001	48.7	4.1	7.2	33.6	2.0	13.4	39.7	46.9
2002	51.8	5.4	8.0	29.2	1.2	13.8	42.4	43.8
2003	61.7	5.6	8.1	29.6	1.2	13.6	42.0	44.5
2004	71.7	5.6	7.8	28.4	1.7	11.0	45.4	43.5
2005	72.8	5.3	7.3	26.2	2.0	10.1	49.0	40.9
2006	77.8	5.5	7.5	25.7	2.1	9.4	49.8	40.8
2007	77.7	6.3	7.9	26.1	2.2	9.0	48.4	42.5
2008	91.4	6.4	8.2	25.7	1.9	9.2	48.6	42.2
2009	91.0	6.6	7.7	24.4	1.6	10.3	49.4	40.3
2010	105.1	8.0	8.2	23.7	2.5	11.3	46.2	42.5
2011	117.2	8.4	7.9	26.3	2.6	11.7	43.2	45.2

Note: EU includes 27 member countries; 'JKT' includes three eastern Asia economies, Japan, South Korea and Taiwan; 'CA' includes Canada and Australia; BRIITM include 6 emerging countries, Brazil, Russia, India, Indonesia, Turkey and Mexico. Developed economies include USA, EU, JKT, and CA.

Although OEI of China has increased more quickly than OEE in the past two decades, OEI was always lower than OEE in this period (Figure 3). In other words, China was a net exporter of embodied crude oil in trade (the blue line in the Figure 3 (a)), whereas it was a net importer of crude oil (the red line in the Figure 3 (a)). Figure 3 (a) shows that net exports of embodied crude oil of China steadily increased during 2001-2007, while its net import of crude oil also increased significantly in this period. However, the net exports of embodied crude oil decreased quickly during 2008-2011, due to substantial increase of OEI in this period (Table 3). However, the net exports of embodied crude oil from China to different countries or regions can be very different. Figure 3 (b) shows China is net exporter of embodied crude oil to the USA, the EU and the CA (Canada and Australia), whereas China is net importer of embodied crude oil from the JKT and the ROW. China is also net importer of embodied crude oil from the BRIITM countries before 2005 and net exporters of embodied crude oil to these countries after 2005.

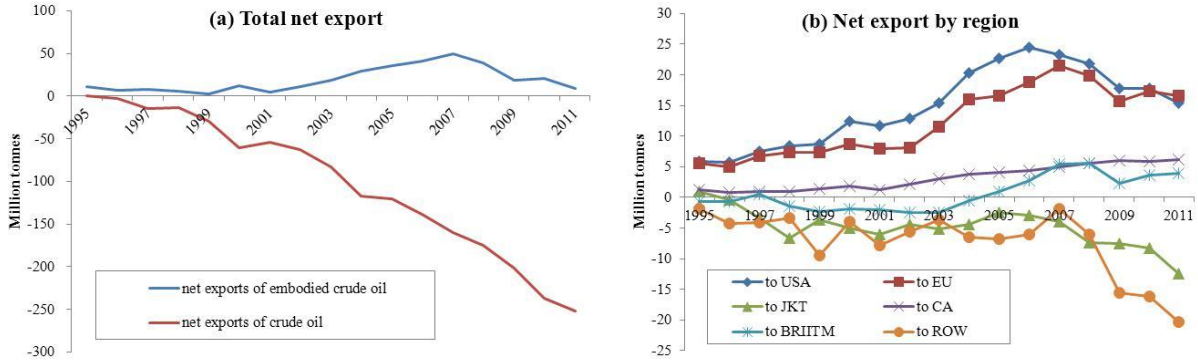

Figure 3. Net exports of crude oil embodied in trade of China during 1995-2011.

Note: Net exports of embodied crude oil equals the OEE of China minus by the OEI of China.

3.3 Production-based and consumption-based demand for crude oil of China

As shown in column (1) of the Table 4, China's production-based demand for crude oil (PBD) increased from 149.6 Mt in 1995 to 437.7 Mt in 2011, or by 193%. The average growth rate per annum of PBD was 6.9%. Meanwhile, China's consumption-based demand for crude oil (CBD) increased significantly in the study period, from 138.6 Mt to 428.4 Mt, or 209% (column (2) of the Table 4). The average growth rate per annum of CBD was 7.3% which was greater than that of PBD. In 2011, China after the USA was the world's second largest crude oil consumer either according to its production-based or consumption-based oil demand.

In the period of 1995-2011, the PBD of China was larger than the CBD. The gap between PBD and CBD shrunk during 1995-1999, whereas it enlarged quickly during 2001-2007 (column (6) of Table 4). The gap shrunk again after the financial crisis in 2008. As shown in equations (6) and (7), the gap between PBD and CBD just equals net export of embodied crude oil. Therefore, the variation of the gap between PBD and CBD of China have been reflected in the variation of net exports of embodied crude oil as shown in Figure 3 (a).

The final demand includes three categories: household consumption, government consumption, and investment (Gross fixed capital formation, Changes in inventories and valuables). Therefore, we can further decomposed CBD of China by final demand category (columns (3)-(5) in Table 4). In 2011, crude oil demand induced by the investment of China accounted for more than half (58.7%) of China's CBD. Crude oil demand induced by Chinese household consumption accounted for 29.2% of China's CBD. And 12.1% of CBD come from the government consumption in China. During 1995-2011, crude oil demand induced by the investment had always accounted for the major part of CBD of China, whose shares ranged from 43%~60%. There were opposite trend for the demand share from household consumption and investment in the study period. The demand share from investment decreased before 2000, whereas the demand share from household consumption increased. On the contrary, in the period of 2001-2008, the demand share from investment increased significantly by 11 percentage points, while the demand share from household consumption decreased by 10 percentage points. In 2009, the demand share from household consumption decreased 2 percentage points after the financial crisis. However, the demand share from investment further increased by 3 percentage points in the same year resulting from the

investment-focused stimulus package launched by the Chinese government as discussed above. In a word, investment has played major and increasing important role in shaping China's consumption-based demand for crude oil since 2000.

Table 4. Production-based and consumption-based demand for crude oil of China

	PBD (Mt) (1)	CBD (Mt) (2)	Household consumption (%) (3)	Government consumption (%) (4)	Investment (%) (5)	Gap between PBD and CBD (%) (6)
1995	149.6	138.6	37.7	11.7	50.6	8.0
1996	160.3	154.0	37.4	12.5	50.2	4.1
1997	174.9	166.6	37.6	13.4	49.1	5.0
1998	174.1	168.9	38.9	13.2	48.0	3.1
1999	189.3	187.2	40.4	13.1	46.5	1.1
2000	223.8	211.6	42.9	13.4	43.7	5.7
2001	218.1	213.0	41.9	12.9	45.2	2.4
2002	229.6	218.9	40.7	12.0	47.3	4.9
2003	253.1	234.5	38.4	12.5	49.1	8.0
2004	293.8	265.0	36.0	12.8	51.2	10.8
2005	302.1	266.9	34.1	12.7	53.2	13.2
2006	323.1	281.7	32.5	12.5	55.0	14.7
2007	346.3	296.9	32.6	13.3	54.1	16.7
2008	370.5	331.4	31.4	12.5	56.1	11.8
2009	395.8	377.3	29.1	11.4	59.5	4.9
2010	422.4	402.2	29.2	12.0	58.8	5.0
2011	437.7	428.4	29.2	12.1	58.7	2.2

Note: PBD stands for production-based demand for crude oil, CBD for consumption-based demand for crude oil.

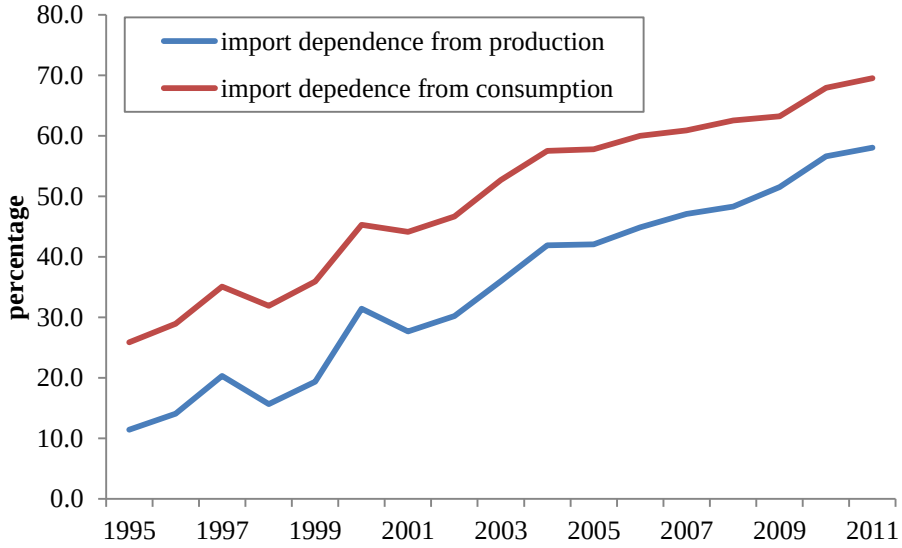

Figure 4. Crude oil import dependence of China from production and consumption

Note: Import dependence from production is the share of imported oil in production-based oil demand, whereas import

dependence from consumption is the share of imported oil in consumption-based oil demand. Imported oil is calculated using equations (10) and (11).

Based on equations (10) and (11), we can decompose PBD and CBD into two components, Chinese oil (crude oil from extraction in China) and imported oil (crude oil from extraction outside China), respectively. We have defined the import dependence from production as the share of imported oil in PBD and defined the import dependence from consumption as the share of imported oil in CBD. Figure 4 shows the variation of import dependence during 1995-2011 based on these two indicators. We find that import dependence both from production and consumption rose up greatly during 1995-2011. Import dependence from production increased from 11.4% to 58%, while import dependence from consumption increased from 25.8% to 69.5%. The import dependence from consumption in all years had been greater than that from production. In reality, from the equation (10), we can see that import dependence from production equals the share of directly imported crude oil in domestic oil use of China by production. In other words, the indirect import of crude oil via importing *non-oil* goods and services in China is not considered in import dependence from production. However, indirect import of crude oil is included in the import dependence from consumption. In a word, Figure 4 shows that China's dependence on the crude oil extracted in the foreign countries is heavier when assessed from consumption than from production.

4. Conclusions and discussion

This article examined embodied crude oil in China's foreign trade and final consumption in the period 1995-2011 using a global MRIO model. It's an important supplement to existing studies based on direct imports and exports of crude oil in China. Although China's direct exports of crude oil is very small now, embodied oil in its exports of goods and services is remarkable and increased significantly after China's entry into the WTO. China has been the world's second largest importer of crude oil and devoted great efforts to secure oil abroad, which incurs some controversies in the international community. However, about one fifth to one third of imported oil is used to producing exports in China. As the world's largest workshop, China is actually playing the role as a transit hub of natural resources from extraction to final consumers. Therefore, consumers of goods produced in China also benefit from China's global hunt for natural resources. In fact, they also benefit from China's huge subsidies for various energy products. These facts are obviously not considered adequately by critics of China's oil thirst. However, it should be noticed that embodied oil in China's imports also increased significantly, with higher growth rate than that of embodied oil in exports in the last few years. Although China was net exporter of embodied oil, the gap has shrunken quickly in recent years.

Both China's production-based and consumption-based oil demand are tremendous, with the former slightly larger than the latter recently. More than half of consumption-based oil use has served China's investment demand. The high and rising import dependence of crude oil from production end has incurred concerns among scholars and policy makers in China. The import dependence of crude oil from production end does not consider embodied imports of crude oil, whereas the import dependence of crude oil from consumption end does. We found

that import dependence from consumption end was in fact even higher than that from production end.

The responsibility of natural resource consumption and pollution emissions has been traditionally allocated to only producers. In other words, the producer responsibility principle is used in the traditional allocation approach of environmental responsibility. However, the consumer responsibility principle for emissions and material accounting has been advocated by many scholars (e.g., Davis and Caldeira, 2010; Giljum et al., 2014; Munksgaard and Pedersen, 2001; Peters and Hertwich, 2008; Tukker et al., 2014; Wiedmann et al., 2015). As an important supplement to traditional producer responsibility principle, the consumer responsibility principle can monitor environmental burden shifting across countries and promote global sustainable development by affecting the consumers' behavior.

China's efforts to encourage its national oil companies to explore the offshore oil and gas reserve, particularly those in some less-developed countries of Africa and South America, have been usually criticized by analysts and politicians from western countries. However, these criticisms are also based on pure producer responsibility principle, overlooking the responsibility of consumers. As shown in this article, about 21%~37% of China's oil consumption actually served the final consumption of foreign countries, mainly developed countries. In other words, foreign consumers should have born substantial part of responsibility for China crude oil thirst under the consumption-based accounting. China has become the 'world factory' and been in shortage of various natural resources. Therefore, tremendous natural resources have been imported to China to producing its exports as the case of crude oil shown in the present article. The globalization of production has closely connected consumers to resource exploration and ecological consequences in remote countries. The role as 'transit hub' of natural resources China is playing indicates it might be more appropriate and productive to encourage and support China's improvement of resource efficiency rather than criticize its resource imports and consumption. In other words, cooperation rather than confrontation between China and the other major oil consumption countries would be helpful for promote sustainable use of crude oil.

Moreover, although crude oil demand from consumption is slightly lower than that from production in China in recent years, the volume of China's consumption-based demand is enormous due to its economic size and growing rapidly. Given tightening limit on global natural resources and environmental space, China can never repeat the resource-intensive growth path taken by high-income countries in their development history.

Therefore, China should endeavor to curb its oil dependence from both production and consumption for the sake of energy secure and sustainable development. The Chinese government has shown great determination and ambition to transform its traditional resource-intensive and pollution-intensive economy to an environment-friendly and sustainable one in the recent official development roadmap. Vigorous reforms on environmental governance and energy market has been undergoing. However, there exist great challenges for China's ambition in consideration of its huge, growing economic size and the lack of advanced technology. Besides China's domestic efforts, closer international cooperation particularly between China and advanced countries might be indispensable to control China's thirst for natural resources, which will significantly promote sustainable development of global production and consumption.

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