An extended overview of natural gas use embodied in world economy and supply chains: Policy implications from a time series analysis

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Abstract: As an extension of our previous study on natural gas use in world economy (Kan et al, Energy Policy 124 (2019) 215-225), this paper explores policy implications based on a time series analysis uncovering the evolution of natural gas use embodied in global supply chains during 2000-2011. Due to increasing gas supply from gas-rich regions to gas-scarce regions and outsourcing of energy-intensive industries, trade imbalance of embodied natural gas is intensifying globally, corresponding to strengthening gas resource relocation and environmental stress shift. Regarding trade patterns, EU and Russia remain the leading (net) importer and exporter of embodied gas, respectively. And global trade relations are diversifying over time, with more suppliers and recipients joining the international trade. Based on the New Policies Scenario provided by IEA, a long term forecast of embodied gas use illustrates need to prepare for a world with changing energy mix, with respect to growing availability of low-cost natural gas and robust demand growth coming from emerging economies, especially China, who is struggling to fight against air pollution through coal-to-gas switch. Potential room to expand natural gas utilization is also targeted, and the expansion requires coordination of all the agents in global supply chains.

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1. Introduction

Reducing greenhouse gas emissions from fossil fuel combustion is an issue of increasing concern for global sustainability (IPCC, 2015). Moreover, a large number of serious health risks are regarded to be associated with energy use, most of which is in the form of fossil fuels (Wilkinson et al., 2007). However, economic growth and population expansion are inevitably accelerating energy consumption. In this context, natural gas is gradually reshaping global energy landscape, with growing share in energy mix on both supply and demand sides (BP, 2018a; IEA, 2018d). On the one hand, it produces less CO_2 and other harmful pollutants in comparison to oil and coal (Dong et al., 2018; Heath et al., 2014). On the other hand, natural gas is proved to be more economical than nuclear and many renewables currently, since it requires lower investment cost (MIT, 2018; Stram, 2016) and production cost (Wang et al., 2014). The easy access to shale gas and the flexibility in the trade of LNG (liquefied natural gas) also boost the expansion of natural gas supply and demand (IGU and BCG, 2018).

Natural gas has been increasingly traded directly and indirectly in the globalized world economy. Countries/regions with insufficient gas resources can rely on foreign natural gas directly by importing natural gas as a kind of commodity, or indirectly by importing gas-intensive commodities with natural gas as commodity embodiment. Moreover, on account of environmental costs, more and more countries are inclined to outsource energy-intensive industries and import finished products, in order to avoid pollutions occurring in the energy extraction and combustion process (Wiedmann and Lenzen, 2018). Whereas, most current studies on natural gas, such as natural gas demand in China (Chai et al., 2018; Zeng and Li, 2016) and Europe (Dilaver et al., 2014), the relationship between gas consumption and economic growth in China and Japan (Furuoka, 2016), EU (Balitskiy et al., 2016) and all top10 gas consumers (Aydin, 2018) and international trade of natural gas (Geng et al., 2014), only consider natural gas consumed within an economy's territory boundary and direct trade of natural gas but neglect overseas gas use driven by its final consumption as well as gas transferred as commodity embodiment. To identify an economy's system-wide dependence on natural gas, the notion of embodied energy can be employed, which is defined as the total energy (direct plus indirect energy use) required to produce and sustain a certain good or service (Chapman, 1974; Costanza, 1980). The concept has been widely applied to investigate embodied energy use at urban scale (Chen et al., 2017b; Li et al., 2014), sub-national scale (Chen et al., 2017c; Gao et al., 2018; Zhang et al., 2015), national scale (Lenzen, 1998; Su and Ang, 2017; Zhang et al., 2017) and global scale (Gasim, 2015; Kan et al., 2019a; Wu and Chen, 2017). It has been also extended to evaluate individual energy source, such as embodied oil use (Tang et al., 2012; Wu and Chen, 2019), embodied coal use (Wu and Chen, 2018; Xia et al., 2017) and embodied nuclear energy use (Cortés-Borda et al., 2015), as well as many other elements like carbon emissions (Su and Ang, 2015; Su et al., 2017), methane emissions (Wang et al., 2019; Zhang et al., 2016) and PM emissions (Meng et al., 2016). However, very few efforts have been devoted to analyzing embodied natural gas use.

Furthermore, the current world economy features a complex economic network. For one thing, the resources and materials required to support production are relatively geographically concentrated, while demand for them comes from all over the world. For another, global supply chains are fragmented as a result of intensified globalization and a high degree of specialization. The spots of production and consumption of a product are always spatially separated and span multiple economic units (i.e., sectors, cities and countries) (Wiedmann et al., 2015). Therefore, these units are ever-increasingly connected with each other through intra- and inter-national trade, and massive physical trade flows of goods/services form a worldwide economic network. Along with physical goods/services flows are also embodied energy flows (embodied natural gas flows in this case). Once being exploited from the environment, natural gas enters the economic system and is traded between different economic units, either as a kind of commodity or as embodiment in goods/services, before it is eventually consumed by final consumers (Kan et al., 2019b). By circulating in the world economic system, embodied natural gas flows also form a virtual biophysical network consequently. Studies focusing on a single segment of natural gas flows fail to capture the complexity of global embodied-natural-gas network and can only provide partial and limited views in both academic understanding and suggestions for policy makers. In this sense, it is imperative to present a systematic overview of natural gas use across global supply chains. It should also be noted that, fragmented global supply chains give rise to unprecedented trade volume of intermediate products (Meng et al., 2018), triggering unprecedented amounts of energy embodied in intermediate trade, which is often ignored in existing literatures too. Actually, in 2013, of total energy embodied in international trade, 85% is attributed to intermediate trade (Wu and Chen, 2017).

Given all this, this paper endeavors to track direct and indirect natural gas use from primary supply to final consumption along global supply chains for the globalized world economy during 2000-2011, with due attention paid to both intermediate and final trade. As an extension of our previous work (Kan et al., 2019b), it performs a time series analysis with the time horizon from 2000 to 2011, instead of focusing on a single benchmark year, in order to reveal the evolving profiles of embodied-gas-related final consumption structures and import/export patterns for dominating agents in global supply chains (e.g., exploiters, final consumers, intermediate and final importers and exporters) as well as international trade flows and trade relations. By revealing these dynamic change patterns, time series analysis can not only be applied to assess efficacy of existing policies on natural gas but also provide comprehensive references for policy makers to predict future natural gas trade and use, and eventually help to promote local and global sustainable gas use in the context of a changing natural gas landscape.

The outline of this paper is as follows. Section 2 elaborates the method used and data sources and Section 3 presents results and analyses. Related discussions are provided in Section 4 and conclusions are drawn in Section 5.

2. Methodology and data sources

2.1 Embodiment accounting

After the pioneering work by Leontief to integrate environmental externalities into input-output analysis (Leontief, 1970), Bullard and Herendeen proposed a biophysical energy balance model (Bullard and Herendeen, 1975a), which is applied in a series of studies accounting embodied energy based on input-output accounts (Bullard and Herendeen, 1975b; Bullard et al., 1978). Chen and his colleagues further extended the model to account various embodied ecological elements besides total primary energy, such as water (Chen et al., 2018; Han et al., 2017), land (Chen et al., 2018; Chen and Han, 2015; Guo et al., 2019) and mercury (Chen et al., 2017a; Chen et al., 2019; Li et al., 2017).

Based on multi-regional input-output (MRIO) analysis, the world economy is simulated as *m* regions, each consisting of *n* sectors and final demand. As introduced in the last section, once being exploited from the environment, natural gas enters the economic system and is traded between regions and sectors in intermediate trade, either as a kind of commodity or as commodity embodiment, before it finally flows to final demand. Final demand covers final consumption (e.g., by households and government) and capital goods. According to Wu et al. (Wu et al., 2018; Wu et al., 2019), natural gas embodied in the former part is consumed and leaves the world economy permanently, while that embodied in the latter part is supposed to return to the economic system as primary input to support production. Therefore, each sector receives natural gas exploited from the environment directly, embodied in capital goods as primary input and embodied in imported goods/services as intermediate input. Meanwhile, it also provides natural gas embodied in exported goods/services for other sectors and final demand. As sectoral input of embodied natural gas equals to sectoral output, the biophysical balance for sector *i* in region *r* can be expressed as:

$$ng_i^r + \sum_{s=1}^{m}\sum_{j=1}^{n}(\varepsilon_j^s z_{ji}^{sr}) + \varepsilon_{p_i}^{\ r} p_i^r = \varepsilon_i^r(\sum_{s=1}^{m}\sum_{j=1}^{n} z_{ij}^{rs} + \sum_{s=1}^{m}(\sum_{k=1}^{l} f_{ik}^{rs} + f_{ic}^{rs})) \qquad (1)$$

where ng_i^r represents natural gas extracted from the environment by this sector. z_{ji}^{sr} and p_i^r denote intermediate input from sector *j* in region *s* and primary input to the sector, respectively. z_{ij}^{rs}, f_{ik}^{rs} and f_{ic}^{rs} stand for the sector's output to region *s*, for intermediate use by sector *j*, final consumption *k* and capital goods use, respectively. Except ng_i^r, all variables mentioned above are in monetary terms. $\varepsilon_{p_i}^{\ r}$ represents embodied natural gas intensity of primary input to this sector. $\varepsilon_i^r/\varepsilon_j^s$ denotes embodied natural gas intensity of output by sector *i* in region *r* / sector *j* in region *s*. By applying the equation to all the sectors and defining $x_i^r = \sum_{s=1}^{m}\sum_{j=1}^{n} z_{ij}^{rs} + \sum_{s=1}^{m}(\sum_{k=1}^{l} f_{ik}^{rs} + f_{ic}^{rs})$ can we get the matrix form:

$$\boldsymbol{NG} + \boldsymbol{\varepsilon Z} + \boldsymbol{\varepsilon_p P} = \boldsymbol{\varepsilon X} \quad (2)$$

where $\boldsymbol{NG} = (ng_i^r)_{1\times mn}$, $\boldsymbol{\varepsilon} = (\varepsilon_i^r)_{1\times mn}$, $\boldsymbol{Z} = (z_{ij}^{rs})_{mn\times mn}$, $\boldsymbol{\varepsilon_p} = (\varepsilon_{p_i}^r)_{1\times mn}$, $\boldsymbol{P} =$ diag $(p_i^r)_{mn\times mn}$, $\boldsymbol{X} = \mathrm{diag}(x_i^r)_{mn\times mn}$.

Meanwhile, natural gas embodied in capital goods equals that embodied in primary input to support production (Wu et al., 2018; Wu et al., 2019). But the relationship between capital goods and primary input is unavailable currently, leaving $\varepsilon_{p_i}^r$ for each sector unknown. As a simplified treatment, they are assumed to be the same value ε_p. Therefore, the balance equation for natural gas embodied in capital goods and primary input is:

$$\varepsilon_p \sum_{r=1}^{m}\sum_{i=1}^{n} p_i^r = \sum_{r=1}^{m}\sum_{i=1}^{n}\sum_{s=1}^{m}(\varepsilon_i^r f_{ic}^{rs}) \quad (3)$$

written in the matrix form as:

$$\varepsilon_p P_{sum} = \boldsymbol{\varepsilon F}_C \quad (4)$$

where P_{sum} is the monetary value of total primary input and $\boldsymbol{F}_C$=$(\sum_{s=1}^{m} f_{ic}^{rs})_{mn\times 1}$. By defining $\boldsymbol{P_0} = (p_i^r)_{1\times mn}$ and combining equation (2) and (4) can we obtain:

$$\boldsymbol{\varepsilon} = \boldsymbol{NG}\left(\boldsymbol{X} - \boldsymbol{Z} - \frac{1}{P_{sum}}\boldsymbol{F_C P_0}\right)^{-1} \quad (5)$$

By multiplying the monetary value of a specific good/service and corresponding intensity can we get the amount of natural gas embodied in it. Therefore, for region *r*, natural gas embodied in final consumption (*EGC*), intermediate imports (EGI_{int}) and exports (EGE_{int}), final imports (EGI_{fin}) and exports (EGE_{fin}) can be calculated as:

$$EGC^r = \sum_{s=1}^{m}\sum_{j=1}^{n}\sum_{k=1}^{l}(\varepsilon_j^s f_{jk}^{sr}) \quad (6)$$

$$EGI_{int}^r = \sum_{s=1(s\neq r)}^{m}\sum_{j=1}^{n}\sum_{i=1}^{n}(\varepsilon_j^s\, z_{ji}^{sr}) \quad (7)$$

$$EGE_{int}^r = \sum_{s=1(s\neq r)}^{m}\sum_{j=1}^{n}\sum_{i=1}^{n}(\varepsilon_i^r\, z_{ij}^{rs}) \quad (8)$$

$$EGI_{fin}^r = \sum_{s=1(s\neq r)}^{m}\sum_{j=1}^{n}(\varepsilon_j^s(\sum_{k=1}^{l} f_{jk}^{sr} + f_{jc}^{sr})) \quad (9)$$

$$EGE_{fin}^r = \sum_{s=1(s\neq r)}^{m}\sum_{i=1}^{n}(\varepsilon_i^r(\sum_{k=1}^{l} f_{ik}^{rs} + f_{ic}^{rs})) \quad (10)$$

2.2 Data sources

The EXIOBASE 3 is adopted to provide the multi-regional input-output tables (IOTs), due to its time series data on annual basis and high sectoral resolution (natural gas sector is set as an individual sector instead of being incorporated to an aggregate mining sector for all energy sources) (Stadler et al., 2018; Wood et al., 2014), while databases with wider geographic coverages, such as GTAP (141 regions) and Eora (190 regions), either do not have good data continuity or do not provide an individual natural gas sector (Aguiar et al., 2019; Lenzen et al., 2013). EXIOBASE 3 simulates the world as a 49-region, 163-sector coupled network, discerning 43 major countries, Taiwan (, China), and five composite *rest of world* region. Some of the countries and regions listed in EXIOBASE 3 multi-regional IOTs are merged in this paper for research purpose. In the following context, China includes mainland China and Taiwan, EU includes 27 member countries (excluding UK), Africa includes South Africa and RoW Africa, and Middle East includes Turkey and RoW Middle East (excluding Cyprus, which is included in EU category). Detailed information of regions and sectors are listed in Appendix Table A1 and A2. Data of natural gas extraction and direct consumption are collected from IEA (IEA, 2018b), with only natural gas for energy use taken into account. The latest EXIOBASE 3 IOT is for the year 2011 when this paper is in preparation, natural gas use for the world economy during 2000-2011 is therefore investigated.

3. Results

3.1 Natural gas extraction and consumption

3.1.1 Extraction of natural gas

For the world as a whole, natural gas extraction for energy use experiences continuous increase between 2000-2011, except for 2009 as a result of financial crisis (IEA, 2018e). When it comes to individual country or region, Russia, USA, Middle East, Canada and Africa stand out as the five largest natural gas exploiters, measured by average annual gas extraction. As shown in Fig. 1, Russia and USA take a safe lead in comparison to other exploiters, with extraction increasing from 497 bcm (billion cubic meters) to 583 bcm in Russia and from 472 bcm to 559 bcm in USA. They together contribute more than 40% of world total gas supply during the period concerned. Extraction by Middle East witnesses the fastest growth (more than doubled) and reaches 416 bcm in 2011. Extraction by Canada and Africa both remain below 200 bcm. And Canada’s extraction falls gradually, exceeded by Africa in 2005.

3.1.2 Natural gas embodied in final consumption

Fig. 2 depicts EGC for ten major final consumers of embodied natural gas. Five leading exploiters mentioned above remain dominant final consumers. EU proves to be the largest final consumer during the whole period, with its EGC greater than 600 bcm most of the time, despite the lack of natural gas endowments. EGC of USA fluctuates around 400 bcm. But in other countries/regions, EGC is basically less than 200 bcm. As regards changes of EGC over time, it can be found that EGC changes relatively moderately in developed economies (e.g., EU, USA, Japan and UK), possibly because these economies have passed through the most unstable stages of socioeconomic development fueled by energy. By contrast, it's typical of developing countries/regions to see rapid increases in embodied gas consumption, partly as a result of robust industrialization and economic expansion. For example, EGC climbs up steadily from 55 bcm to 186 bcm in China, and rises from 30 bcm to 206 bcm (nearly sevenfold) in Russia. There is also an obvious growth in EGC in Middle East.

Fig. 2 also illustrates sectoral contribution to final consumption. 163 sectors listed in EXIOBASE 3 multi-regional IOTs are aggregated into 7 categories according to International Standard Industrial Classification (UN, 2008), with detailed information provided in Appendix Table A2. Several sectoral structures occur. USA, Japan, EU, UK and China share similar sectoral structure, with the majority of EGC coming from *Services and Public Administration* and *Manufacturing* sectors (USA:76%-80%, Japan: 76%-78%, EU: 66%-73%, UK: 71%-75%, China:75%-83%). EGC from *Services and Public Administration* constitutes relatively higher share in USA, Japan and China, while EGC from *Manufacturing* is slightly more in EU and UK. EGC from *Manufacturing* takes up an especially big chunk in Mexico (66%-75%). In the economies mentioned above, natural gas is primarily embodied in finished products (e.g. wearing apparel and furniture) and services (e.g. education, health and social work, public administration and defense), and therefore consumed in an indirect way. By comparison, EGC from *Mining* sector occupies more than 70% of total share in Russia and Canada, reflecting that natural gas is mainly consumed directly by households, government and non-profits organizations (e.g., for household heating), instead of to support the production of other final products and services. Regarding Middle East and RoW Asia and Pacific, *Services and Public Administration, Manufacturing* and *Mining* sectors are all important sources of final consumption. Moreover, sectoral contribution changes over time. It can be noted that EGC from *Services and Public Administration* and *Manufacturing* sectors both ascend in China, Russia and two composite regions, revealing either higher proportion of natural gas in energy mix or growing importance of the two sectors in economic structure. And EGC from *Mining* sector increases dramatically in Russia, indicative of surging direct demand on natural gas by residents.

3.2 Natural gas embodied in international trade

It should be noted that, the amount of natural gas embodied in international trade is underestimated in this paper, because EXIOBASE 3 merges some countries into composite regions. But 43 major countries in terms of GDP and volume of foreign trade have been listed as individual countries in the database, most of which are also dominant primary suppliers of natural gas (e.g., Russia, Canada, USA) or final consumers of embodied natural gas (e.g., USA, Canada, Japan, UK, many EU members, China and Russia), enabling analysis of major trade flows of embodied natural gas. Also, to provide the overview of natural gas use across global supply chains, a composite region as a whole can be also regarded as an agent in the supply chains. It is therefore reasonable to neglect the effect of the country aggregation. In the following context, total natural gas embodied in international trade refers to that embodied in trade between EXIOBASE 3 countries and regions, just to simplify expressions.

Primary suppliers of natural gas, intermediate producers of gas-consuming products and final consumers of embodied natural gas are connected through international trade. Increasing amounts of natural gas are associated with international trade, in magnitude rising from 66% in 2000 to 84% in 2011 of total gas extraction for energy use. Meanwhile, trade of intermediate products has become a driving force of international trade. Between 2000 and 2011, natural gas embodied in intermediate trade rises from 868 bcm to 1482 bcm, in comparison to 499 bcm and 827 bcm of final trade. The ratio of intermediate trade volume to total trade volume fluctuates around 60%.

3.2.1 Trade patterns of major net importers and exporters

Fig. 3 depicts trade patterns of major net importers and exporters in the international trade. In intermediate trade, major net importers are EU, China, Mexico, Japan and Brazil. EU is the largest net importer, with net imports approximately ranging between 300 and 400 bcm, indicating a heavy reliance on foreign natural gas resources. In China, both imports and exports increase with time slowly at first, but imports soar abruptly after 2009. As a result, net imports remain flat before 2009 (below 31 bcm) and then climb drastically to 127 bcm, making China overtake other countries and regions as the second largest net importer in 2011. Leading net exporters are Russia, Middle East, USA, Africa and RoW America. Russia is the largest net exporter due to abundant domestic natural gas production. But its exports show a downward trend. Also, it is interesting that the changes in exports of Russia is highly correlated with changes in imports of EU, mirroring a close connection between the two economies in the trade of embodied natural gas. In Middle East, net exports grow steadily from 58 bcm to 203 bcm, driven by the increase of domestic extraction. USA is also an important supplier, with its exports changing around 100 bcm between 2002-2010 and hit 225 bcm in 2011. But its exports are largely offset by large volume of imports. For all these intermediate importers and exporters, trade of embodied natural gas mainly takes place in *Mining* sector. In other words, natural gas is mainly traded directly instead of being traded as commodity embodiment. But in China, US and EU, there is still a considerable amount of traded natural gas that is embodied in *Manufacturin*g sector. And the amount grows obviously in China and US.

In final trade, EU and Russia consolidates the dominant position as leading net importer and exporter, respectively. Net imports of EU and net exports of Russia both show upward trend with fluctuations, and the correlation between them remains. USA becomes the second largest net importer, with its net imports presenting a "W" shape. By contrast, China turns from a major net importer to a major net exporter, perhaps as a result of processing trade. Moreover, share of embodied gas from *Manufacturing* sector is generally higher in final trade than that in intermediate trade, especially in EU, US and China.

It can be inferred that leading importers and exporters play distinct roles in the global supply chains. For example, EU is a typical final consumer, absorbing natural gas from *Mining* sector and gas-consuming commodities from *Manufacturing* sector in both intermediate and final trade. By contrast, Russia is a dominant primary supplier of natural gas, as it exports large amounts of natural gas via *Mining* sector. China and Mexico play a role as intermediate producers, since they import extensive natural gas in intermediate trade and export products embodying natural gas in final trade (export of Mexico is displayed in more details in next section). USA plays multiple roles, because both its imports and exports from *Mining* and *Manufacturing* sectors are large in intermediate and final trade.

3.2.2 Trade relations

Last section analyzes imports and exports of countries and regions, this section further explores their trade relations. Shown in Fig. 4 are major trade flows of embodied natural gas between countries/regions and their evolution with time in both intermediate and final trade. To make the figures clearer to readers, only trade flows above 10 bcm are drawn.

In intermediate trade, Russia, Middle East and Africa are leading suppliers, exporting embodied natural gas to satisfy the demand of EU, East Asia and other Asia and Pacific countries. Meanwhile, a large amount of embodied natural gas is traded in North America. In specific, all the largest trade flows in the four years are from Russia to EU. But EU is diversifying its embodied gas sources, with more and more imports from Norway, UK, Africa and Middle East. While its imports from Russia decline from about 289.7 bcm in 2004 to 251.1 bcm in 2008 and to 178.3 bcm in 2011. Imports by China escalate after 2008, just as shown in the last section. And it can be seen that China's growing demand is mainly supported by imports from RoW Asia and Pacific and Middle East. Middle East also exports increasing amount of embodied gas to South Korea and Japan. Moreover, USA reduces its exports to Japan but expands its exports to Mexico and Canada steadily, with trade flow to Mexico up from 40.1 bcm to 70.4 bcm and trade flow to Canada up from below 10.0 bcm to 100.1 bcm. Exports by Canada to USA also rises slightly.

Most major trading economies in intermediate trade (e.g., EU, Russia, Middle East, China and USA) still play important roles in final trade，though with different trade connections, and new supplier (Indonesia) and receiver (RoW Europe) emerge. EU remains a dominant receiver of embodied natural gas, with its imports from Russia, Africa and Middle East all keeping an upward trend. Quite different from its performance in intermediate trade, EU starts to receive growing volume of embodied natural gas from China and provide embodied gas for USA and UK. RoW Europe becomes a major importer as well, with embodied gas imports mainly from RoW Asia and Pacific and Russia. The trade flow from RoW Asia and Pacific to RoW Europe reaches 61.4 bcm in 2004 and even 105.8 bcm in 2008 but falls to 20.0 bcm in 2011. China plays a role of an important supplier in final trade, exporting more and more embodied gas to EU, USA and RoW Asia and Pacific. Regarding North America, the relationship between USA and Mexico is reversed compared to that in intermediate trade. This is possibly because USA exports raw materials and semi-products to Mexico for further manufacturing in intermediate trade and then imports finished products and services in final trade.

Generally, global trade relations are diversifying over time in both intermediate and final trade of embodied natural gas, with more suppliers and recipients participating in the international trade. In particular, EU is seeking for multiple supply sources of embodied natural gas and China becomes a noticeable intermediate producer providing gas-consuming products for a growing variety of countries and regions.

4. Discussion

4.1 Prepare for a world with changing energy mix

As illustrated in the introduction, natural gas is projected to transform current energy structure. On the supply side, growing availability of low-cost natural gas is underpinned by shale gas revolution and the expansion of LNG. In 2018, global natural gas production increased by 5.2%, with almost half of the growth coming from US, where production growth was mainly driven by shale gas. Meanwhile, international trade of natural gas more than doubled the 10-year average, largely propped up by LNG (BP, 2018a). On the demand side, broad-based gas demand is also expected due to higher level of industrialization powered by energy, increasing awareness of sustainable development as well as lower cost of natural gas (BP, 2018b). The robust demand growth mainly comes from emerging Asia, especially China, who is struggling to fight against air pollution through coal-to-gas switch (IEA, 2018c; NDRC, 2016). With the ambition in economic growth and the determination in environmental protection, gas consumption by emerging economies is anticipated to rise constantly. Currently, studies only concentrate on how the new energy order influences future direct natural gas demand, none has explored this influence from embodiment perspective. Therefore, this section takes into account changes in gas production and focuses on future embodied natural gas consumption by abovementioned major final consumers, aiming to help economies take precautions in the context of changing energy mix.

To preliminarily investigate this impact, supplies by different energy sectors in 2011 IO table are adjusted according to predicted energy structure. Gas production by different countries and regions is consistent with predicted gas production from IEA. All the reference statistics are collected from New Policies Scenario provided by IEA (IEA, 2016). In the estimation (see Fig. 5), all the consumers concerned are likely to see mounting embodied natural gas consumption. EU and USA still take a far lead. China is expected to overpass Russia as the second largest final consumer. Strong demand will also take place in emerging India, Brazil and Africa.

General increase in natural gas embodied in final consumption provides different implications for economies with different gas endowments. For those with insufficient gas production, like EU, Japan and China, growing embodied gas consumption means heavier reliance on imported natural gas and gas-consuming products. Hence, they are suggested to improve natural gas security, for example, by diversifying supply sources of both natural gas and gas-consuming products and by utilizing other energy sources. It can be seen from Section 3.2 that EU and China having been making effort to achieve diversification of import sources, while Japan depends heavily on the imports from Middle East, which poses potential threat on its natural gas security. Meanwhile, for those with abundant gas wealth, such as Russia, it is crucial to achieve balance between gas supply for domestic use and for export, because natural gas consumed to satisfy their domestic final consumption is also expected to grow. Moreover, considering growing global demand for natural gas and finite gas reserves, it is encouraged to strengthen the communications across the natural gas supply chains so that all the agents can seek cooperation to achieve efficient use of natural gas.

4.2 Target potential room to expand natural gas use

As natural gas is considered as the bridge fuel to transit towards a clean energy mix, global gas consumption grows consecutively year on year. However, natural gas use still contributes a meager share in total fossil fuels consumption (below a quarter) since 2000 (IEA, 2018b). As for individual economies, Fig. 6 explores the contribution of embodied natural gas use to total embodied fossil fuels use in 10 typical economies, with comparison to the share of direct gas use in total direct fossil fuels use, marked as ER (consumption-based perspective) and DR (production-based perspective) respectively.

Generally, DR in developed economies is higher than that in many developing economies. And as time goes on, DR experiences slight growth in developed economies but changes a little in most developing economies (except Brazil and Mexico). Therefore, it can be deduced that, when it comes to domestic production and consumption, developed economies tend to give more priority to natural gas than developing economies do, and during 2000-2011, developed economies are gradually replace oil and coal with natural gas, while such replacement is lacking in many developing economies, including Russia, China, India and South Africa. However, the situation changes when taking into account energy consumed indirectly overseas driven by an economy's final consumption. Due to increasing international trade between the rich and the poor, the shares of gas consumption from consumption-based perspective are likely to be dragged down compared to that from production-based perspective in developed economies, and pushed up in developing economies. However, with growing amount of energy-intensive industries shifted to developing countries and regions which prefer dirtier fossil fuels and adopt energy-consuming technologies, local oil-to-gas and coal-to-gas efforts in developed countries/regions can be offset by ascending oil and coal consumption elsewhere, and even leads to lower share of gas use on a global scale. Thus, along with the transfer of industries, developed economies are suggested to share low-carbon and energy-efficient technologies. Transnational enterprises also ought to take the responsibility to encourage their offshore plants to utilize natural gas or cleaner energy by undertaking partial or total economic costs.

Besides, in spite of slight increase in DR in many developed economies, there are no obvious improvements in oil-to-gas and coal-to-gas switch generally. Thus, more efforts should be made. According to IEA (IEA, 2018a), industry, electricity and transport sectors are leading CO_2 emitters, and industry and transport sectors are also major energy consumers (IEA, 2018f). However, as seen in Section 3.1, only a low portion of natural gas embodied in final consumption comes from these sectors. Therefore, there is plenty of room for the expansion of gas use in residential electricity supply, residential transport and upstream industrial sectors like manufacturing (both home and abroad). Regional goals can be achieved through strong policy pushes for the decarbonization of local energy mix (e.g., "coal-to-gas switching policy" adopted by China (NDRC, 2016)), enterprise transformation and upgrading (e.g., weed out old plants that reliant on dirty energy), and invests in the construction of gas infrastructure (e.g., storage facilities and pipelines). The price of natural gas should also be taken into account, which is one of the most sensitive issues for consumers. And to boost gas use in upstream economies, low-carbon production can be promoted by taking incentive mechanism (Li et al., 2018), such as imposing tax on high-carbon production and imports while offering subsidies for low-carbon ones. Also, governments can guide private enterprises to consciously trade with eco-friendly foreign partners.

Nevertheless, the expansion of gas use may induce new problems. For example, though shifting from coal to gas is a crucial strategy to reduce CO_2 emissions, production of natural gas gives rise to massive methane leakage. It is reported that more than 15 teragram of methane emissions are associated with global gas system in 2011 (Höglund-Isaksson, 2017). And Alvarez et al. found that methane emissions per unit of natural gas consumption will produce radiative forcing comparable to CO_2 emissions generated from natural gas consumption in the long run (Alvarez et al., 2018). Of particular note, share gas has become a significant driving force to push up and underpin natural gas supply. However, an early study has pointed out that methane emissions from share gas production are at least 30% more than those from conventional gas production (Howarth et al., 2011). Emissions of a variety of other climate forcers in natural gas supply chains also pose an impediment to climate change mitigation (Tanaka et al., 2019). Moreover, horizontal drilling and hydraulic fracturing used in the extraction of unconventional natural gas are potential causes of regional water pollution (Vidic et al., 2013). And during the life cycles, natural gas is likely to require more land than many kinds of renewable energy (e.g., PV, wind and biomass) to generate the same amount of electricity (Fthenakis and Kim, 2009; Jordaan et al., 2017). Therefore, what energy mix is reasonable and sustainable is still a question which needs further analysis.

4.3 Trade-offs between two implications of embodied gas trade imbalance

Trade can be measured from many aspects. Along with trade flows are currency flows, goods/services flows, energy embodiment flows and so on. As the direction of currency flows are opposite to goods/services and energy embodiment flows, monetary trade surplus/deficit also means corresponding energy deficit/surplus. Whereas, international trade is always measured by monetary imbalance, insufficient attention is paid to energy trade imbalance, especially natural gas trade imbalance. To fill this blank, this section further investigates trade imbalance of embodied natural gas based on the results of Section 3.2. In Fig. 7, intermediate and final trade imbalances are respectively measured by net intermediate and final imports, and the size of the circles represents total trade volume.

In 2000, most countries and regions cluster around the origin, with small values of net imports. But they spread out over time gradually, indicating intensified trade imbalance of embodied natural gas. Some typical trade patterns emerge, for example, Russia is confronted with severe trade deficit in both intermediate and final trade in the four years, while EU is at the opposite extreme. Despite large trade volume and the trade surplus observed in final trade, USA is close to trade balance in intermediate trade in 2000, 2004 and 2008. And in 2008, its intermediate and final net imports hit the lowest record, before both of them rebound to the highest levels in 2011. Meanwhile, China faces trade surplus in intermediate trade and deficit in final trade. This may be explained by the fact that it assembles and processes imported raw materials and semi-products and then re-exports the finished products. Also, China is inclined to deviate from the origin, with expansion in intermediate import and final export.

In general, with growing demand for natural gas as well as increasing degree of specialization and cooperation, intensified trade imbalances of embodied natural gas have been witnessed these years. One coin has two sides. On the one hand, it implies the optimization of gas resource allocation. Since large share of traded natural gas is from *Mining* sector, it can be inferred that growing amount of natural gas (as a commodity) is transferred from countries and regions who own a rich wealth of gas to those in need and facing gas scarcity, such as the trade between Russia and EU. Globalization has fostered this allocation and enabled wider use of natural gas rather than other fossil fuels, subsequently promoting the smooth transition to a cleaner energy system. On the other hand, it confirms growing trend of energy stress shift. Take embodied gas trade surplus (or corresponding monetary trade deficit) as an example, when an economy imports gas-consuming products from abroad, it avoids gas extraction as well as negative environmental impacts in the extraction and combustion process. Therefore, trade-offs between both implications should be taken into account in policy makings. On the trajectory to obtain universal access to clean energy, one should also consider energy and environmental stress beyond national boundaries. In this sense, trade imbalance analyses from energy perspective can offer a supplementary view for policy makings contingent to monetary trade imbalance, helping to facilitate widespread natural gas use as well as mutual environmental responsibility.

5. Conclusion and policy implications

Considering the increasing significance of natural gas in global energy mix and its growing indirect use caused by fragmented global supply chains, this paper carries out a time series analysis to track direct and indirect use of natural gas from primary supply to final consumption along global supply chains during 2000-2011, uncovering evolving pictures of embodied-natural-gas-related final consumption structures, import/export patterns for dominating agents in global supply chains as well as international trade flows and trade relations.

During the period concerned, Russia and USA are two largest gas exploiters, followed by Middle East with rapidly ascending extraction. EU is the largest final consumer of embodied natural gas, and USA, Canada, UK, Japan, China, Russia, Mexico, Middle East and RoW Asia and Pacific are also among the top ten final consumers. Natural gas embodied in final consumption changes moderately in developed economies (e.g., EU, USA, Japan and UK), but increase rapidly in many developing countries/regions (e.g., China, Russia, Middle East and RoW Asia and Pacific). *Services and Public Administration, Manufacturing* and *Mining* sectors are all important sources of final consumption. Natural gas associated with international trade among EXIOBASE 3 regions rises from 66% to 83% of global gas extraction in magnitude, with intermediate trade representing around 60% of total trade. Dominant primary suppliers (e.g., Russia, USA and Middle East), producers (e.g., China, USA and Mexico) and final consumers (e.g., EU, USA and Japan) are major importers and exporters in intermediate and final trade. Trade relations are increasingly diversifying, especially for EU (who is diversifying supply sources of embodied natural gas) and China (who becomes an important intermediate producer).

Based on the New Policies Scenario provided by IEA, a long-term forecast of embodied gas use shows strong demand for embodied natural gas, led by EU and USA as well as many emerging economies. Economies with insufficient gas production, like EU, Japan and China, are suggested to improve natural gas security by diversifying supply sources of both natural gas and gas-consuming products and by utilizing other energy sources, while it is crucial for those with abundant gas wealth, such as Russia, to achieve balance between gas supply for booming domestic and foreign demand. Considering current low share of gas use in total fossil fuels use, potential room to expand natural gas utilization is also targeted, including residential electricity supply, residential transport and upstream industrial sectors. Regional goals can be achieved through strong policy pushes for the decarbonization of local energy mix, enterprise transformation and upgrading, invests in the construction of gas infrastructure and appropriate gas price. And to boost gas use in upstream economies, low-carbon production can be promoted by taking incentive mechanism, such as imposing tax on high-carbon production and imports while offering subsidies for low-carbon ones. However, various adverse impacts in the supply chain of natural gas should be considered in the meanwhile. Finally, intensified trade imbalance of embodied natural gas is witnessed globally, corresponding to strengthening gas resource relocation and environmental stress shift. Therefore, on the trajectory to obtain universal access to clean energy, one should also consider energy and environmental stress beyond national boundaries. In sum, economies are suggested to prepare for a changing natural gas landscape and promote sustainable gas use through both regional effort and global cooperation.

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