Beyond wells: towards demand-side perspective to manage global methane emissions from oil and gas production

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Abstract: The international trade of oil/gas-implicated commodities could potentially jeopardize global methane mitigation targets when exporting countries have loose or even no methane regulations. Therefore, this paper constructs a demand-driven impacts model to uncover the impact of global consumption and international trade on regional oil and gas methane emissions in 2014. It's estimated that more than three-fifths of global oil & gas methane emissions are embodied in international commodity trade (e.g., petroleum, chemicals), primarily from large oil and gas suppliers (e.g., Russia, Nigeria and Iran) to large consuming economies (e.g., China, Japan and USA). Notably, more than three quarters of oil & gas methane emissions embodied in EU's final consumption occurs in other regions. Our results could facilitate targeted demand-side mitigation strategies (e.g., labelling low-emission products, shifting to a circular bio-economy) to complement supply-side efforts, especially considering the relatively loose supply-side methane regulations on oil and gas sectors in large exporting regions.

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1. Introduction

Reducing greenhouse gas (GHG) emissions is a global priority for climate change mitigation. As a powerful driving force of climate change, global methane emissions continued to increase by 1.8% in 2018, accounting for about one fifth of total GHG emissions (Olivier and Peters, 2020). Methane's heat-trapping ability, aka., global warming potential, is 25 times greater than that of carbon dioxide on the 100-year time horizon under the United Nations Framework Convention on Climate Change (UNFCCC), while atmospheric methane concentration has already more than doubled since the Industrial Revolution (Reay et al., 2018). It's estimated that more than 60% of the methane emissions are contributed by intensive anthropogenic activities (e.g., agricultural and fossil fuel production) (Saunois et al., 2016). The surging concentrations of methane emissions make it the second most important human-induced GHG after carbon dioxide. Meanwhile, the relative short lifespan of methane in the atmosphere offers a unique opportunity to take actions that have immediate beneficial impacts on climate change. Therefore, achieving the 2 °C and even 1.5 °C target by 2030 requires more urgent and stringent policy interventions targeted on methane control (Fletcher and Schaefer, 2019). Reducing methane emissions could also deliver significant co-benefits to human health and agricultural production through ozone air quality improvement (Avnery et al., 2013; West et al., 2006).

Oil and gas sectors play an indispensable role in global methane profile. Methane leakage could occur at multiple stages of the oil and gas supply chains (Brandt et al., 2014; Caulton et al., 2014; Konschnik and Jordaan, 2018; Nature, 2005; Schneising et al., 2014; Zavala-Araiza et al., 2015), especially the production and gathering stages. According to the Global Methane Budget, annual methane emissions from oil and gas sectors are estimated to be 69-88 Tg, accounting for about 65 % of total fossil methane emissions or one quarter of global anthropogenic methane emissions (Saunois et al., 2016; Saunois et al., 2020). More recent studies have indicated that the oil and gas methane emissions are substantially underestimated by around 20-60% in some regions (e.g., USA) and the whole world (Alvarez et al., 2018; Hmiel et al., 2020; Schwietzke et al., 2016). Notably, limiting methane losses from oil and gas operations is hindered by the world economy's foreseeable huge demand for oil and gas. On one hand, crude oil is likely to maintain the lion's share of global energy consumption in the next two decades (IEA, 2017), accounting for around one third global energy demand in 2040 in the Current Policy Scenario. On the other hand, natural gas is seen as a bridge fuel to smooth the ongoing energy transition towards a carbon-neutral energy mix for many coal-dominant regions such as China (Qin et al., 2017; Tanaka et al., 2019). The gradual replacement of coal with natural gas is expected to push up gas demand, which further exacerbates the headwinds for methane reduction. It's estimated that coal-to-gas transition would lead to additional warming out to mid-22nd century if the methane leakage rate is around 10% (Wigley, 2011).

Numerous efforts have been devoted to assisting the oil and gas sectors in methane management. A comprehensive and reliable emission inventory is prerequisite for mitigation initiatives. Therefore, many studies focus on compiling oil and gas methane emission inventories at various stages of supply chain (e.g., production, processing, transmission, storage, distribution and end-use) on different scales, including field (Allen et al., 2013; Karion et al., 2013), city (McKain et al., 2015; Plant et al., 2019), basin (Harriss et al., 2015; Karion et al., 2015), national (Alvarez et al., 2018; Dedikov et al., 1999; Sheng et al., 2017; Zhang et al., 2022; Zimmerle et al., 2015), regional (Brandt et al., 2014; Nara et al., 2014) and global (Hausmann et al., 2016; Höglund-Isaksson, 2017) scales. These studies have also identified major sources of oil and gas methane emissions, including the flaring, venting and unintended leakage during production. Accordingly, some supply-side measures have been advocated to reduce methane leakage and improve recovery rate, such as mandatory leakage detection and reporting, rapid retrofit/replacement of outdated equipment, accelerating elimination of venting and flaring from oil and gas wells, and installation of vapor recovery units, which contributes greatly to global methane control efforts.

It’s proved that a large amount of oil and gas initially extracted in some countries (e.g., North Africa and Russia) will finally be consumed by others (e.g., EU and China) through the complex global supply-chain network (Kan et al., 2020; Kan et al., 2019b; Wu and Chen, 2019). In other words, the demand for goods and services in consumer countries are driving production of oil and gas in other countries, which in turn aggravates methane leakage. The international trade of oil and gas as well as oil & gas-reliant products can be regarded as transfer of methane emissions that are embodied in these products, and therefore could jeopardize global methane mitigation targets when exporting countries have loose or even no methane regulations on oil and gas industries. The above-mentioned evidences suggest that only supply-side mitigation measures are sometimes inadequate to achieve an ambitious methane reduction goal. Hence, demand-side mitigation options aimed at global consumption and international trade could serve as a complement to supply-side practices. Most previous studies focused on the carbon dioxide emissions driven by international trade (Baumert et al., 2019; Davis and Caldeira, 2010; Li et al., 2020; Ottelin et al., 2019). A universal finding is that 23-30% of global carbon dioxide emissions could be attributed to international trade (Wiedmann and Lenzen, 2018). Only a few studies paid attention to methane emissions exclusively embodied in international trade. For example, Subak showed that the methane leakage associated with international trade of rice, meat and milk products can jeopardize the effectiveness of Framework Convention on Climate Change (Subak, 1995). More recent studies uncovered the role of international meat (Caro et al., 2014), dairy(Wu et al., 2022) as well as general commodity trade (Fernández-Amador et al., 2020; Wang et al., 2019; Yan et al., 2021) in redistributing regional methane emissions. Notably, little efforts have been devoted to revealing how global consumption and international trade reshape the profile of regional oil and gas methane emissions, especially from the perspective of both oil & gas sectors as well as non-oil & gas sectors.

In specific, this study aims to (1) shed light on how export-oriented production induces methane losses in large oil and gas producing regions, (2) map the trade routes underpinned by global supply-chain network between final consumers and primary oil and gas suppliers, and (3) identify regions with large consumption-based impacts on global oil and gas methane leakages, in order to facilitate tailored demand-side mitigation strategies. This work goes beyond simple oil and gas methane emissions mapping, in that it unveils a global supply-chain network that tele-connects onsite methane emissions during oil and gas production with international trade and global consumption, based on which comprehensive demand-side policies could be formulated to manage global methane emissions from oil and gas production.

2. Methodology and data sources

2.1 Demand-driven impacts model

In order to evaluate methane emissions driven by demand and international trade, environmentally extended input-output analysis (EEIOA) is adopted, which is widely acknowledged as a powerful tool to reveal the connection between onsite resource use/environmental impacts and demand of final consumers (Leontief, 1970; Wiedmann, 2009; Wiedmann and Lenzen, 2018). The method incorporates production-based environmental inventories (i.e., oil and gas methane emissions) into global multi-regional input-output (GMRIO) tables that capture trade flows between industrial sectors and from these sectors to final consumers. Methane emissions can therefore be traced across global supply chains from where they are produced to where the emission-inducing products are consumed via international trade.

Table 1 The scheme of environmentally-extended global multi-regional input-output model

<table>
<tr><td colspan="3" rowspan="3">Output / Input</td><td colspan="7">Intermediate use</td><td colspan="7">Final use</td><td rowspan="3">Total output</td></tr>
<tr><td colspan="3">Economy 1</td><td rowspan="2">…</td><td colspan="3">Economy m</td><td colspan="3">Economy 1</td><td rowspan="2">…</td><td colspan="3">Economy m</td></tr>
<tr><td>Sector 1</td><td>…</td><td>Sector n</td><td>Sector 1</td><td>…</td><td>Sector n</td><td>Category 1</td><td>…</td><td>Category k</td><td>Category 1</td><td>…</td><td>Category k</td></tr>
<tr><td rowspan="7">Intermediate input</td><td rowspan="3">Economy 1</td><td>Sector 1</td><td colspan="7" rowspan="7">z_{ij}^{rs}</td><td colspan="7" rowspan="7">y_{ik}^{rs}</td><td rowspan="7">x_i^r</td></tr>
<tr><td>⋮</td></tr>
<tr><td>Sector n</td></tr>
<tr><td colspan="2">⋮</td></tr>
<tr><td rowspan="3">Economy m</td><td>Sector 1</td></tr>
<tr><td>⋮</td></tr>
<tr><td>Sector n</td></tr>
<tr><td colspan="3">CH_4 emissions from oil & gas production</td><td colspan="7">e_i^r</td></tr>
</table>

The GMRIO model has been applied to account various ecological elements, such as energy use (Chen et al., 2018b; Kan et al., 2019a; Oswald et al., 2020), land use (Chen et al., 2018a; Kan et al., 2021; Kan et al., 2023; Pendrill et al.), water use (Lenzen et al., 2013a; Liu et al., 2020; Lutter et al., 2016), carbon emissions (Acquaye et al., 2017; Davis and Caldeira, 2010; Kanemoto et al., 2016; Li et al., 2020) and other air pollutant emissions (Chen et al., 2019; Li et al., 2017; Long et al., 2022; Meng et al., 2016). Table 1 illustrates the scheme of environmentally-extended GMRIO model. Accordingly, the world is divided into *m* regions, each including *n* industrial sectors and *k* kinds of final demand. Sectoral total output (measured by monetary value) consists of output to other sectors and output to final demand, which can be expressed as:

$$\begin{pmatrix} \boldsymbol{A}^{11} & \boldsymbol{A}^{12} & \cdots & \boldsymbol{A}^{1m} \\ \boldsymbol{A}^{21} & \boldsymbol{A}^{22} & & \boldsymbol{A}^{2m} \\ \vdots & & \ddots & \vdots \\ \boldsymbol{A}^{m1} & \boldsymbol{A}^{m2} & \cdots & \boldsymbol{A}^{mm} \end{pmatrix} \begin{pmatrix} \boldsymbol{x}^{1} \\ \boldsymbol{x}^{2} \\ \vdots \\ \boldsymbol{x}^{m} \end{pmatrix} + \begin{pmatrix} \sum_1^m \boldsymbol{y}^{1s} \\ \sum_1^m \boldsymbol{y}^{2s} \\ \vdots \\ \sum_1^m \boldsymbol{y}^{ms} \end{pmatrix} = \begin{pmatrix} \boldsymbol{x}^{1} \\ \boldsymbol{x}^{2} \\ \vdots \\ \boldsymbol{x}^{m} \end{pmatrix} \text{ (or } \mathbf{AX}+\mathbf{Y}=\mathbf{X}) \quad (1)$$

where $\boldsymbol{A}^{rs} = (a_{ij}^{rs})_{mn \times mn}$ (the technology coefficient matrix), with $a_{ij}^{rs} = z_{ij}^{rs}/x_i^r$ representing output of sector *i* in region *r* to support one unit of production of sector *j* in region *s*; $\boldsymbol{x}^r = (x_i^r)_{n\times 1}$ (sectoral output matrix), with x_i^r standing for the total output of sector *i* in region *r*; $\boldsymbol{y}^{rs} = (y_{ik}^{rs})_{n\times \mathrm{k}}$ (final demand matrix), with y_{ik}^{rs} denoting output of sector *i* in region *r* to satisfy the final demand *k* of region *s*. To better describe the relationship between total output matrix and final demand matrix, the equation can be transformed as follows:

$$\mathbf{X}=(\mathbf{I}\text{-}\mathbf{A})^{-1}\,\mathbf{Y} \quad (2)$$

where **I** is the identity matrix.

If we define $\boldsymbol{E}^r = (e_i^r)_{1\times mn}$ as the direct emissions intensity vector whose elements represent production-based methane emissions per unit of sectoral output (oil and gas sectors in this study), the demand-driven emissions (**DE**) can be calculated by:

$$\mathbf{DE}=\mathbf{EX}=\mathbf{E}(\mathbf{I}\text{-}\mathbf{A})^{-1}\,\mathbf{Y} \quad (3)$$

The matrix **Y** can be considered as a combination of multiple components, such as final demand satisfied by domestic and foreign sectors respectively or sectoral output for domestic and foreign final demand respectively. $\mathbf{E}(\mathbf{I}\text{-}\mathbf{A})^{-1}$ is the sector-specific embodied emission intensity vector, defined as the sum of direct (on-site) and indirect (upstream) emissions generated to produce per unit final demand (monetary value) of the sector. Accordingly, methane emissions driven by different components can be distinguished. From this framework, methane emissions embodied in international trade could be obtained by:

$$\mathbf{DE^{rs}} = \mathbf{\tilde{E}^{r}}(\mathbf{I}-\mathbf{A})^{-1}\mathbf{\tilde{Y}^{s}} \quad (4)$$

where $\mathbf{DE^{rs}}$ denotes the methane emission from oil and gas production in region *r* related to cross-regional final products and services consumed in regions *s*. $\mathbf{\tilde{E}^{r}}$ represents the direct emission intensity vector for region *r* but zero for all other regions, while $\mathbf{\tilde{Y}^{s}}$ is the final demand vector for region *s* but zero for all other regions.

2.2 Data sources

The model inputs include national methane emission from oil and gas production and the GMRIO table. National on-site methane emissions from oil and gas production are collected from EDGARv6.0 (Crippa et al., 2020), which provides complete national methane emission inventories from different sources (including oil and gas production) during 1970–2021. The GMRIO table for the year 2014 is derived from Global Trade Analysis Project (GTAP) 10 database (Andrew and Peters, 2013), after comprehensive comparisons between various databases regarding the geographic coverage and sectoral resolution. On one hand, GTAP 10 disaggregates 141 regions, allowing for detailed analysis for a wide range of individual countries (A. Aguiar, 2016), while EXIOBASE and World Input-Output Database (WIOD) only cover less than 45 countries with others merged to composite regions (Dietzenbacher et al., 2013; Stadler et al., 2018). On the other hand, oil and gas sectors are separated from an aggregated mining sector as two specific sectors in GTAP, which is different from Eora, a database also with a high country resolution (Lenzen et al., 2013b). The oil and gas sector methane emission inventory derived from EDGAR are directly allocated to oil and gas sector in GTAP, respectively. However, the EDGAR doesn’t distinguish methane emissions from venting and flaring between oil and gas sector. Thus, we allocate the methane emissions from venting and flaring to oil and gas sector separately according to a previous study (Höglund-Isaksson, 2017). Detailed information for regions and sectors is presented in Appendix Table 1 and 2, and the mapping between EDGAR and GTAP sectors is summarized in Appendix Table 3. Consequently, the oil and gas methane emission matrix $\boldsymbol{E}^r$ in equation (3) and (4) is thus constructed.

2.3 Uncertainty analysis

The overall uncertainties of the results stem from two sources, namely, the national oil and gas methane emission inventory and GMRIO table. EDGAR database provides uncertainties reported within twice the standard deviation of the mean value for major economies, such as China ±57%, USA ±32% and EU ±32~57% (Janssens-Maenhout et al., 2019). Regarding the GMRIO table, spatial resolution (Su and Ang, 2010), sector aggregation (Zhang et al., 2018) and price variability (Wiedmann et al., 2015) all have certain impacts on the uncertainties. Many studies have validated that the GMRIO data contributes around ±2-20% to the consumption-based impacts evaluation at national level (Hertwich and Peters, 2009; Moran and Wood, 2014; Rodrigues et al., 2018).

This study further adopts a stochastic modelling to estimate the overall uncertainties quantitatively (Haoran Zhang et al., 2019; Lenzen et al., 2018; Lenzen et al., 2010). The error of each raw data point is propagated by introducing the standard deviation (SD) based on Monte Carlo simulation. The approach takes the assumption that observation of multi-regional input-output entries follow the lognormal distribution (Haoran Zhang et al., 2019; Lenzen et al., 2010). The simulation is conducted for 10,000 iterations to obtain the overall uncertainties of national demand-driven oil and gas methane emissions. More technical details and simulation codes could be found in our previous study (Long et al., 2022; Wei et al., 2021; Wei et al., 2020). The relative standard deviation (RSD) of methane emissions inventory and GTAP MRIO table are derived from (Janssens-Maenhout et al., 2019) and (Hertwich and Peters, 2009), respectively (see Appendix Table A4).

3. Results

3.1 Global demand driving oil and gas methane emissions

In 2014, the world total methane emissions from oil and gas production amount to 71.3 Tg (trillion gram), of which more than half (38.5 Tg) are sourced from the gas production and the rest (32.8 Tg) from oil production. Strikingly, from the consumption-based perspective, only 18% of methane emissions are driven by demand for oil and gas products (mainly petroleum), while the remainder are primarily induced by other manufacturing and tertiary sectors to provide finished products and services for final consumers (see Fig. 1). Specifically, Construction accounts for the largest share of non-oil & gas-caused methane emissions (11%), followed by Transport (10%), Electricity (8%), Human health and social activities (4%), Whole sale (4%), and Chemical products (4%). When looking at methane emissions from global gas system alone, even higher proportion (87%) are associated with demand from non-oil & gas sectors.

At the national scale, consumption-based methane emissions are dominated by a handful of developed countries, such as USA, Japan and many EU members, as well as large developing countries, such as China, Russia and India (as shown in Fig. 1). Final demand of USA drives 11.2 Tg of oil and gas methane emissions, approximately to the sum of emissions by China (7.2 Tg) and Russia (4.7 Tg), who are the second and third largest final consumers of emission-inducing products. USA alone drives 16% of global total emissions, and the six largest consumers altogether almost contribute 50% of the total. Among the leading 15 consumer countries, non-oil & gas sectors remain the major driving force, accounting for 72%~90% of the consumption-based emissions. Moreover, source structures of consumption-based methane emissions vary across countries. For India and USA, around 60% of the country's consumption-based emissions are sourced from global oil system, while the proportion is generally lower in Russia, Japan and Mexico. Meanwhile, the simulated uncertainty range of the national consumption-based oil and gas methane emissions are approximately [-11.3%, +12.9%], [-12.7%, +14.4%], [-31.0%, +44.3%], [-10.5%, +12.3%] and [-11.7%, +14.7%] at the 95% confidence intervals for USA, China, Russia, Japan and India, respectively. (Uncertainties for other regions are presented in Appendix Table A5).

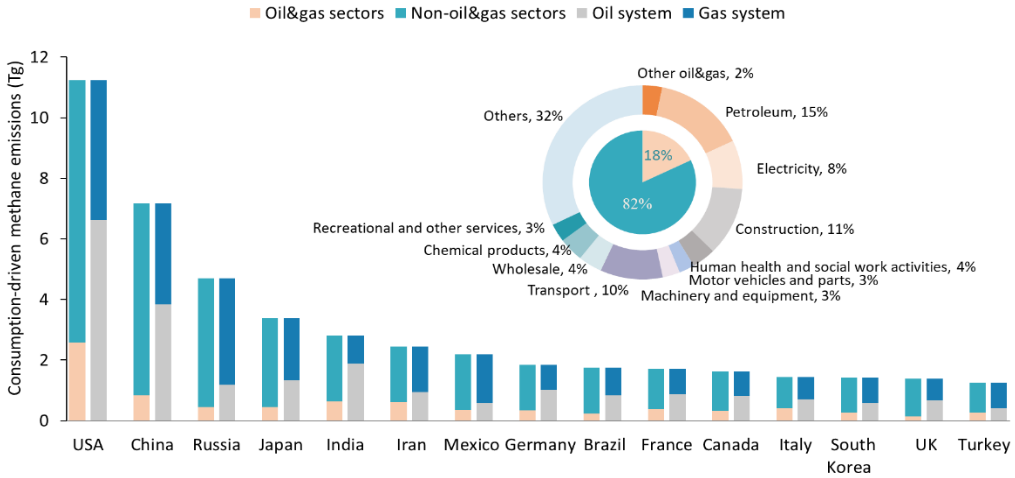

Fig.1 Demand-driven methane emissions by sector and source for the world economy and major final consumers (The left and right bar show national demand-driven methane emissions by two broadly classified sectors, i.e. oil & gas sectors and non-oil-&-gas sectors, and by two sources, i.e. oil and gas production, respectively. The pie chart shows global demand-driven methane emissions by major sectors. Detailed information of GTAP regions and sectors are provide in Appendix Table A1 and A2.)

From the perspective of embodied emission intensity (as shown in Fig. 2), different oil and gas closely-connected sectors in different regions have varied embodied intensities. In general, Oil, Gas and Petroleum sectors have larger embodied emission intensities. Notably, those oil and gas-based sectors like Chemical products, Rubber and plastic products and Transport, though they don’t emit methane emissions directly. However, the production of these oil and gas-based products would require upstream oil and gas inputs and therefore result in methane emissions.

Unit: t/thousand USD	Oil	Gas	Petroleum	Chemical products	Rubber and plastic products	Electricity	Transport nec	Water transport	Air transport
China	10.3	970.8	10.1	2.7	1.6	2.0	2.0	3.5	3.5
Japan	17.5	2852.9	6.9	3.3	1.5	7.8	1.5	13.0	2.2
India	8.8	136.4	12.6	7.5	4.7	2.0	3.7	8.9	2.5
Canada	25.2	22.5	17.5	5.6	2.1	5.8	6.4	10.6	7.0
USA	13.5	122.6	13.5	2.9	1.2	3.4	4.7	2.1	5.6
Mexico	12.6	120.6	18.6	8.4	5.4	37.0	4.3	2.8	5.3
Brazil	6.4	61.9	9.1	2.8	1.3	6.2	3.2	2.9	3.3
Germany	6.1	305.7	9.0	2.0	0.9	1.4	1.1	33.1	4.3
Italy	4.2	706.4	14.6	2.6	1.2	3.9	2.3	5.6	5.6
UK	2.1	82.0	7.1	1.5	0.7	2.8	1.4	3.1	2.5
Norway	4.0	11.4	4.9	1.8	0.8	0.2	1.0	3.8	2.2
Russia	13.6	61.4	13.5	12.0	17.7	18.3	6.5	3.5	4.9
Iran	25.1	1136.2	47.0	29.7	14.3	28.1	22.1	71.8	17.6
Saudi Arabia	5.4	40.3	8.7	5.8	3.6	13.7	8.5	6.1	7.2
Nigeria	30.4	37.9	25.4	3.0	2.5	5.7	3.6	4.8	5.0
Turkey	5.3	3383.8	16.7	5.2	2.7	12.7	2.9	2.7	4.7
Mexico	12.6	120.6	18.6	8.4	5.4	37.0	4.3	2.8	5.3

Fig.2 Embodied methane emission intensities of oil and gas closely-connected sectors in major countries

3.2 International trade reshaping global oil and gas methane emissions

Methane emissions displaced via international trade reaches 45.2 Tg, accounting for 63% of global total oil and gas methane emissions. Fig. 3 depicts the share of methane emissions mediated by international trade in terms of how much of a region's local methane emissions are driven by external demand and how much of its consumption-based methane emissions are displaced outside its own border. There is a cluster of countries and regions (henceforth simplified as countries) centered in the bottom right corner of the figure, characterized with high proportion of methane-intensive export production on the production side and low share of emission displacement on the demand side. The cluster consists of countries recording considerable local methane emissions, including Russia, Iran, Saudi Arabia and some other African and Western Asia countries. However, for most of them, local demand only drives few emissions compared to major final consumers. There is also a group of countries lying close to the upper left corner, including Japan, India and Italy. They observe small amounts of domestic methane emissions, with most of the emissions transferred offshore. USA is the only country that drives substantial emissions both at home and abroad. Meanwhile, two-fifths of its domestic emissions are associated with exports. Mainland China shows a similar situation but produces less emissions on both production and demand side. Located near the upper right corner, Norway, Spain and France witness large share of emissions both displaced into and out of their territories.

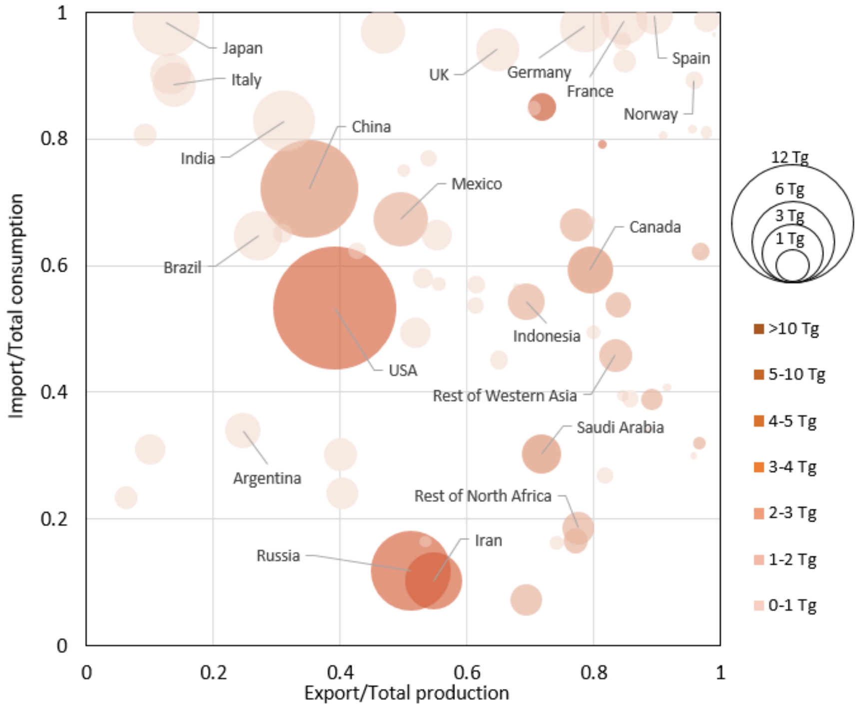

Fig.3 The share of methane emissions mediated by international trade

(The horizontal axis represents the ratio of emissions caused by export production to total production-based emissions and the vertical axis denotes the ratio of emissions embodied in imports to total demand-driven emissions. The size of the circles reflects the volume of total consumption-driven emissions and the shade of color reflects the amount of production-based emissions. For regions that does not record local oil and gas methane emissions, export/total production is set to be 0.)

In order to uncover how much emissions produced in a certain source country are induced by the demand of a certain sink country, a source-to-sink budget is provided in Fig. 4, which captures the relations between direct methane emitters and final consumers via the connection by final producers (supplying products to final consumers rather than intermediate agents). It can be seen that the driving effect of final demand is mainly transmitted to domestic final producers first before to primary suppliers, and the displacement of methane emissions is basically from EU, USA, China, Japan and India to Russia, Iran, Saudi Arabia and Africa. For Russia, the second largest methane emitter, 20% of its emissions are driven by demand of EU, 54% by itself, 3-4% by USA and China each. Regarding Rest of Asia, there are also around 50% of emissions induced by export production. Japan accounts for the largest share (12%), followed by China, EU, and India. While exported emissions reaches 68% of total share in Rest of Africa, dominated by EU (26%) and China (12%), with USA accounting for 6%. On the demand side, EU is highly reliant on foreign emission-intensive production (78% is displaced) and mainly displaces emissions to Russia, Rest of Africa and Rest of Asia. While for USA, China, Japan and India, primary suppliers are relatively diversified. Furthermore, oil system not only produces more methane emissions than gas system, but contributes more to the emission displacement.

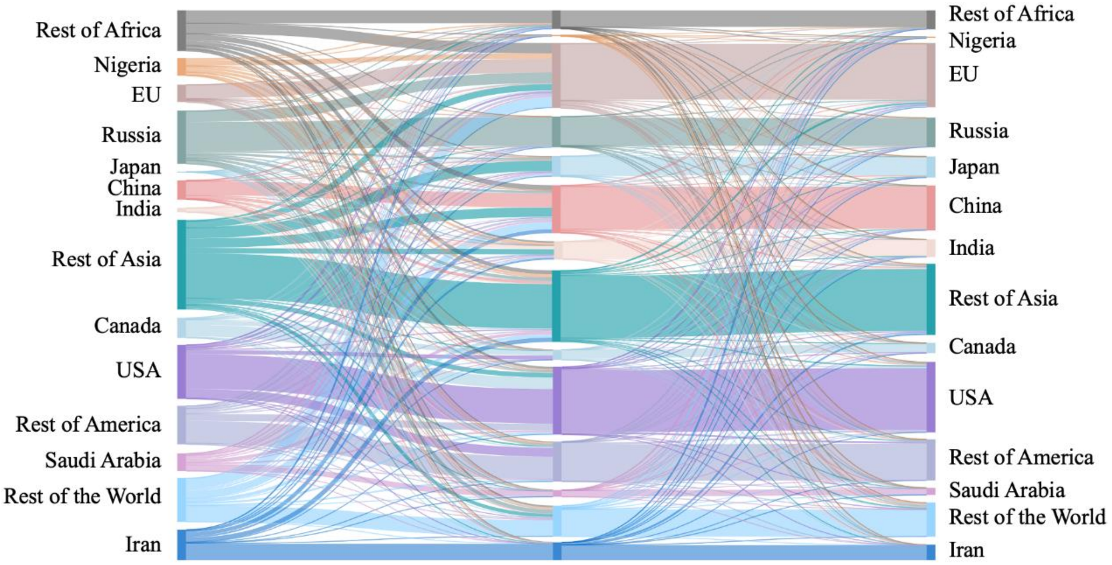

Fig.4 Source-to-sink budget of global oil and gas methane emissions

(The left, middle and right columns are direct methane emitters, final producers and final consumers of emission-inducing products, respectively. The thickness of the flows (using exporters' colors) denotes the amount of emissions embodied in trade flows.)

Fig. 5 shows the sectoral contribution of methane emissions embodied in trade for top 5 net importers and exporters. Among the 141 regions, 102 regions gain an embodied oil and gas methane emissions surplus, while the other 39 regions have a deficit. China, Japan and USA are among the largest net methane emissions importers, exactly the major consumers, while Russia, Nigeria and Iran are the largest net exporters, mainly the global oil and gas suppliers. Oil, Gas and Petroleum sectors dominate the transferred methane emissions for major net exporters (77%~99%). It should be noted that though Iran exports large amount of oil and gas, it also imports gas from Turkmenistan to meet its domestic demand (Hafeznia et al., 2017), resulting in the large oil and gas methane emissions imports for Iran. In contrast, sectoral contributions are more diversified for the top net importers. Generally, Chemical products, Transport and

Computer, electronic and optical products together account for 25%, 20% and 14% for Germany, China and USA, respectively.

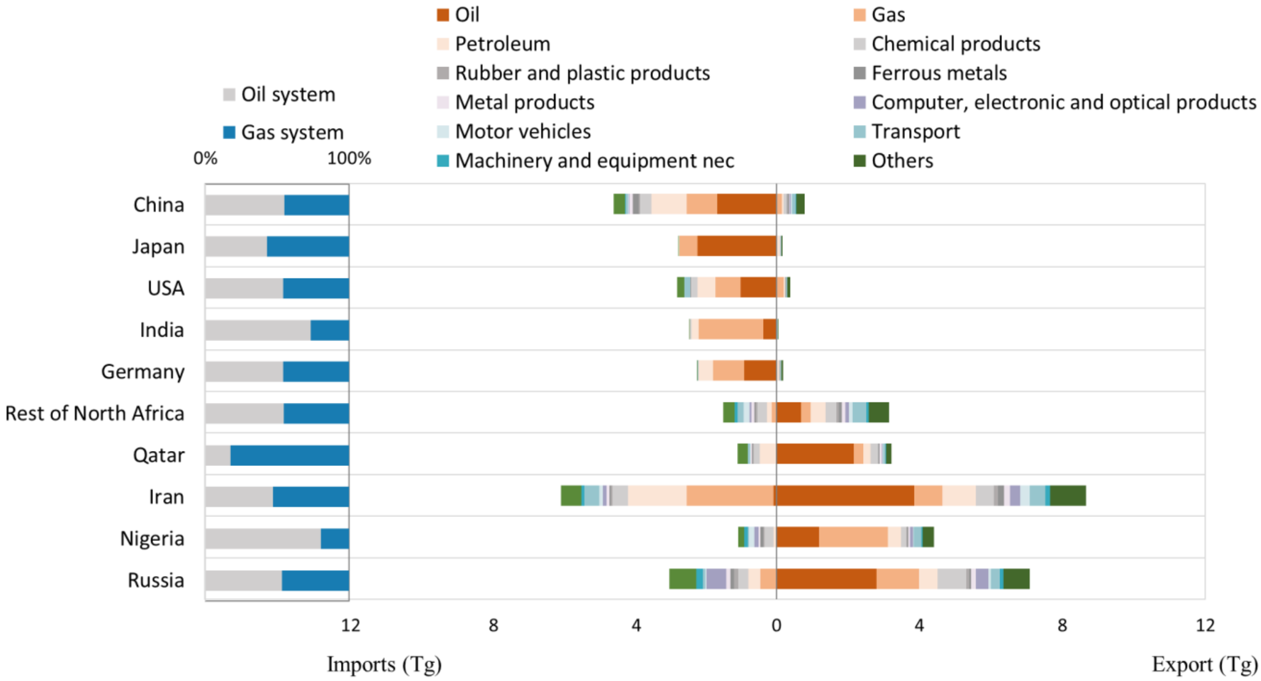

Fig.5 Methane emissions embodied in imports and exports by sector for top 5 net importers and exporters

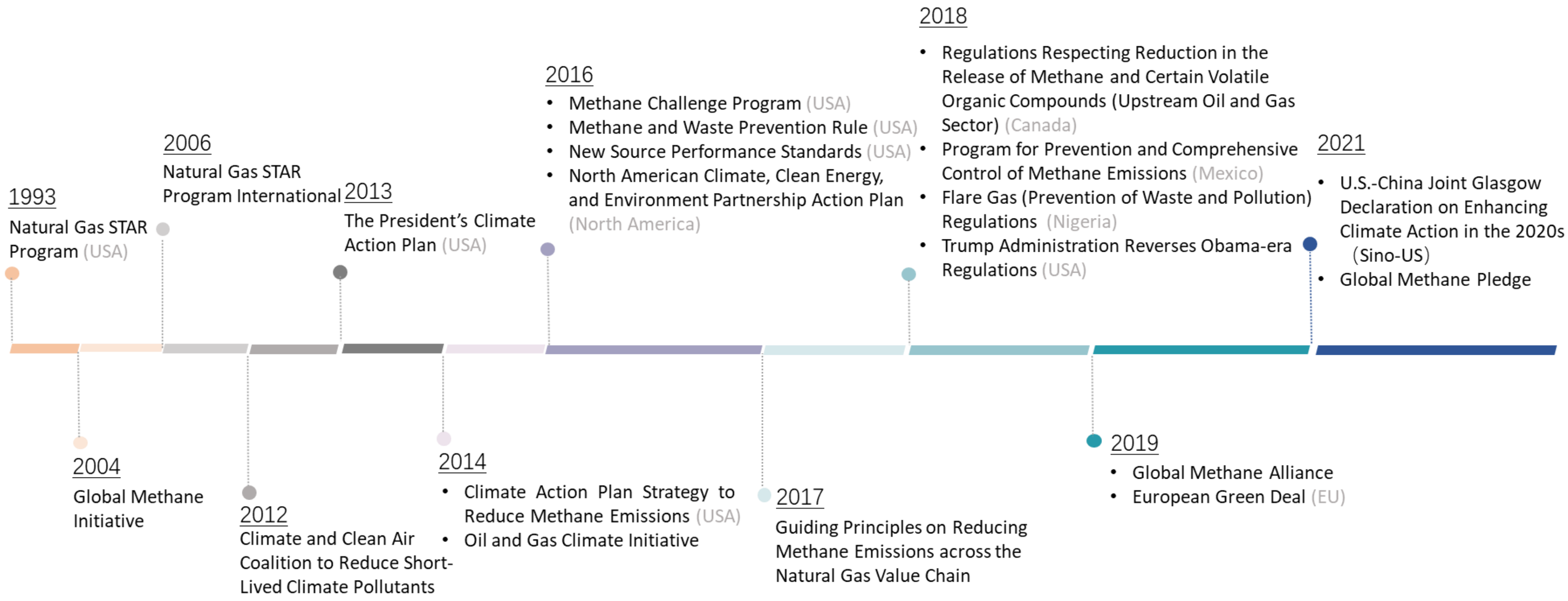

Fig.6 Major oil and gas methane control efforts (Those without country tags are at a transnational scale.)

4. Conclusions and policy implications

Reducing a short-lived climate pollutant like methane can buy us time to act more decisively in mitigating carbon dioxide emissions (Montzka et al., 2011). Recent years have witnessed the incremental policies and regulatory frameworks addressing methane emissions from oil and gas sectors (see summary in Fig. 6), with USA, Canada and Mexico taking a leading role. Meanwhile, the *Global Methane Alliance* has also urged its members to achieve an absolute reduction target of at least 45% reduction by 2025 or near-zero methane emissions in oil and gas sectors (CCAC, 2019). The most recent Global Methane Pledge, launched by USA, EU and other over 100 countries, commit to reduce global methane emissions by at least 30% from 2020 levels by 2030. However, our analysis has proved that supply-side measures are sometimes unable to capture the full impacts of a region due to increasing international trade, prompting the need to quantify oil and gas methane emissions induced by a region's final consumption, both from home and abroad. Otherwise, a reduction illusion may occur as some import-dominated consuming regions could achieve the methane mitigation target by outsourcing oil & gas methane emissions to export-oriented producing regions, which undermines the global methane reduction efforts. According to our results, for example, more than three quarters of oil & gas methane emissions embodied in EU's consumption comes from other regions (e.g., Russia, Rest of Africa and Rest of Asia). In the pursuit of de-carbonization of local energy sector, EU has proposed the European Green Deal, striving to be climate neutral in 2050 (EC, 2019), while less emphasis has been put to address the oil & gas methane emissions generated along EU's upstream supply chains. Consequently, it is needed to set a consumption-based targets (e.g., 40%~45% reduction in EU's consumption-driven oil & gas methane emissions by 2025) through various consumer-oriented policies, such as labelling low-emission products, encouraging more energy efficient vehicles and shift to a bio-based circular economy (IPCC, 2022; Moran et al., 2018). Technology and invest transfer to upstream suppliers is also conducive to the reduction of EU's methane footprint, as they can help to enhance methane leakage detection measures or improve methane recovery (Bjørn et al., 2018; Wood et al., 2017). Such policies are especially crucial when methane emissions are displaced from developed regions to developing regions where regulations are loose and technological and financial support are lacking generally. Moreover, USA, one of the largest oil & gas producer and once a pioneer in methane control in oil & gas sectors, has recently rolled back curbs on oil and gas methane emissions (EPA, 2020). Considering that consumption of USA also drives considerable oil & gas methane emissions, such demand-side measures could well complement the supply-side deregulation in USA.

The significant role of international trade in reshaping global oil & gas methane profile also creates additional opportunities for demand-side intervention. Our results show that more than three-fifths of the global oil & gas methane emissions are embodied in international, primarily exporting from large oil and gas suppliers (e.g., Russia, Nigeria and Iran) to large consuming economies (e.g., Mainland China, Japan and USA). The comparison of the major findings in this study with previous studies is shown in Appendix Table A6. It should be noted that the proportion of oil and gas methane emissions embodied in international trade is much higher than agricultural methane emissions embodied in rice, meat and milk products trade or methane emissions embodied in all commodity trade. Thus, the displacement of oil and gas methane emissions need more intervention. Meanwhile, the major embodied methane trade players are different when considering different methane sources and trade commodities. For example, Russia is a net exporter in terms of oil and gas methane emissions embodied in international trade, but a net importer in terms of livestock methane emissions embodied in international meat trade.

For import-dominated consumers, they should develop a comprehensive framework to measure, monitor and track the trajectory of methane emissions embodied in their imported goods and services along the global supply chains. Some fiscal instrument could be adopted, such as taxes on methane-intensive imports (Chaves et al., 2020; Fahimnia et al., 2015), but they should be treated with extreme cautions. For example, stimulated by the coal-to-gas switching policy, China imports increasing amount of natural gas, which also generates substantial methane leakages (Gan et al., 2020). Therefore, these regions should integrate methane emissions embodied in imports into their national commitment to methane reduction. For export-oriented producers, their oil and gas companies should improve the measurement, verification and transparency of methane leakage data to enhance green supply chain management, which could increase green competitiveness in global oil and gas markets (Ahmad et al., 2017; Yang et al., 2013). Moreover, international platforms (e.g., Global Methane Alliance, Global Methane Pledge and et al.) could scale up actions by developing tailored scheme to reduce the international oil and gas methane leakage. Since sectors, institutions and governments are brought together, coordinated efforts are more easily achieved than countries working alone.

Another interesting finding of our study is the critical but often overlooked role of non-oil & gas-sectors. Oil and gas as important energy sources and raw materials are primarily used as intermediate input to industrial production, methane emissions from oil and gas production are therefore transferred across global supply chains firstly as embodiments in a wide range of oil & gas-reliant non-oil & gas semi-processed products and eventually as embodiments in non-oil & gas highly-processed final products. Our results confirm that oil and gas sectors only captures roughly 18% of global total consumption-driven and displaced methane emissions respectively. In this case, it is necessary to trace oil and gas methane from the origin of emissions to the actual final products that are mostly provided by non-oil & gas-sectors. Otherwise, consumption-driven methane emissions will be mistakenly attributed to the intermediate agents rather than the real final consumers, which will lead to the underestimation of emission displacement and the responsibility of real final consumers, in turn misguiding policy makers in formulating consumption-based mitigation strategies. This particularly requires attention when major driving forces behind oil and gas methane emissions are found to be the demand of many developed economies (e.g., USA, EU and Japan). On one hand, as the largest final consumer, USA has strict methane regulations for oil and gas sectors, demand-side actions could serve as a complement to supply-side supervision and mitigation measures. On the other hand, developed economies usually have mature and complete regulatory systems, advanced technological support as well as sufficient financial resources. Fully realizing the decisive influence of these developed economies on oil and gas methane emissions can promote their participation in transnational methane control initiatives, making reduction practices more feasible and cost-effective. Moreover, revealing the role of non-oil & gas-sectors also provides detailed references for downstream sectors of oil and gas sectors (e.g., Construction, Transport, Electricity, Human health and social activities, Whole sale and Chemical products) to implement industry-scale policies. For example, these sectors should both improve resource-efficiencies in the production and green its upstream supply chains, for example, by shifting from fossil-based raw materials to bio-based raw materials (Yang et al., 2021).

Differentiating specific emission sources is also helpful to control methane emissions. It is reported that oil and gas methane emissions is dominated by emissions from venting of petroleum gas and unintended leakage due to oil production in Russia, China and many countries in central & western Asia and Africa as well as emissions from unintended leakage in gas production in USA and Canada (Höglund-Isaksson, 2017). Under the circumstances, direct emitters and corresponding final consumers should target on different emission sources. While future changes in energy structure should also be considered. For example, the USA is expected to contribute the largest increase in oil production between 2018 and 2040 (IEA, 2019). Therefore, it should not only focus on methane emissions from gas system but also watch out for potential emissions from oil production. Moreover, it is found that reduced methane emissions from extended associated petroleum gas recovery in recent years is largely offset by the growing methane emissions from unconventional gas expansion in USA and Canada. In the meanwhile, gas production is estimated to grow in the presence of stated policies, with the growth led by unconventional gas (e.g., shale gas) since the shale gas revolution in USA is in full swing (IEA, 2019). The increasing contribution of unconventional gas extraction therefore deserves additional attention in future efforts to reduce methane emissions.

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